# Land Cover Effects on Hydrologic Regime within Mixed Land Use Watersheds of East-Central Ontario

A Thesis Submitted to the Committee on Graduate Studies in Partial Fulfilment of the Thesis Requirements for the Degree of Master of Science in the Faculty of Arts and Science

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# Abstract

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Land cover change has the potential to alter the hydrologic regime from its natural state. Southern Ontario contains the largest and fastest growing urban population in Canada as well as the majority of prime (Class I) agricultural land. Expansions in urban cover at the expense of agricultural land and resultant ‘agricultural intensification’, including expansion of tile drainage, have unknown effects on watershed hydrology. To investigate this, several streams with a range of landcovers and physiographic characteristics were monitored for two years to compare differences of flashiness and variability of streamflow using several hydrologic metrics. Urban watersheds were usually the flashiest while agriculture had moderate flashiness and natural watersheds were the least flashy across all seasons, signifying that landcover effects were consistent across seasons. Tile drainage increased stream flashiness during wet periods, but minimized the stream response to an extreme rain event in the summer, perhaps due to increases in soil moisture storage. A sixty-year flow analysis showed that flashiness and streamflow increased ($p < 0.05$) above a development threshold of ~10% of watershed area. Flashiness was also greater in wetter years suggesting that climate shifts may enhance stream variability in developed watersheds.

**Keywords**

Landcover, Landcover Change, Urban, Agriculture, Natural, Streamflow, Precipitation, Hydrologic Regime, Tile Drainage, Flashiness, Principal Component Analysis, Hydrologic Metrics, Flow Duration Curve

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# 1.0: Literature Review

Areas of forests and wetlands have been drastically reduced in southern Ontario since European settlement in order to create space for urban and agricultural development (Butt et al., 2005). Approximately 1/3 of the total area in southern Ontario is currently classified as agriculture, including land devoted to livestock pasture and row crop production (Weng, 2017). This area is also home to almost 40% of Canada's population (Statistics Canada, 2022), the majority of whom (~90%) reside in urban areas (Ahmed, 2019). Notable population increases are projected for the Greater Golden Horseshoe from ~10 million currently (2019) to 14.8 million by 2051 (Ontario Ministry of Transportation, 2022) and continued expansion of urban cover puts pressure on existing agricultural land and may have consequences for the quantity and quality of water resources.

Approximately half of Canada's endowment of 'prime' agricultural land (Class 1; defined as having no significant limitations for crop production; Ontario Ministry of Agriculture Food, and Rural Affairs, 2016) is located within southern Ontario (Hofmann et al., 2005) due to the coexistence of deep soils, relatively gentle topography and a warm, temperate climate during the growing season that allows for high crop yield (Hofmann, 2001). There is increasing concern that further population growth within urban areas in southern Ontario will consume surrounding agricultural land (Hofmann 2001). Competition for increasingly scarce agricultural land may also drive increases in the intensity of agriculture (Hofmann, 2001). Agricultural intensification is defined here as farming techniques that result in a larger yield of output per unit area and includes increased inorganic fertilizer application, reduced crop variety and installation of tile drainage (TD). In southern Ontario, crop production has become more intensive since the

1940s as row crops are replacing pastureland used for cattle production (Smith, 2015). Grain corn and soybeans are the primary row crops grown in eastern Canada and the total areas of these crops have drastically increased (~500% and ~300% increase, respectively) since the 1960s (Smith, 2015). Tile drainage is often installed beneath row crop fields ~1m in depth to increase crop yield and extend the growing season by limiting spring flooding for earlier crop planting (Tan et al., 1999). These shifts in land use and trends toward increasing urbanization and agricultural intensification may affect water quality and quantity, although there have been fewer studies of the effects of mixed land use changes on watershed hydrology compared with water quality (Hoghooghi et al., 2018).

The water balance equation provides a useful framework for examining the effects of land cover change on watershed hydrology. The water balance relates the amount of incoming precipitation with the amount of water exiting the system via evapotranspiration (ET) and runoff, with the difference attributed to storage and residuals in errors of estimation (RESW) (Equation 1.0).

Equation 1.0

$$Runoff = Precipitation - Evapotranspiration \pm \Delta\, Storage + RESW$$

Land cover changes that lower the amount of water lost via ET will result in a larger fraction of incoming precipitation being translated into runoff if storage remains unchanged. Likewise, any changes in watershed storage will also affect the amount of runoff generated from precipitation (or snowmelt) inputs. Topography and surficial deposits also influence the runoff response, as sloped watersheds (e.g., > 5 degrees) tend to generate more surface runoff leading to rapid changes in flow (Wainwright & Parsons, 2002), and fine-textured soils that are dominated by clay have reduced infiltration and more rapid runoff responses compared with sandy-textured soils (Groenendyk et al., 2016). Urbanized watersheds often exhibit a rapid hydrologic response to precipitation inputs due to large amounts of impervious surfaces that shed water quickly into streams as surface runoff and limit infiltration and soil moisture storage. Evapotranspiration is also typically reduced due to generally less vegetation cover in urban areas compared with pre-development (Taha, 1997). Further reductions of ET are caused by impermeable urban cover limiting soil moisture storage that can be transpired by plants, but this process is severely hampered by the relative lack of vegetation in some urban areas (Booth, 1991). Alternatively, evapotranspiration can be enhanced in urban areas that are irrigated (i.e. lawn watering; Peters et al., 2011). Evapotranspiration can be further altered in urban compared with rural areas by the heat island effect, which results in warmer temperatures that melt and evaporate winter snow, effectively decreasing runoff (Mazrooei, 2021). Winter snow removal can additionally alter the water balance by transporting snow across watershed boundaries (Bengtsson & Westerström, 1992).

Agriculture may also alter the landscape water balance; however, agriculture is typically considered to be less impactful compared with urban coverage. In southern Ontario, the primary shift in agriculture has been toward increased row crop production at the expense of pastureland and mixed agricultural production (Smith, 2015). Annual row crops tend to have lower ET losses compared with forests, and conversion of natural land to row crops is estimated to have reduced ET by 5-15% and increased total runoff by 10-30% relative to pre-settlement in the Great Lakes basin (Mao & Cherkauer, 2009). In addition, the replacement of perennial grasses that typify pastureland with annual corn and soybean has been shown to reduce ET and increase runoff by approximately 10%, some of which is contributed by subsurface TD (Schilling et al., 2008). Seasonal shifts in hydrology are also important to note in the Great Lakes context. For example, a combination of frozen soils and plant dormancy in the winter and spring months reduce the potential ET and water storage capacity of soils and result in a larger runoff response to rainfall or snow melt events (Mahmood et al., 2017). The reduction of ET may be more important for agricultural land cover hydrologic response since natural cover (i.e. deciduous forests) can still transpire in spring months and limit runoff (Nehemy et al., 2022; Young-Robertson, 2016). Subsurface TD affects the water balance (shown in Figure 1.1) by increasing how much water the top layers of soil can hold by lowering the water table and allowing plants roots to extend deeper into the soil profile (Irwin & Whitely, 1983). Rain is then absorbed by the drier soil and converted to ET by plants resulting in less runoff during the growing season (Irwin & Whitely, 1983). However, several studies have noted the effect of antecedent moisture content on the runoff response of tile drained fields. For example, high antecedent moisture conditions may lead to more runoff generation in tiled fields due to greater hydrologic connectivity with streams, especially when ET is low after crops are harvested (Macrae et al., 2010; King et al., 2014).

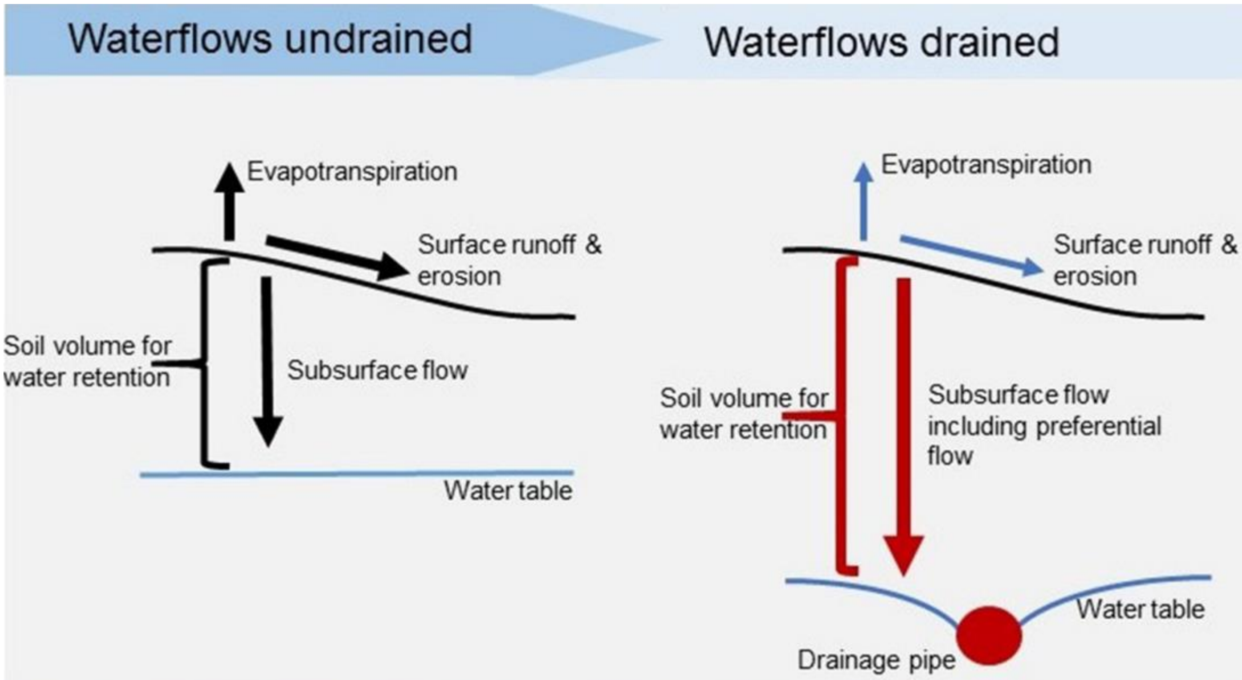



Figure 1.1. Hydrologic pathways before and after installation of tile drainage. Red arrows represent increased fluxes, blue arrows represent decreased fluxes. Figure originally from Gramlich et al. (2018).

Hydrographs are a way to visually assess a stream's response to precipitation inputs as well as to compare patterns of streamflow between watersheds that have variable land cover. Urban watersheds tend to exhibit steeper rising limbs, higher peak flows and steeper declines in flow following storm peaks as a result of smaller storage capacities, less infiltration and lower evapotranspiration losses (Konrad & Booth, 2005). Conversely, more natural streams tend to have hydrographs with slower-rising, smaller peaks that are associated with greater storage of soil water that is released more slowly to the stream. These differences between 'flashy' and 'stable' streams are illustrated in

Figure 1.2, which shows the hydrograph response of a rural watershed undergoing urbanization.

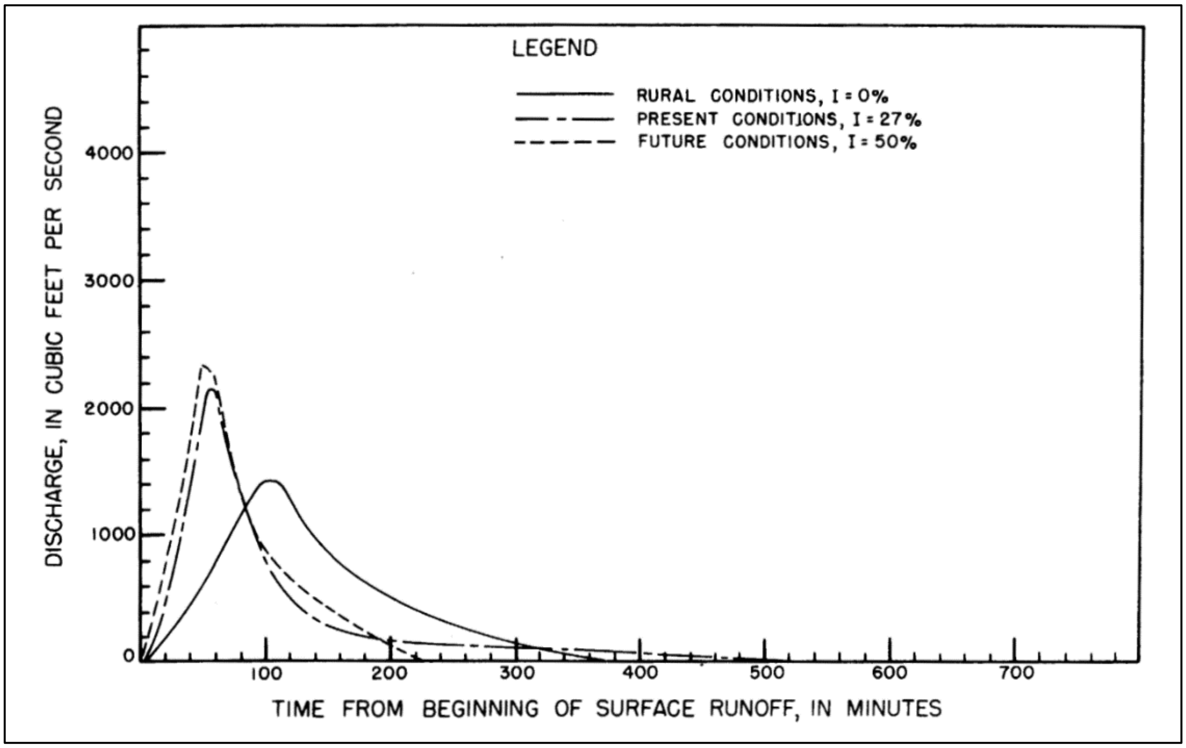
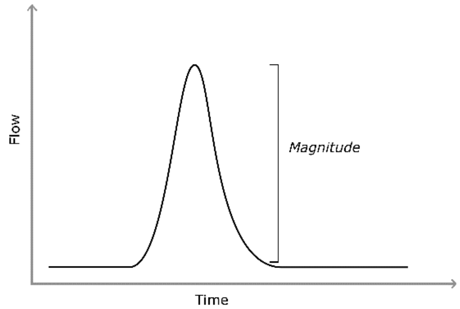


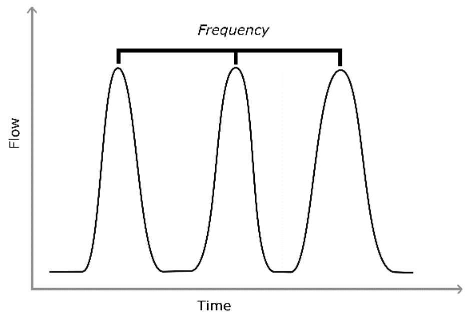

Figure 1.2. Runoff response to increases in impervious cover at a rural watershed, from Espey et al. (1966). ‘I’ represents the proportion of impermeable surface coverage in the watershed.

Patterns of runoff in a watershed ultimately determine the ‘hydrologic regime’ of a stream. The hydrologic regime describes patterns of streamflow that are affected by the proportion of flow occurring as baseflow vs. stormflow, the seasonal distribution of flow, and storage of water in soils and snow. Natural factors that can influence the hydrologic regime include topography, climate, soil type, watershed size, and vegetation cover (Poff et al., 1997; Baker et al., 2004). Five important runoff characteristics that characterize the hydrologic regime include: i) <u>magnitude</u> (e.g., maximum and minimum flows), ii) <u>frequency</u> (i.e., how often high or low flow events occur), iii) <u>duration</u> (i.e., how long a flow threshold is exceeded), iv) timing (e.g., regular patterns and predictability of flow), and v) rate of change (i.e., how quickly flow changes) (Poff et al., 1997). Further explanation of each of these components is provided in Figure 1.3 below.



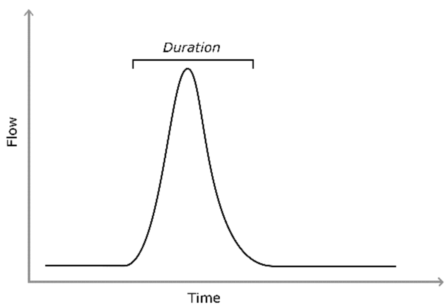

Magnitude

- Measurement of flow at any given moment. Usually, the highest and lowest magnitudes of flow are of interest when comparing different flow regimes.
- Particularly important for baseflow index and $T_{\mathbf{Q}\text{mean}}$ flow metrics which measure the amount of time (T) flow (Q) exceeds a threshold.



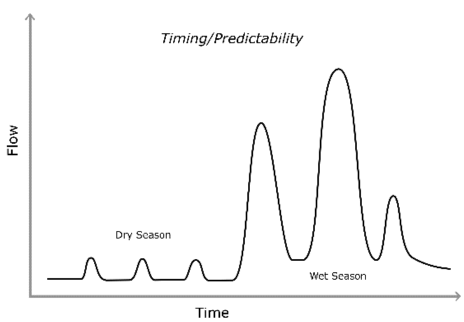

Frequency

- Describes how often peak flow events reach a certain magnitude over a given period of time. Often used with flood frequency analysis.
- Important for Richards-Baker Index (RBI), flow duration curves, baseflow index, and coefficient of variation flow metrics.



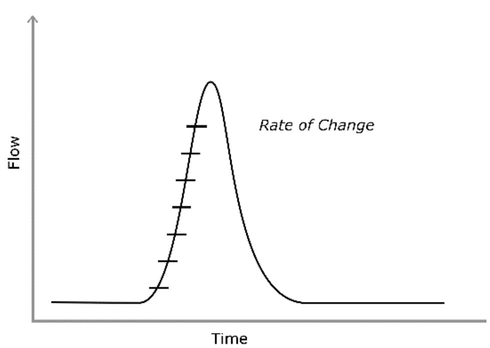

Duration

- Time period when flow meets certain conditions. This could be the length of time from the start of the rising limb to the end of the falling limb (as depicted), or the length of time flow exceeds a certain threshold.
- Especially important for $T_{\mathbf{Q}\text{mean}}$ metric.




Timing/Predictability

- The regularity of streamflow over multiple years of record. For example, the proportion of baseflow vs. event flow by season.




Rate of Change/Flashiness

- How quickly flow changes from one interval of flow to another.
- Especially important for calculating Richards-Baker Index flow metric.

Figure 1.3. Graphical examples depicting components of the flow regime. Flow metrics are described in Table 2.4 of Chapter 2.

These five components describe the hydrologic behavior of a watershed and are useful metrics for assessing changes in streamflow caused by human alteration of land cover. Land cover changes that modify hydrologic flow pathways through the landscape include impervious or paved surfaces from sidewalks, buildings and roads in urban areas, as well as surface and subsurface drainage pipes in urban areas and agricultural fields (King et al., 2014). Furthermore, changes in vegetation, including reductions in total cover within urban areas or shifts from perennial to annual crops in agriculture, can also influence flow pathways (Connolly et al., 1997). These changes in land cover commonly lead to increases in runoff that can affect the five components of the flow regime mentioned above.

The effect of land cover change on the **magnitude** of streamflow is frequently considered in the literature because larger flows can potentially cause damaging flood events and alter stream geomorphology. Urban cover is recognized for enhancing runoff from rain or snowmelt events and causing higher magnitude streamflow (Rosburg, 2017; Sheeder et al., 2002). Miller et al. (2014) found that after 33% of a watershed was urbanized, the magnitude of peak flow events increased by 400% when compared with pre-development.

The **frequency** of flow refers to how often streamflow of a particular magnitude occurs and commonly focuses on extreme flows, especially those that cause flooding. Moscrip & Montgomery (1997) found that urbanizing watersheds (~15 to 45% of total area) experienced 10-year flood events more frequently over time such that they became one-to-four-year flood events. In contrast, the effect of agricultural development on flood frequency is not as clear, perhaps due to the diversity of agricultural practices within agricultural watersheds and other factors such as topography and climate (Villarini et al., 2011).

**Duration** of flow can be expressed as either the total amount of time between the start and end of a flow event (see Figure 1.3), or the amount of time that flow exceeds a particular rate threshold. Flow duration curves (FDC) are a common way to express this metric and show the percent of time specific discharges are equaled or exceeded during a given period. Flow duration curves are usually plotted using data collected over a relatively long period of time (e.g., >10 years) and can be used to illustrate changes to flow resulting from land modification. For example, land cover changes that increase runoff tend to result in more variable flow regimes with steeper FDCs whereas flow in groundwater-fed natural streams is more stable and their FDCs tend to be flatter (Searcy, 1959).

**Timing** and **predictability** of flow are important indicators of stream ecological health (Poff et al., 1997), and may be responsive to both land cover and climate change. The timing of rapid urbanization over the course of several decades coincided with increased peak flows at several watersheds in the eastern U.S. (Hopkins et al., 2015). In addition, climate change is expected to advance the timing of melt events in seasonally snow-covered regions such that peaks may occur earlier and with higher magnitude in the winter and early spring from more frequent rain-on-snow events (Contosta et al., 2019).

The **rate of change/flashiness** is of interest in this study because developed land cover typically conveys precipitation or snowmelt more rapidly toward streams. Poff et al. (1997) defined flashiness as simply “the rate of change of flow from one magnitude to another” (p. 771). Baker et al. (2004) expanded the definition to include “frequency and rapidity of short-term changes of streamflow that occur during runoff events" (p. 503). Hydrologically stable streams, by contrast, are associated with greater baseflow or groundwater inputs that slowly respond to rain or snowmelt events (Baker et al., 2004).

Flashiness may be an effective *composite* metric because as a stream becomes flashier, the other four flow regime components are affected, including the magnitude of peak flow, the frequency of flooding, the duration of high flows, and changes in the timing of flow events (Rosburg et al., 2017; Hopkins et al., 2015; Conly & Van der Kamp, 2001; Baker et al., 2004; Poff et al., 1997). Likewise, the water balance (Equation 1.0) is a useful tool for evaluating how human-altered land covers affect runoff, which may lead to higher flashiness. The effects of land cover and climatic shifts on stream flashiness are described further below.

## Land Cover Effects on Flashiness

### *Urban Cover*

Compared with other forms of human development, urban land cover is usually thought to have the greatest impact on hydrologic regime. Impervious surfaces move water faster due to less frictional resistance, negligible infiltration and smaller soil water storage, resulting in flashier streamflow (Konrad & Booth, 2005). Additionally, stormwater pipes move water quickly off the landscape (especially from impervious surfaces) and increase hydrologic connections between land and streams (Graf, 1977). These changes to hydrologic pathways affect the amount of streamflow occurring as baseflow vs. storm flow (Leopold, 1968). For example, urbanization of Long Island, New York reduced the proportion of streamflow occurring as baseflow from 95% to 20% as a result of limited infiltration and water storage (Simmons & Reynolds, 1982). Additionally, peak flows can be 100 – 300% larger in watersheds with a high proportion (> 60%) of impermeable surfaces (Valtanen et al., 2014). Conversely, other studies have shown that low to moderate increases of urban cover can increase baseflow by funneling water to low lying areas (e.g., retention ponds) where it is slowly released and/or recharged to groundwater (Brandes et al., 2005). Modern best management practices in urban environments, including stormwater ponds, can increase storage capacity and intercept fast moving runoff before it enters streams, thus lowering the rate of flow change. Pennino et al. (2016) showed that peak runoff was decreased by 44%, runoff events were 26% less frequent, and flow variability was decreased by 26% by adding flow detention and retention best management practices near Washington D.C., United States.

*Agriculture*

Agriculture encompasses a variety of land uses ranging from pastureland for livestock to tile-drained row crop fields to vineyards and various horticultural uses. Overall, agricultural land use has been shown to have a more moderate effect on flow magnitude compared with urban land cover (Sheeder et al., 2002, Eimers & McDonald, 2015); however, agriculture may alter the hydrologic regime through affecting stream flashiness. Hollis (1975) determined that undeveloped land is overall less flashy than urban environments but can still generate large amounts of overland flow when soil is saturated with water, particularly during spring melt when soils remain frozen. Baker et al. (2004) found that increases in the proportion of agriculture within Ohio watersheds increased stream flashiness, although not as substantially as for urban cover. They also noted that agricultural land can have complicated and varied effects on hydrology that are dependent on soil management, riparian zones, crop type and artificial drainage (Baker et al., 2004).

Tile drainage is a common and potentially impactful hydrologic alteration associated with agricultural intensification. In Ontario, TD is associated with expansions of row crop agriculture. The role of TD is to lower the water table which allows plants to grow deeper roots, remove excess water during spring months for earlier planting and in the fall months for later harvesting for longer crop maturity, and reduce the risk of compaction of saturated soils (Irwin & Whiteley, 1983; Plamenac, 1988). A lower water table further reduces the risk of fields flooding, especially after snowmelt (Seuna & Kauppi, 1981; Skaggs et al., 1994) and limits the amount of overland flow and theoretically the flashiness of the watershed (Blann et al., 2009). However, drainage pipes can also increase hydrologic connectivity and increase subsurface flow between fields and streams by removing the frictional forces soils have on infiltrating water that would originally slow runoff rates, similar to urban storm drainage (Skaggs et al., 1994). These two conflicting effects can lead to inconsistent reports of TD either decreasing or increasing peak flows, which may in part be due to antecedent soil moisture conditions. For example, Schilling et al. (2019) found that tile drains did not flow during the summer months when soil moisture was low and ET was high whereas flow resumed after crops senesced in October and November, and soil moisture was higher. This suggests that flashiness may be more seasonal in watersheds dominated by tile drained fields. In addition, watershed physiographic characteristics such as slope and soil texture can influence whether TD promotes higher peak flows (Holden et al., 2006), although TD tends to create higher peak flows when compared with natural, untouched land (Skaggs et al., 1994). The intricacies of agricultural land use change demonstrate how impacts to the hydrologic regime can be highly variable from region to region, establishing the need for research in small watersheds that considers the influence of local factors such as soil texture and climate.

Crop type can also affect the runoff response of agricultural lands. In Ontario, increases in row crop agriculture at the expense of pasture for livestock may alter runoff generation via changes in ET and flow pathways (Veeman & Gray, 2010). For example, in the prairies of the U.S., naturalization projects that converted annual crops (corn and soy) to native prairie grasses reduced peak flows by 37% on average (Hernandez-Stanan et al., 2013). The authors suggested that the deeper root systems of perennial plants created more macropores that allowed water to penetrate deeper into the soils, ultimately reducing event runoff and contributing to storage in soils. Notably, runoff from pasture is typically higher than from natural land covers due to soil compaction caused by livestock that promotes surface runoff. One study in Brazil, where deforestation is promoted to create pastureland, found that a small watershed dominated by pastureland generated 17 times more surface flow volume relative to a comparable forested watershed (Germer et al., 2010). Similarly, another study in New Zealand found that pasture generated 1.6 to 2.1 times more annual flow than forested catchments (Dons, 1987).

**Climatic Variability**

*Precipitation*

The amount, form, timing and intensity of precipitation also affect the runoff response of streams, and changes in precipitation regime associated with climate change may compound the effect of land use changes on catchment hydrology. Saturated overland runoff is typically produced from high intensity precipitation events that exceed the infiltration-capacities of soils (Horton, 1933) as well as snowmelt events over frozen soils. Any increase in the intensity or frequency of large precipitation events may therefore contribute to increases in stream flashiness. Research has shown that higher amounts of rainfall at the annual scale enhance stream flashiness (Saharia et al., 2021; Bezak et al., 2015). Precipitation is expected to become more extreme with climate change. Zhang et al., (2019) predicted that extreme events will become more common over the course of the 21st century across Canada. They also noted that the frequency of extreme events is more uncertain and is harder to detect due to high inter-annual variation (Zhang et al., 2019). Contrary to this result, Deng et al. (2016) found that the frequency of both heavy (≥ 10mm) and very heavy (≥ 20mm) precipitation days were likely (67-90 % chance) to increase over the next century in southern Ontario. They also predicted that the number of days with precipitation ≥ 10mm would increase by 4-6 days by 2100 from a current frequency of 27-29 days/year (Deng et al., 2016). Another study analyzed flooding frequency caused by climate change in southern Ontario and showed that the duration and number of peak flows that cause small flood events have increased in Ontario over the past 80 years using reference watersheds that have not had substantial changes to their land cover (Burn & Whitfield, 2016). Thus, any evaluation of flow response to land cover change must also consider the effects of changes in weather extremes.

*Air Temperature*

Warming temperatures from climate change can alter the timing and magnitude of hydrologic events and influence the seasonality of flashiness, usually associated with snow melt in southern Ontario. Average air temperatures in southern Ontario are predicted to increase by ~2.2°C over the next five decades which will increase the amount of rain vs. snow falling in the winter, reduce snowpack depth and duration and create smaller and/or earlier spring melt during the winter months (Grillakis et al., 2011). This change, along with increases in extreme precipitation, can potentially generate larger peak flows (Jiang et al., 2020). However, a decreasing snowpack in the early winter months may reduce the total volume of snow melt and result in a more episodic or protracted winter flow regime. A study of watersheds in the eastern U.S. found that warmer winters had thinner snowpacks and usually smaller, but more frequent peak flow events in late March than colder winters, which had deeper snowpacks and larger runoff peaks caused by snow melt towards the end of May (Ford et al., 2021).

These differing results demonstrate the complex effect of climate change on snow melt patterns and winter/spring runoff generation. Snow depth affects the extent, depth and duration of soil freezing in the winter months; a deeper snowpack insulates the ground from cold air temperatures, reducing the freezing depth, while shallower snowpacks can allow deeper freezing if air temperatures are cold enough (Zhang, 2005).

Consequentially, while a shallow snowpack would reduce the total volume of spring melt, it may paradoxically promote more overland flow as a result of soil frost causing larger peaks and flashiness earlier in the winter. Warmer air temperatures may also lead to more frequent freeze-thaw cycles, which could influence runoff flow paths during winter.

Warming temperatures are also predicted to increase ET. In Canada, most climate models predict that winter and spring will become wetter from increases of precipitation, and more specifically rainfall, whereas summer and fall will become drier as a result of more ET, especially towards the end of the 21st century (Tam et al., 2019). Southern Ontario is expected to follow this trend although with more moderate wetting and drying compared with other parts of the country (Tam et al., 2019). Both impacts can alter the seasonal water balance and flow regimes, and drier summers may result in more frequent or extreme droughts.

Droughts are defined as a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance" by the American Meteorological Society (1997, p. 785). Droughts put stress on services that require water, such as irrigation in agriculture and drinking water in urban areas. Notable droughts occurred three times in Canada over the 20th century, including the 1930s, 1960s, and late 1990s, when a string of sequential years in each decade received between 10% and 20% less precipitation and warmer-than-average temperatures (Klaassen, 2003). The author also noted that the 1998-1999 drought may have been exacerbated by especially high temperatures in this year causing higher ET. The frequency and intensity (or duration) of dry periods are also expected to increase with climate change, which will reduce soil moisture and stream runoff (Cook et al., 2020; Maloney et al., 2014). An overall reduction in streamflow due to lower precipitation could reduce conditions that create flashiness such as high soil moisture and frequent rain events.

Drought conditions may also affect runoff flow paths and stream flashiness when soils are rewet following subsequent rain events. For example, soils may become hydrophobic during extended dry periods, which may favour overland flow generation and hasten runoff delivery to streams (Witter et al., 1991). Conversely, soil cracking that occurs in clay-rich soils that are dried may enhance macropore drainage and allow more rapid drainage when soils are rewet by subsequent rain events (Nimmo, 2012). Both conditions could potentially lead to more flashy stream conditions. These complexities of soil dryness make determining how quickly water will run off following drought conditions difficult to predict.

**Hydrologic Metrics**

A variety of metrics can be used to analyze the hydrologic regime of streams and evaluate their response to land cover and/or climate change. Hydrologic metrics are often used to evaluate baseflow for ecological protection and assess changes in the frequency of flood events (Clausen & Biggs, 1997). Variation of flow and flashiness are common themes when comparing streamflow over time and to other streams. Several metrics can be used to quantify variation in flow including the coefficient of variation, which describes some aspects of flashiness, but does not account for the rate of change in flow during peak flow events. In contrast, metrics such as the Richards-Baker Index (RBI) quantify flashiness by calculating how quickly flow rises and falls over a period of time using continuous flow data (Baker et al., 2004). All of these metrics are commonly used to investigate changes in flashiness caused by land cover (Booth and Konrad, 2017) or, less commonly, precipitation variation potentially caused by climate change (Holko et al., 2011). In addition, the hydrologic regime can be described by assessing changes in flow components including baseflow and peak flow. Konrad & Booth (2005) compared several metrics (e.g., coefficient of variation, $T_{Qmean}$, flow percentiles), that target different aspects of the flow regime and suggested that some metrics may be more useful than others for detecting changes in flow patterns caused by urbanization. In contrast, there have been relatively few hydrologic assessments of changes in agricultural watersheds, especially those that are undergoing shifts from less intensive pasture to more-intensive tile-drained row crop systems. Furthermore, there have been few if any comparisons of agricultural vs. urban development effects on hydrologic response in mixed land use watersheds such as those that dominate southern Ontario since most studies focus on one type of land use in a watershed (Gyamfi et al., 2016).

**Importance and Objectives**

In light of these knowledge gaps, the overarching objective of this study was to investigate the effects of land cover change on the hydrologic regime in southern Ontario. Several hydrologic metrics to quantify flow variability and flashiness were used to identify differences in mixed use watersheds with varying land cover. In addition, metrics describing flashiness and variation of flow were used to quantify and compare how different land covers affect flow at different time scales (annual and seasonal) and better understand how hydrologic conditions, such as snowmelt, may obscure or amplify flow response. In the first research chapter, the primary objective was to compare the hydrologic response of watersheds with different proportions of urban or agricultural land using several metrics that quantify flashiness and variability of flow. Watersheds were selected to include a gradient of land cover and range from entirely urban or intensively agricultural to predominantly natural land cover. The second research chapter aimed to identify long-term trends in flashiness resulting from precipitation changes and increased urban cover since the 1960s in quaternary watersheds flowing into Lake Ontario. Results of this study can provide insight into the hydrologic effects of current land cover regimes and give information for watershed planners to further protect the natural flow regime.

# 2.0: Varying Landcover and Physiography Effects on Flashiness

## 2.1 Introduction

The hydrologic regime of streams consists of flow patterns that are influenced by many factors, including land cover, climate, and other watershed characteristics such as slope and soil type (Poff et al., 1997). Land cover change is a common and well researched alteration to watersheds that is known to change the natural flow regime rapidly, while other factors that influence flow patterns usually change over longer periods of time, such as climate and soil characteristics. Despite variable hydrologic responses to forest management (Dan Moore & Wondzell, 2005), many studies in northern experimental forests have shown that complete removal of natural vegetation (i.e. clear-cutting) causes increases in annual runoff and peak flow compared with pre-cutting flows (Whitehead & Robinson, 1993). The resulting increases of runoff and peak flows are primarily explained by decreases in evapotranspiration (Yang et al., 2017). These types of studies suggest that similar impacts will occur when natural vegetation is removed for other land uses such as urban or agricultural development. The hydrologic regime can be further altered by changes in drainage density associated with urban and agricultural developments including storm sewers and subsurface tile drainage (TD) that can increase runoff and move water faster into streams (Ogden et al., 2011; Schilling et al., 2015). Faster transfer of water contributes to stream 'flashiness', which Poff et al., (1997) describes as a component of the hydrologic regime.

Currently, watersheds in southern Ontario exhibit a mosaic of urban, agricultural and natural cover, and further land cover change is expected to occur over the next few decades due to large increases in population. More specifically, by 2046, populations in most urban areas near Lake Ontario are expected to grow by more than 20% (Ontario Ministry of Finance, 2021). Expansions in urban cover to accommodate growing populations have historically replaced valuable agricultural land (Hofmann 2001; Ali, 2008). The type of agriculture practiced in Ontario has also changed dramatically over the past several decades with major increases in row crop production (primarily corn, soybeans and wheat) at the expense of mixed farming and pastureland (Smith, 2015). Corn and soy have increased significantly in total area by approximately 4x and 5x, respectively, since the 1950s (Smith, 2015). Although TD has historically dominated the relatively flat and fine-textured soils in southwestern and eastern Ontario, there have been major increases of TD in the east-central region where watersheds are more sloped and soils are coarser, characteristic of the Oak Ridges Moraine (ORM). Increased focus on corn-soy production, which is often tile-drained and reliant on inorganic fertilizer (instead of manure), is a common component of ‘agricultural intensification’. The combination of agricultural intensification and urban expansion in southern Ontario is expected to alter hydrologic regimes which may enhance stream flashiness.

While there have been a relatively large number of studies that have described the various effects of urban cover on hydrology (e.g. Baker et al., 2004; Booth & Konrad, 2017; Eimers & McDonald, 2015; Clausen & Biggs 2000), the influence of agricultural intensification is less clear. Furthermore, most urban areas in southern Ontario are surrounded by agricultural landscapes, and intensification within the agricultural headwaters could enhance the hydrologic response of downstream urban areas. As such, it is important to characterize ‘baseline’ hydrologic conditions across a range of common land covers and within mixed landscapes to identify the hydrologic metrics that are most responsive to land cover change. To that end, the objective of this study was to evaluate stream flashiness across a gradient of land cover using a variety of metrics that have been shown to be sensitive to either urban or agricultural cover. This analysis was done at both the annual and seasonal scales as snow cover/snow melt and rainfall volumes may obscure (or amplify) the hydrologic response to land cover change.

This research chapter tested the following hypotheses:

i) The Richards Baker (RBI) and coefficient of variation (CV) metrics are most sensitive to urban cover and the base flow index (BFI) metric is most sensitive to natural cover.

ii) Flashiness as indicated by RBI and CV is greatest at urban watersheds, followed by intensive agricultural and then non-intensive agriculture watersheds, and the hydrologic regime at natural watersheds is the least flashy.

iii) Flashiness is best observed at the annual time scale, and flashiness is higher in years with more precipitation due to more frequent runoff responses.

## 2.2 Methods

*Study Area*

Nineteen watersheds were selected for study within the east-central portion of southern Ontario, broadly defined as the area south of the ORM and Rice Lake, and north of Lake Ontario, between Newcastle and Cobourg (Figure 2.1). This area was selected because it contains a mixture of agricultural, natural and urban land uses (see Figure 2.2), which makes it ideal for investigating the response of streamflow to land cover change. The ORM region is primarily forested, especially in the Ganaraska Forest Conservation Area and Northumberland Forest to the west and south of Rice Lake, respectively. Soils within the headwater region of the ORM are commonly coarse textured with rapid drainage (Figure 2.3). In contrast, agriculture dominates land use south of the ORM where soils transition to loams of finer texture with pockets of sand or clay-based soils closer to Lake Ontario (Figures 2.2 & 1.3; Webber et al., 1946). Agriculture in this region includes both 'intensive' row crop farming (herein defined as fields devoted to corn-soybean-wheat rotation), as well as livestock and pastureland. Small areas of urban land are located throughout the study area, although many of the larger urban centres are located along the lake shore (e.g. Port Hope, Cobourg, Bowmanville). The region has a humid temperate climate and falls within the Koppen *Dfb* sub-type that is characteristic of hot summers and cool winters with precipitation distributed relatively evenly throughout the year. Annual average precipitation between 1971-2000 at Oshawa was 872 mm (839 mm to 907 mm, CI = 95%) of which 14% fell as snow, and average monthly temperatures range from 20.2°C to -5.3°C in July and January, respectively (Environment and Climate Change Canada, 2019).

A combination of eleven existing Water Survey of Canada (WSC) flow monitoring sites and eight new flow stations were established to evaluate the influence of land cover on streamflow characteristics (Figure 2.1). Stations were selected based on small watershed size and some were targeted due to their relatively homogeneous land cover. For example, most watersheds are less than 100 $km^2$ (Table 2.1) to limit the influence of size on hydrologic patterns. Accessibility to sites year-round was also a consideration in site selection, and some sites were rejected due to not having permission to enter private property or because they were inaccessible due to terrain. In addition, watersheds that had higher wetland cover and/or poorly defined banks were also avoided, due to difficulties in estimating discharge from flood-prone areas. Streams also had to be perennial so that data could be collected year-round for seasonal analysis.

The relatively small size of watersheds allowed specific land uses to be targeted (i.e. larger watersheds tend to have more mixed land cover). Fourteen of the study watersheds have a dominant land cover (~60% or greater) of either urban, agricultural (intensive vs. non-intensive), or natural. Specifically, Gan Nat 1, Gan Nat 2, Gan NW and Gan Osaca are predominantly natural (forested), and range in size from 9.3 – 72 $km^2$. In contrast, Gan 1, Gan 2, Cobourg Up, Gage East, Gage West, Brand, and Mystery are primarily agricultural, with Cobourg Up having a greater area of pasture and the rest having more row-crop cover (Table 2.1). Of these row-crop dominated watersheds, TD also varies – the most heavily tile-drained watersheds are Mystery, Brand and Gage West with 100%, 85%, and 38% of row crop area recorded as tile drained, respectively (Table 1.1).  For this thesis, Mystery Creek is considered the most ‘intensively’ agricultural, followed by Brand Creek. Although most study sites were located between Newcastle

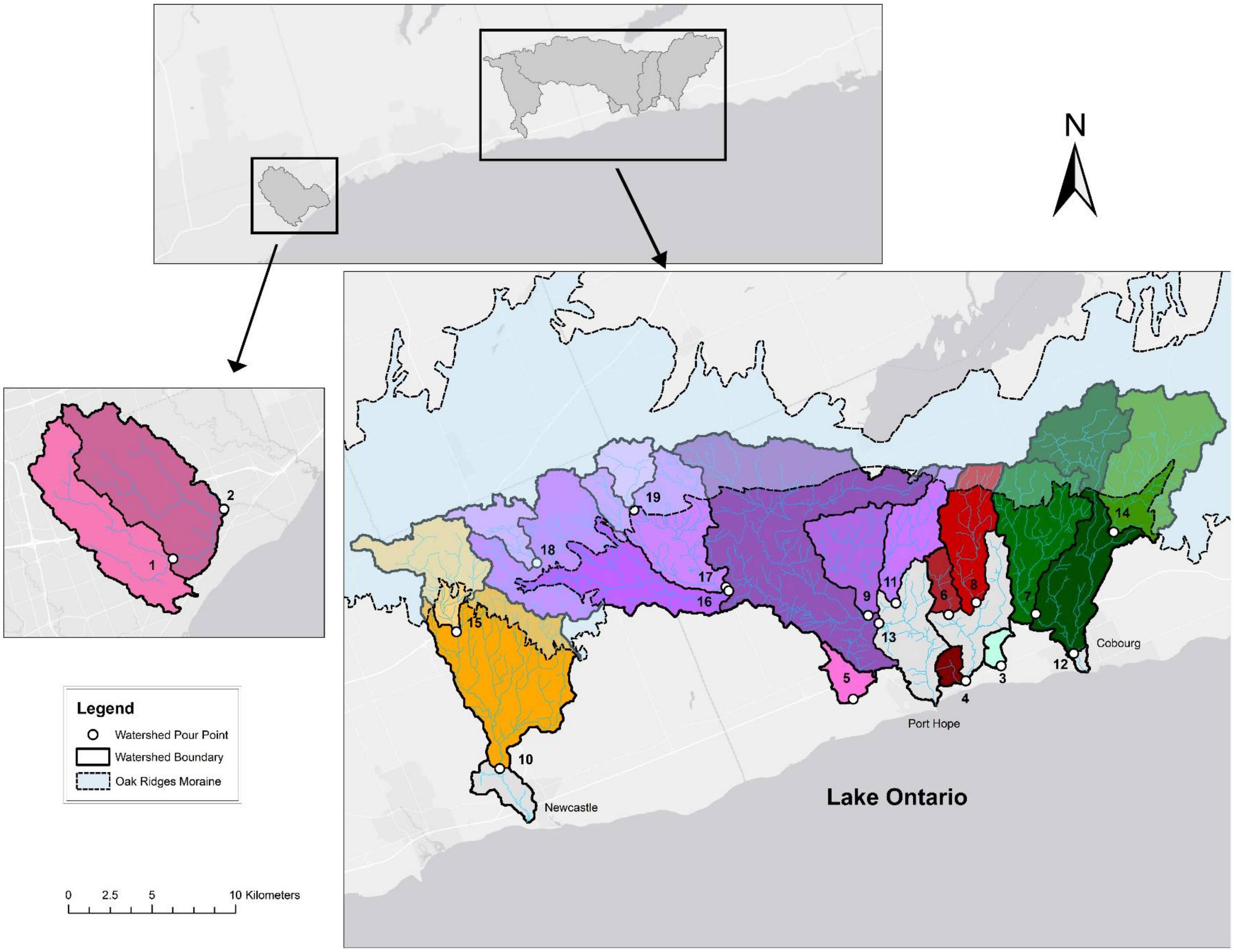



Figure 2.1. Map of the study area showing the 19 study watersheds and limits of the Oak Ridges Moraine. Watershed labels match with Table 2.1.

*Watershed land cover and physiography*

Contributing watershed areas were estimated using the Ontario Flow Assessment Tool (OFAT; Ministry of Natural Resources and Forestry, 2020) with pour points located at the gauging stations. Land cover within each watershed was estimated using the Agriculture and Agri-food Canada (AAFC) land usage/crop inventory layer for 2018 (Agriculture and Agri-Food Canada, 2018). Land cover data are available in OFAT, but were not used in this analysis because OFAT groups all types of agriculture into a single category called “undifferentiated agricultural land” and does not distinguish between crops and pasture (Ministry of Natural Resources and Forestry, 2020). OFAT has a higher resolution of 15 m cells which is more accurate compared with the AAFC’s 30 m; however, the AAFC layer is revised annually while OFAT is currently using 2016 data. The more recent data were a compensation for loss of accuracy. Both layers were created similarly, from satellite imagery and LiDAR. The AAFC layer was produced using three satellite images collected over the course of the growing season to identify crop types and has a reported > 85% accuracy (AAFC, 2018). Recent (2018) TD area was calculated using the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) layer for Southern Ontario (OMAFRA, 2018). AAFC defines ‘urban’ land use as the combination of impermeable surfaces (e.g., roads, buildings) and pervious soils (e.g., lawns, gardens). These values are reported as “urban” in Table 2.1. For this study, the category ‘Row Crop’ was estimated as the sum of three specific crop areas including grain corn, soy and winter wheat, since this is the most common crop rotation in Ontario (Smith 2015); whereas the area of pasture plus forage was taken directly from AAFC. Other types of agriculture including orchards, horticulture, and tree nurseries are relatively rare in the study area and comprise a small proportion of most watersheds (< 5%) and therefore were not included in land cover analyses. The sum of ‘Row Crops’ plus ‘Pasture’ therefore represents total agriculture coverage in the watersheds. The sum of agriculture and urban coverage was also computed and is reported as ‘disturbed’ land cover. ‘Forested’ area includes the sum of coniferous, broad-leafed and mixed forests. Shrubland and grassland areas were combined into a single ‘grassland’ land use category, and the sum of ‘forests’, ‘grasslands’ and ‘wetlands’ is reported as ‘natural cover’. ‘Barren land’ is soil that is non-vegetated (e.g., gravel pits or burned areas) and is not related to agriculture. Because barren land represents a very small area in most watersheds (< 8%) it was not considered in land cover analyses. Land cover across the study region is presented in Figure 2.2.

Physiographic characteristics for each of the study watersheds were calculated using data from a variety of sources. Texture was derived from the Ontario Ministry of Northern Development, Mines and Forestry surficial geology layer. The texture of surficial deposits (i.e., soil parent material) was classified into three categories including ‘coarse’, ‘fine’, and ‘variable’ (Table 2.2; see Figure 2.3). These three texture categories were identified from the primary materials that were part of the depositional environment (e.g., glaciolacustrine deposits primarily consist of clay and silt particles, which are classified as ‘fine’ textured). OFAT was used to calculate the mean slope of each watershed using the Ontario Integrated Hydrology (OIH) digital elevation model layer and a cell size of 30m x 30m. The percent of each watershed that was located on the ORM was calculated by summing the areas within the boundaries of the ORM land use designation layer (LIO, 2006).

Table 2.1. Land cover and physiographic characteristics of the 19 study watersheds presented as a percentage of total watershed area. Sites shaded purple are considered mixed land use watersheds, red are urban dominated watersheds, yellow are agriculturally dominated, and green are predominantly natural. The eight sites with asterisks were instrumented by Trent University for this study, whereas the other 11 sites are Water Survey of Canada stations.

| Site Number | Site Name | Urban | Agriculture | | | | Sum of Agriculture and Urban (Disturbed) | Natural | | | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pasture | Row Crop | Total Agriculture | % of Watershed Tile Drained | | Forest | Grassland | Wetland | Barren Land |
| 1 | Highland West | 96 | 0 | 0 | 0 | 0 | 96 | 2 | 0 | 0 | 2 |
| 2 | Highland Down | 93 | 0 | 0 | 0 | 0 | 94 | 4 | 0 | 1 | 2 |
| 3* | Mystery | 5 | 2 | 85 | 87 | 89 | 92 | 6 | 1 | 1 | 0 |
| 4* | Gage Urban | 64 | 8 | 15 | 23 | 0 | 87 | 7 | 2 | 2 | 3 |
| 5* | Brand Creek | 7 | 21 | 55 | 76 | 47 | 82 | 7 | 2 | 3 | 5 |
| 6* | Gage West | 3 | 20 | 45 | 65 | 25 | 68 | 28 | 2 | 2 | 0 |
| 7 | Cobourg Up | 7 | 37 | 23 | 60 | 6 | 67 | 24 | 6 | 3 | 1 |
| 8 | Gage East | 3 | 26 | 36 | 62 | 5 | 65 | 27 | 5 | 3 | 0 |
| 9* | Gan 1 | 4 | 18 | 41 | 59 | 3 | 63 | 29 | 4 | 3 | 0 |
| 10 | Wilmot Down | 10 | 27 | 24 | 51 | 2 | 61 | 27 | 4 | 4 | 4 |
| 11* | Gan 2 | 5 | 21 | 29 | 50 | 1 | 54 | 34 | 6 | 6 | 0 |
| 12 | Cobourg Down | 9 | 23 | 20 | 43 | 5 | 52 | 36 | 7 | 3 | 1 |
| 13 | Gan Sylvan | 4 | 19 | 22 | 40 | 3 | 44 | 47 | 4 | 4 | 1 |
| 14 | Cobourg Balt | 4 | 19 | 20 | 39 | 6 | 43 | 46 | 8 | 2 | 0 |
| 15 | Wilmot Up | 9 | 19 | 15 | 34 | 1 | 43 | 40 | 4 | 5 | 8 |
| 16 | Gan Osaca | 4 | 21 | 11 | 33 | 0 | 37 | 53 | 4 | 5 | 1 |
| 17 | Gan NW | 2 | 18 | 11 | 29 | 1 | 32 | 61 | 4 | 3 | 1 |
| 18* | Gan Natural 2 | 3 | 12 | 8 | 20 | 0 | 22 | 67 | 4 | 4 | 3 |
| 19* | Gan Natural 1 | 2 | 0 | 0 | 1 | 0 | 3 | 94 | 2 | 1 | 0 |

Table 2.2. Watershed coverage (%) of land use and physiography. Site numbers with asterisks were instrumented Trent University. Site numbers shaded purple are considered mixed land use watersheds, red are urban dominated watersheds, yellow are agriculturally dominated, and green are dominated by natural land cover.

| Site Number | Site Name | Area ($km^2$) | Parent Material Textures | | | Mean Slope (%) | Watershed Area % in ORM |
|---|---|---|---|---|---|---|---|
| | | | Coarse | Fine | Variable | | |
| 1 | Highland West | 39 | 2 | 0 | 98 | 2.3 | 0 |
| 2 | Highland Down | 91 | 5 | 0 | 95 | 2.7 | 0 |
| 3* | Mystery | 2.6 | 0 | 97 | 3 | 2.0 | 0 |
| 4* | Gage Urban | 3.1 | 2 | 86 | 12 | 2.9 | 0 |
| 5* | Brand Creek | 5.6 | 39 | 56 | 5 | 3.1 | 0 |
| 6* | Gage West | 5.5 | 21 | 38 | 41 | 5.7 | 0 |
| 7 | Cobourg Up | 34 | 40 | 18 | 41 | 8.7 | 28 |
| 8 | Gage East | 21 | 34 | 23 | 43 | 7.1 | 17 |
| 9* | Gan 1 | 17 | 46 | 19 | 35 | 6.1 | 9 |
| 10 | Wilmot Down | 81 | 55 | 6 | 39 | 7.5 | 39 |
| 11* | Gan 2 | 21 | 53 | 13 | 34 | 5.2 | 0 |
| 12 | Cobourg Down | 123 | 58 | 14 | 28 | 7.5 | 53 |
| 13 | Gan Sylvan | 240 | 74 | 8 | 17 | 6.1 | 41 |
| 14 | Cobourg Balt | 41 | 76 | 2 | 23 | 7.2 | 81 |
| 15 | Wilmot Up | 27 | 81 | 6 | 13 | 8.7 | 80 |
| 16 | Gan Osaca | 73 | 78 | 6 | 15 | 7.0 | 64 |
| 17 | Gan NW | 46 | 89 | 1 | 10 | 6.9 | 56 |
| 18* | Gan Natural 2 | 11 | 98 | 1 | 2 | 7.0 | 100 |
| 19* | Gan Natural 1 | 9.3 | 99 | 0 | 1 | 7.7 | 100 |

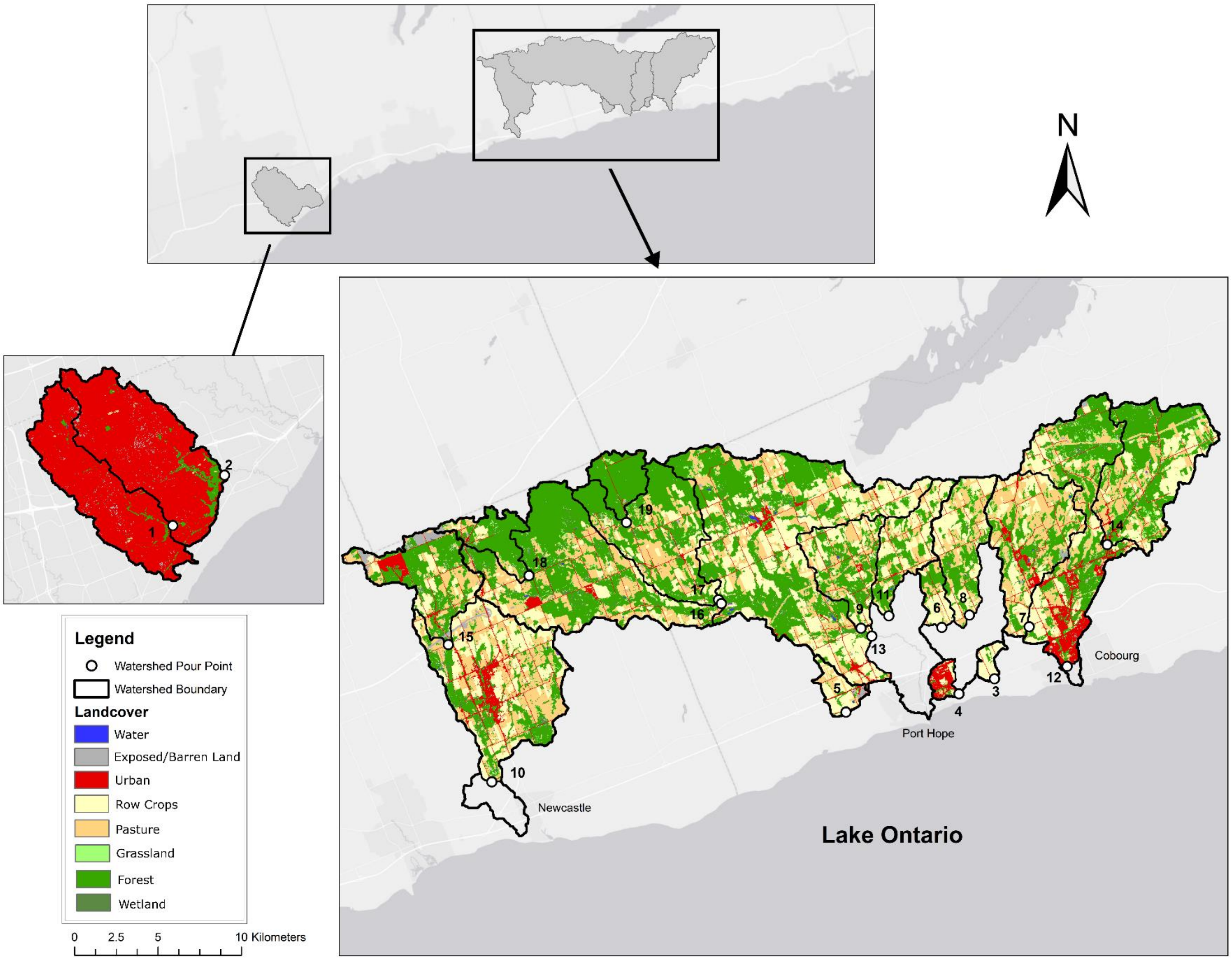



Figure 2.2. Land cover within the nineteen study watersheds. Land cover data are from AAFC 2018.

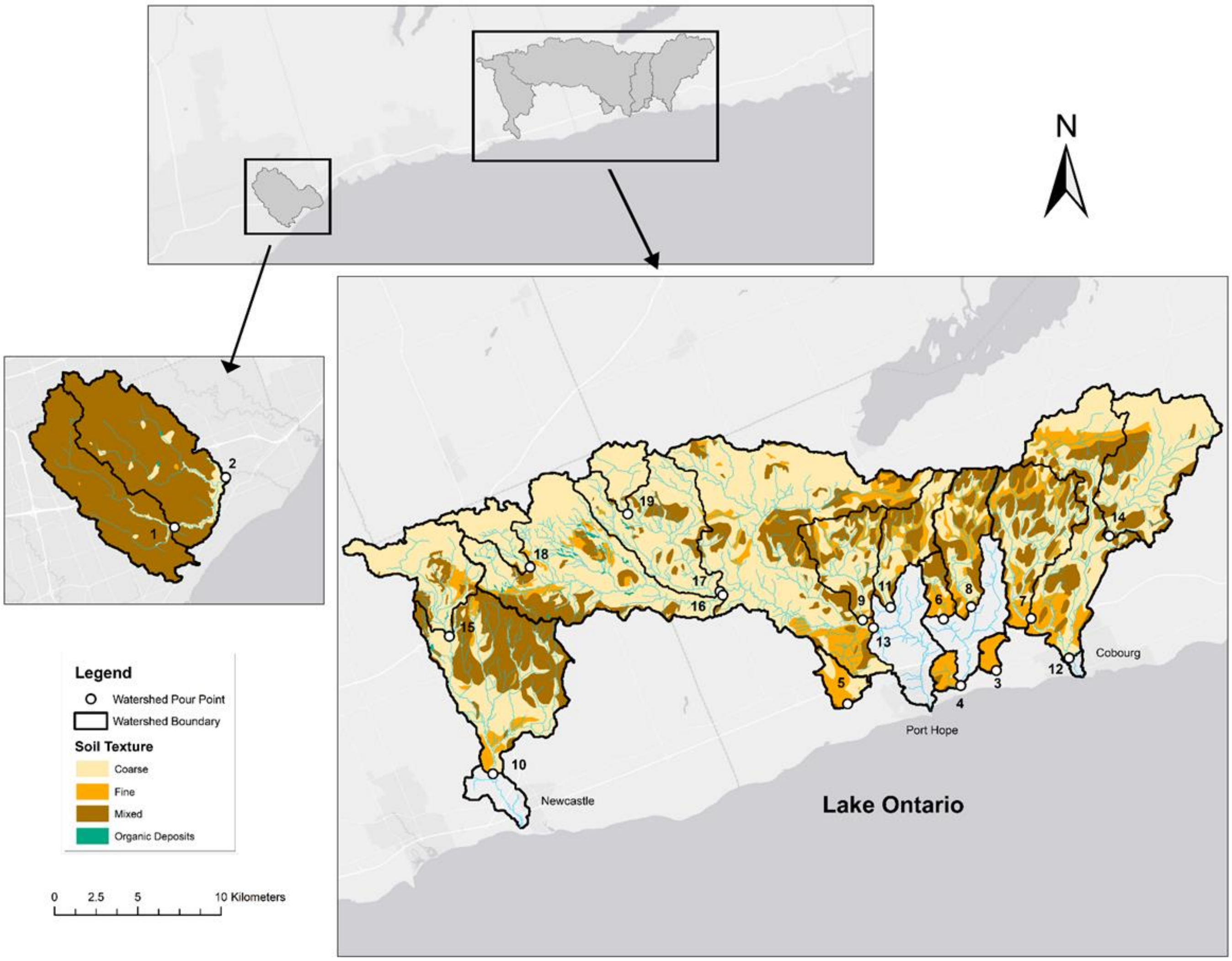



Figure 2.3. Parent material texture within the nineteen study watersheds. Surficial geology data are from Ontario Ministry of Northern Development, Mines and Forestry.

*Flow and Climate Data*

Heron Instruments™ vented pressure transducers were deployed to measure water heights at the eight newly established monitoring stations. Each site was surveyed for straight channels to install the loggers (often near culverts). Loggers were attached to concrete slabs which were secured to the stream bed by hammering reinforcing bar through holes in the slab and into the sediment to keep the loggers at the same depth. Loggers were surveyed relative to culverts to ensure that the loggers were not shifting on the stream beds. Vented loggers automatically compensate for changes in atmospheric pressure and were programmed to record water level every 15 minutes. Loggers were downloaded weekly to ensure data quality and that loggers were not shifting on the stream bed. Weekly hydrographs were also used to aid water sampling decisions for an associated water quality monitoring project (see Liu et al. 2022).

Stage-discharge relationships were established at each site to convert continuous measurements of stream level into discharge. To do this, stream velocity was measured at each stream six to eight times between September 2018 and October 2019 using a Marsh-McBirney Flow-Mate. During each measurement, the width of the stream was measured, and the channel cross-section was divided into five equal panels. Depth was then measured along with stream velocity at 60% of stream depth within each panel (Corbett, 1943). Velocity (m/s) was multiplied by each cross-sectional area panel ($m^2$) and all panels were summed to obtain stream discharge ($m^3/s$). Efforts were made to capture a large range of stream discharge measurements from very low flow in the late summer to peak flow during spring melt (Table 2.3), although some peak flows were not safe to gauge due to deep, fast-moving water. Each stream's rating curve was used to create a continuous record of streamflow. Flows were extrapolated from the rating curves when water depth of creeks exceeded the deepest gauging depth. Table 2.3 illustrates how many flow intervals were extrapolated from rating curves over the course of two years. Each 15-minute flow interval was summed over each day to obtain daily discharge ($m^3$/day). Runoff (mm/day) was calculated by dividing daily discharge by watershed area.

Streams were monitored over two complete water years (September 1 – August 31) beginning September 1, 2018 and ending August 31, 2020. Seasons were thus defined as Fall = September 1 – November 30; Winter = December 1 – February 28; Spring = March 1 – May 31 and Summer = June 1 – August 31.

Table 2.3. Maximum and minimum stage and gauging depths for streams instrumented for this study. Flow that exceeded maximum gauging depth was summed and reported as percentage of total cumulative flow. * = maximum water height was influenced by ice damming during spring melt.

| Watershed | Maximum Stage (m) | Maximum Gaging Depth (m) | Minimum Stage (m) | Minimum Gaging Depth (m) | % of Cumulative Flow Extrapolated Above Highest Rating Curve Measurement |
|---|---|---|---|---|---|
| Gage Urban | 1.072 | 0.569 | 0.178 | 0.240 | 33% |
| Mystery | 0.801 | 0.518 | 0.089 | 0.208 | 17% |
| Brand | 1.820 | 0.812 | 0.180 | 0.268 | 48% |
| Gage West | 1.329 | 0.909 | 0.039 | 0.073 | 8% |
| Gan 2 | 1.187 | 0.642 | 0.148 | 0.155 | 21% |
| Gan 1 | 1.767* | 0.759 | 0.154 | 0.165 | 31% |
| Gan Nat 1 | 0.295 | 0.240 | 0.175 | 0.194 | 1% |
| Gan Nat 2 | 0.463 | 0.373 | 0.181 | 0.198 | 2% |

Precipitation and temperature data were retrieved from Environment Canada's Oshawa climate station (station ID 6155875; Environment Canada, 2020) which was the closest climate station that had a complete record of daily measurements over the period of study. Daily precipitation data were obtained for September 1, 2018, to August 31, 2020.

Thirty-year climate normals were calculated for the years 1971-2000. Climate normals for 1981-2010 could not be calculated due to incomplete records between 2006 and 2010 at the Oshawa station.

*Flashiness Metrics*

A variety of different flow metrics were calculated in order to evaluate hydrologic responsiveness to land cover (Table 2.4). Metrics were selected based on literature reports of their sensitivity to either urban or agricultural land cover.

Table 2.4. Flow metrics computed for the two water years. References with one star represent research that used the metric for urban watersheds, two stars represent agricultural watersheds, and three stars represent multiple land covers. q = flow ($m^3$/s), Q = flow (mm/d), σ = standard deviation, μ = mean, WSC = Water Survey of Canada

| Flow Metric | Abbreviation | Formula | Interval of Flow Used | High Flashiness If Value Is: | References for Land Cover |
|---|---|---|---|---|---|
| **Richards-Baker Index** | RBI | $\frac{\sum_{i=1}^{n} \lvert q_i - q_{i-1} \rvert}{\sum_{i=1}^{n} q_i}$ | Daily Average | Large | Baker et al. (2004)*** Ulén et al. (2016)** Mogollón et al. (2016)*** |
| **Coefficient of Variation** | CV | $\frac{\sigma}{\mu}$ | Daily Average | Large | Konrad & Booth (2005)* Eimers & McDonald (2015)* |
| **Percent Yield of Watershed** | %Yield | $\frac{Total\ Runoff\ (mm)}{Total\ Precipitation\ (mm)}$ | Daily Average | Large | Wang & Alimohammadi (2012)*** |
| **Baseflow Index** | BFI | *Web-based Hydrograph Analysis Tool (WHAT)* *Recursive Digital Filter – BFI Max 0.80 (Default)* | Daily Average | Small | Vittorio & Ahiablame (2015)* Schilling & Jones (2019)** |
| **Flow Duration Curve Slope** | FDC | $\frac{\ln(Q33\ \%) - \ln(Q66\ \%)}{(0.66 - 0.33)}$ | Daily Average | Large | Sawicz et al. (2011)*** |
| **Mean Flow Exceedance** | $T_{Qmean}$ | $\frac{Time\ flow\ exceeded\ average\ flow}{Total\ time}$ | 15 minute 5 minutes (WSC) | Small | Konrad & Booth (2005)* |
| **Median Flow Exceedance** | DUR3, DUR5 | $\frac{Total\ time\ flow\ exceeded\ median\ flow}{Total\ time}$ | 15 minute 5 minutes (WSC) | Small | Clausen & Biggs (1997)*** |

Flashiness metrics were calculated at the annual and seasonal time scales to examine the effects of land use during different times of the WY. Daily average flow was used for most metric calculations except for $T_{Qmean}$ and DUR3 and DUR5, which used data collected at 15-minute intervals at the newly established Trent flow sites, or 5-minute flow intervals at the existing WSC sites. These three metrics were not calculated using daily average flow because they consider the amount of time that flow exceeds the mean or median flow per season or year. The DUR3 and DUR5 metrics indicate the amount of time flow exceeded 3-times and 5-times the median flow, respectively. Percent yield at each watershed was calculated by dividing runoff (mm) by precipitation (mm), measured at the Oshawa climate station.

*Statistical Analyses*

Ranked ANOVA tests (Kruskal-Wallis tests, $\alpha = 0.05$) were used to assess whether flow metrics differed amongst the land cover categories indicated in Table 2.6. Ranked values were used due to the non-normal distribution of land cover throughout the watersheds. Tukey-Kramer post hoc tests were then used to identify if specific land cover types differed from each other using $\alpha = 0.05$ and $\alpha = 0.10$.

Correlation analysis was used to evaluate metric sensitivity to land cover. Normality was tested using the Shapiro-Wilk test and Spearman correlations ($r_s$) were used in all cases due to the non-normal distribution of flow and land cover data. Spearman correlation also allows original data to be used instead of transforming data to be normalized. Correlation matrices (package ‘Hmisc’) and Shapiro-Wilk (basic stats package within R) tests were carried out using R 3.4.1 (R Core Team, 2017).

Principal component analysis (PCA) was performed to investigate metric association with land cover and associations with watershed physiography. PCA was conducted using the 'Factoextra' package in R 3.4.1 (R Core Team, 2017). Data were standardized (Z-score) for use in PCA by subtracting the mean value from the observed value and dividing by the standard deviation of each metric, land cover or physiographic characteristic.

## 2.3 Results

*Land cover and watershed physiography*

The nineteen watersheds examined in this study were selected to capture a broad gradient of land cover, from predominantly natural coverage (97%) at Gan Natural 1 to almost entirely urban (93%) at Highland Down (Table 2.1). Total agricultural land cover also varied widely across sites from 0% at Highland Down to 87% at Mystery Creek, as did the level of agricultural 'intensity' within each watershed. At the two extremes, the most intensively agricultural Mystery Creek has 85% row crop with 89% of the watershed tile drained, whereas Cobourg Up has more pasture (37%) and little recorded tile drainage (6%; Table 2.1).

Several physiographic characteristics were computed for each watershed (Table 2.2) as topography and soil drainage characteristics may also influence stream flashiness. Some physiographic characteristics were strongly associated with land cover. For example, most forested watersheds were located on the ORM, and had a greater proportion of coarse-textured/well-drained soils ($r_s = 0.95$) and steeper slopes ($r_s = 0.61$), whereas the majority of urban and agriculturally dominated watersheds were located south of the ORM and closer to the Lake Ontario shoreline, where slopes are generally flatter and soils are finer textured (correlation between proportional area of agriculture and area of fine textured soils $r_s = 0.81$; Figure 2.3).

*Hydroclimatic context of the study period*

There were substantial differences in precipitation and temperature between the two years of intensive monitoring. The 2019-2020 water year was significantly drier (724 mm) than the long-term average (844-900 mm, 95% CI), whereas 2018-19 was wet but cool (863 mm, 7°C average; Table 2.5). Exceptionally dry conditions in 2019-20 were largely driven by the spring and summer, when total precipitation inputs were substantially lower than long-term averages (Table 2.5). In contrast, the spring and summer of 2018-19 were relatively wet, largely due to several days of prolonged precipitation in April 2019 and one exceptionally large rainfall event in July 2019 (67 mm in 8 hours) that resulted in localized flooding in parts of the Greater Toronto Area (Lapierre, 2019). In contrast, the winter of 2018-19 was drier (134 mm) than average (198 mm), and 61% percent of precipitation occurred as rain, likely resulting in many freeze-thaw events. Despite colder than average temperatures, the fraction of precipitation falling as rain was relatively high in winter 2018-19 (61%) compared with the long-term normal (54%; Table 2.5). Total precipitation in winter 2019-20 was unremarkable; however, relatively warm conditions (-2.9°C; Table 2.5) resulted in more rain vs. snow. In particular, a large 57 mm rainfall event occurred on January 11, 2020, which was almost twice the amount of precipitation that normally occurs in the entire month (32 mm). This event alone accounted for 28% of total winter precipitation

(Table 2.5). In contrast, fall precipitation and temperature were similar between the two WYs, although both study seasons were relatively cool compared with the long-term average (Table 2.5).

Table 2.5. Seasonal and annual precipitation sums (mm) and average temperature for the two years of study and climate normals from the Oshawa weather station. The 95% confidence interval is indicated in brackets.

| **Sep 2018 - Aug 2019** | Annual | Fall | Winter | Spring | Summer |
|---|---|---|---|---|---|
| Precipitation (mm) | 863 | 210 | 134 | 276 | 244 |
| % of Precipitation as Rain | 91% | 99% | 61% | 96% | 100% |
| # of Days Precipitation ≥25mm | 6 | 2 | 1 | 2 | 1 |
| Temperature (°C) | 7.0 | 8.2 | -4.7 | 4.7 | 19.7 |
| **Sep 2019 - Aug 2020** | | | | | |
| Precipitation (mm) | 724 | 216 | 202 | 161 | 146 |
| % of Precipitation as Rain | N/A | 91% | 60% | N/A | N/A |
| # of Days Precipitation ≥25mm | 4 | 2 | 1 | 0 | 1 |
| Temperature (°C) | 8.1 | 8.4 | -2.9 | 6.0 | 21.1 |
| **Climate Normals (1971 - 2000)** | | | | | |
| Precipitation Average (mm) | **872** (844 - 900) | **235** (212 - 258) | **198** (182 - 214) | **210** (191 - 229) | **225** (200 - 250) |
| % of Precipitation as Rain | 86% | 97% | 54% | 91% | 100% |
| # of Days Precipitation ≥25mm | 4.6 | 1.3 | 0.5 | 0.8 | 2.0 |
| Temperature Average (°C) | **7.8** (7.7 - 8.0) | **9.6** (9.3 - 9.9) | **-4.1** (-4.5 to -3.3) | **6.1** (5.7 - 6.7) | **18.9** (18.7 - 19.4) |

*Relationship between land cover and streamflow*

The effects of land cover on streamflow were analyzed using eight metrics including two that consider differences in baseflow (BFI and FDC), three that quantify changes in peak flows ($T_{Qmean}$, DUR3, DUR5) and three that characterize flow variability or flashiness (RBI, CV, and %Yield).

Ranges in each metric for each of the three major land use categories are shown in Table 2.6, and illustrate that urban watersheds tend to have the highest RBI (0.81 to 0.90), CV values (1.53 to 2.53), steepest FDC slopes (1.74 to 3.50), lowest $T_{Qmean}$ values

(15% to 17%) and overall less baseflow relative to total streamflow (0.41 to 0.49). Especially low $T_{Qmean}$ values in urban watersheds indicate that peak flows are short-lived and high in magnitude. At the other extreme, natural watersheds have the highest $T_{Qmean}$ (22% to 34%) and fractions of baseflow (65% to 78%) and lowest RBI (0.08 to 0.42), CV (0.18 to 1.09) and flattest FDC slopes (0.22 to 1.13; Table 2.6). Agricultural watersheds plot somewhere in between, with intensively agricultural basins (i.e., those dominated by tile-drained row crop area like Brand and Mystery) behaving more like urban watersheds, with RBI (0.67 to 1.05), CV (1.79 to 3.84), FDC (2.87 to 3.33) and BFI values (0.31 to 0.51) comparable to or even higher than the most urbanized watersheds (Table 2.6). In contrast, flow at the less-intensively agricultural watersheds (which have a greater proportion of pasture; e.g. Cobourg Up and Gage East) were more similar to the mixed or natural watersheds, with RBI, CV and BFI values ranging from 0.43 to 0.61, 1.13 to 2.02, and 0.52 to 0.66, respectively (Table 2.6).

With the exception of %yield, the majority of flow metrics considered in this study showed some degree of sensitivity to land cover. More specifically, Kruskal-Wallis post-hoc tests indicated that 6 of 8 metrics were significantly different between the urban and natural groups ($\alpha = 0.05$). Only CV (significant at $\alpha = 0.10$) and %Yield (no significance) were not clearly associated with land cover change. Additionally, the RBI, CV, FDC, and BFI were significantly different between agriculture and natural watersheds ($\alpha = 0.05$). Interestingly, no metrics were significantly different when comparing urban to agriculture, likely due to the influence of the two most intensively agricultural watersheds (Brand and Mystery), which had especially high flashiness metric values (Table 2.6).

Table 2.6. Ranges (minimum to maximum) of annual flow metric values for each predominant land cover type within the watersheds.

| | | RBI | CV | %Yield | FDC | BFI Daily | Tqmean | DUR3 | DUR5 |
|---|---|---|---|---|---|---|---|---|---|
| Urban | *n = 3* | 0.81 to 0.90 | 1.53 to 2.53 | 52% to 65% | 1.74 to 3.50 | 0.41 to 0.49 | 15% to 17% | 12% to 19% | 7% to 11% |
| Agriculture | *n = 7* | 0.43 to 1.05 | 1.13 to 3.84 | 36% to 76% | 1.53 to 3.33 | 0.31 to 0.66 | 7% to 29% | 5% to 23% | 2% to 12% |
| Intensive Ag | *n = 2* | 0.67 to 1.05 | 1.79 to 3.84 | 36% to 50% | 2.87 to 3.33 | 0.31 to 0.51 | 7% to 24% | 15% to 23% | 9% to 12% |
| Non-Intensive Ag | *n = 5* | 0.43 to 0.61 | 1.13 to 2.02 | 47% to 76% | 1.53 to 2.77 | 0.52 to 0.66 | 20% to 29% | 5% to 15% | 2% to 8% |
| Mixed | *n = 5* | 0.17 to 0.45 | 0.50 to 1.96 | 64% to 81% | 0.49 to 1.67 | 0.63 to 0.76 | 21% to 28% | 2% to 12% | 0.5% to 6% |
| Natural | *n = 4* | 0.08 to 0.42 | 0.18 to 1.09 | 19% to 64% | 0.22 to 1.13 | 0.65 to 0.78 | 22% to 34% | 0.4% to 9% | 0.1% to 3% |

Consistent with this, correlations between the area of agriculture or urban development and most metrics were statistically significant ($p < 0.10$). Contrary to the hypothesized response, correlations between disturbed land cover and flow metrics were significant in all seasons as well as at the annual scale, suggesting that land cover influences flashiness throughout the year (Table 2.7).

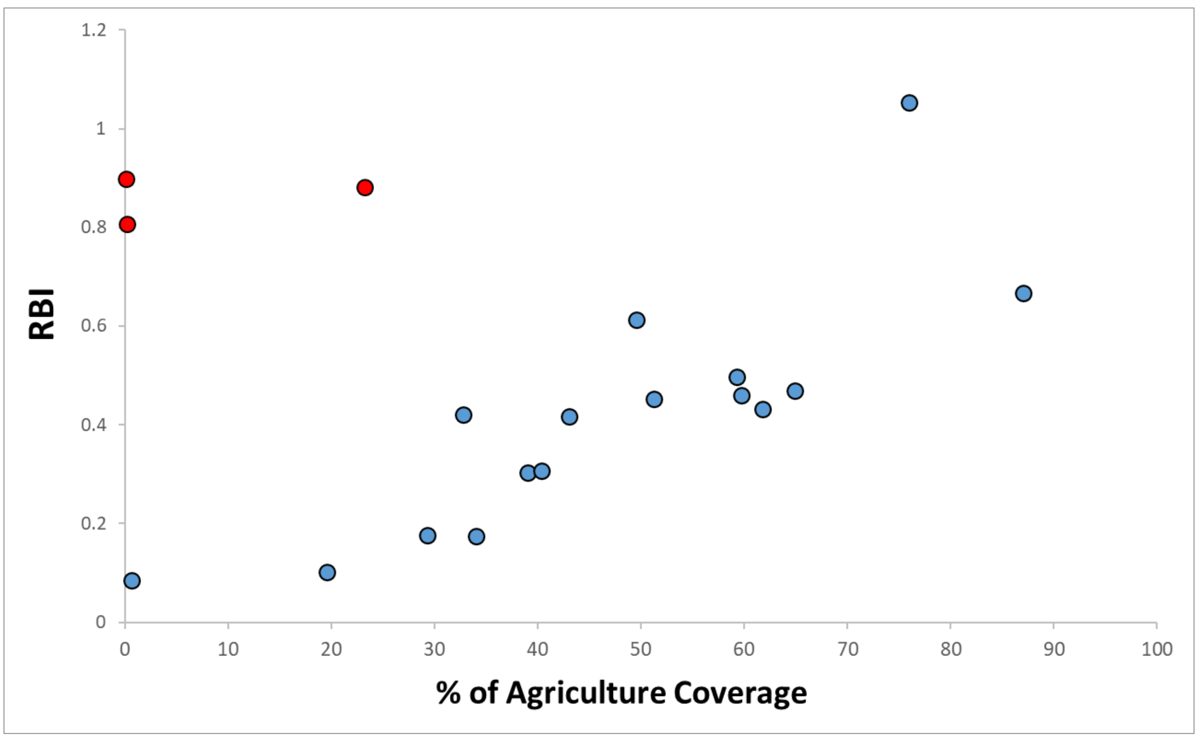



Figure 2.4. Correlation between the RBI metric (annual time scale) and percent agriculture at 16 of the 19 study watersheds. Red circles represent urban dominated watersheds that were removed from the analysis, blue circles indicate mixed landuse watersheds.

Overall, the RBI, BFI, FDC and CV were consistently strongly correlated with disturbed land cover across all time periods, and the RBI and BFI had a particularly strong correlation at the annual time scale ($r_s$ = 0.92 and 0.90 respectively, Table 2.7). Other metrics were only weakly correlated with land cover, or correlations were only significant in some seasons. For example, $T_{Qmean}$ was significantly correlated with disturbed land area ($p < 0.05$) in the fall, summer and annual periods but showed weaker correlations in the winter and spring months (Table 2.7).

The total area of disturbed land (i.e., sum of agriculture plus urban area) within a watershed was usually more strongly correlated with the various hydrologic metrics compared with either urban or agricultural cover alone. In fact, % agriculture was generally poorly correlated with flow metrics compared with urban cover (Table 2.7); however, correlations between total agricultural area and all flow metrics markedly improved when the three most urbanized watersheds were removed from the analysis (Figure 2.4; Table 2.7). This is because urban area in the study watersheds is highly bimodal as only three watersheds have > 63% urban cover whereas the majority have < 10% (Table 2.1). In contrast, the area of agricultural land is more widely distributed (1% - 87%) across the 19 study watersheds (Table 2.1).

Table 2.7. Statistically significant correlations (Spearman $r_s$) between land cover and flashiness metrics between 2018 and 2020. Total = full record of observation between September 2018 and August 2020. Total record/seasonal periods with large bolded $r_s$ values are significantly correlated at $p < 0.05$, non-bolded $r_s$ are $p < 0.1$ and small font $r_s$ were not statistically significant. The three most urbanized watersheds (#1, 3 and 4) were removed from correlations between metrics and Total Agriculture, % Row Crop, and % Pasture. The Table is structured such that metrics describing variation of flow (RBI, CV, %Yield) are at the top, metrics describing baseflow (BFI, FDC) are in the middle, and those describing magnitude of peak flow ($T_{Qmean}$, DUR3, DUR5) are at the bottom.

| *Land Cover* | **RBI** | | | | | **CV** | | | | | **Percent Yield of Watershed** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Fall | Winter | Spring | Summer | Total | Fall | Winter | Spring | Summer | Total | Fall | Winter | Spring | Summer |
| **Urban** | **0.56** | **0.55** | **0.63** | **0.51** | **0.55** | **0.54** | 0.45 | **0.66** | 0.46 | 0.45 | **0.48** | 0.28 | 0.28 | 0.39 | 0.17 |
| **Agriculture** | 0.27 | 0.09 | 0.20 | 0.25 | 0.16 | 0.44 | 0.26 | 0.17 | 0.31 | 0.34 | 0.01 | **-0.50** | 0.11 | 0.01 | **-0.49** |
| **Agriculture (n-3)** | **0.89** | **0.73** | **0.82** | **0.81** | **0.79** | **0.86** | **0.77** | **0.73** | **0.81** | **0.83** | 0.09 | -0.48 | 0.16 | 0.04 | -0.47 |
| **% Row Crop** | **0.90** | **0.71** | **0.85** | **0.83** | **0.72** | **0.87** | **0.75** | **0.76** | **0.87** | **0.76** | 0.07 | **-0.53** | 0.16 | -0.10 | -0.51 |
| **% Pasture** | 0.24 | 0.06 | 0.37 | 0.42 | 0.34 | 0.32 | 0.05 | 0.46 | 0.35 | 0.29 | 0.35 | 0.07 | **0.54** | 0.42 | 0.17 |
| **Disturbance** | **0.92** | **0.84** | **0.87** | **0.83** | **0.86** | **0.79** | **0.84** | **0.79** | **0.76** | **0.84** | 0.14 | -0.10 | 0.17 | -0.03 | -0.21 |
| **Natural** | **-0.90** | **-0.81** | **-0.87** | **-0.82** | **-0.84** | **-0.79** | **-0.80** | **-0.80** | **-0.75** | **-0.83** | -0.16 | 0.09 | -0.15 | 0.01 | 0.16 |

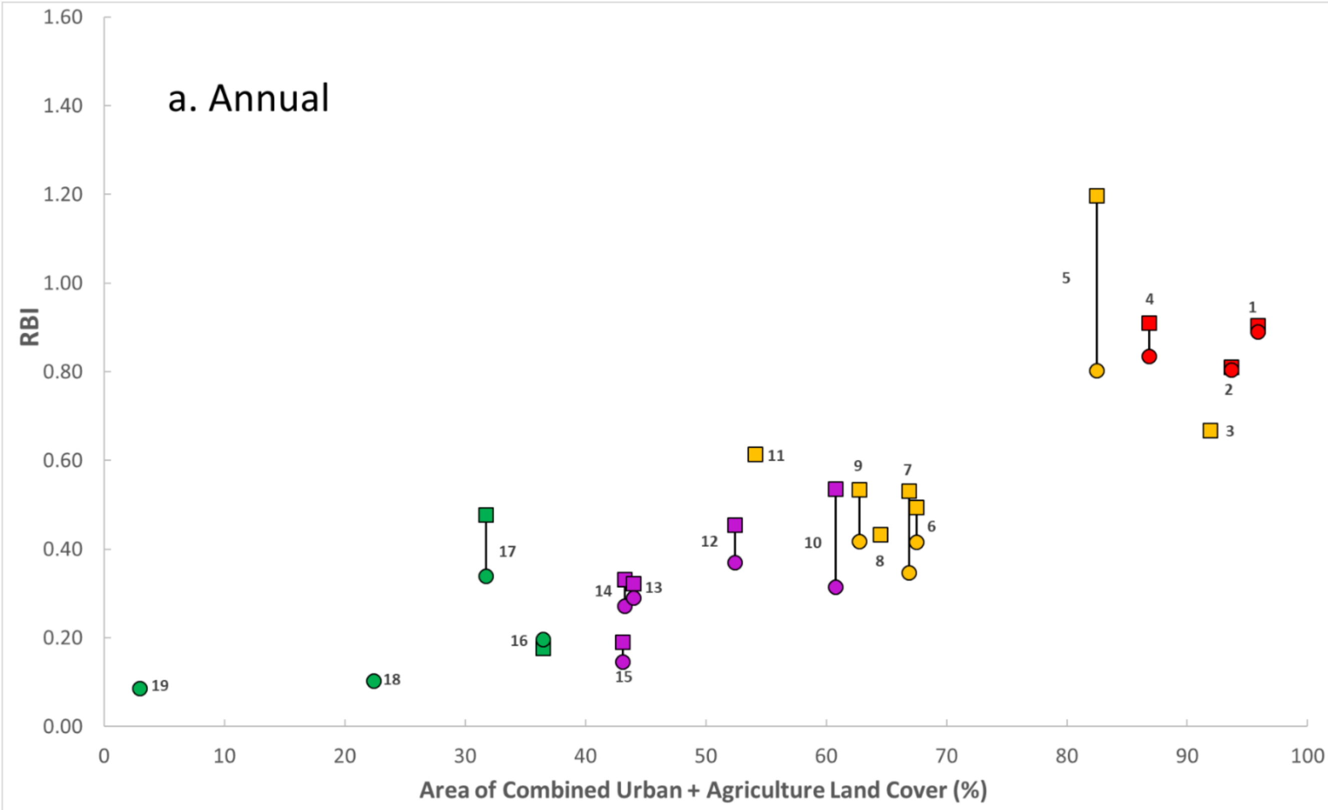
| *Land Cover* | **Slope FDC** | | | | | **BFI** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Fall | Winter | Spring | Summer | Total | Fall | Winter | Spring | Summer |
| **Urban** | 0.39 | 0.25 | 0.33 | 0.31 | **0.49** | **-0.61** | **-0.48** | **-0.54** | -0.43 | **-0.47** |
| **Agriculture** | **0.50** | **0.43** | **0.50** | 0.48 | 0.27 | -0.26 | -0.18 | -0.21 | -0.29 | 0.06 |
| **Agriculture (n-3)** | **0.90** | **0.81** | **0.82** | **0.90** | **0.79** | **-0.86** | **-0.75** | **-0.81** | **-0.78** | -0.46 |
| **% Row Crop** | **0.89** | **0.82** | **0.87** | **0.83** | **0.77** | **-0.87** | **-0.74** | **-0.87** | **-0.81** | -0.33 |
| **% Pasture** | 0.23 | 0.21 | 0.24 | 0.19 | 0.35 | -0.21 | -0.01 | -0.30 | -0.33 | -0.09 |
| **Disturbance** | **0.82** | **0.77** | **0.72** | **0.84** | **0.81** | **-0.90** | **-0.83** | **-0.83** | **-0.79** | **-0.66** |
| **Natural** | **-0.80** | **-0.73** | **-0.69** | **-0.80** | **-0.79** | **0.89** | **0.80** | **0.81** | **0.78** | **0.66** |

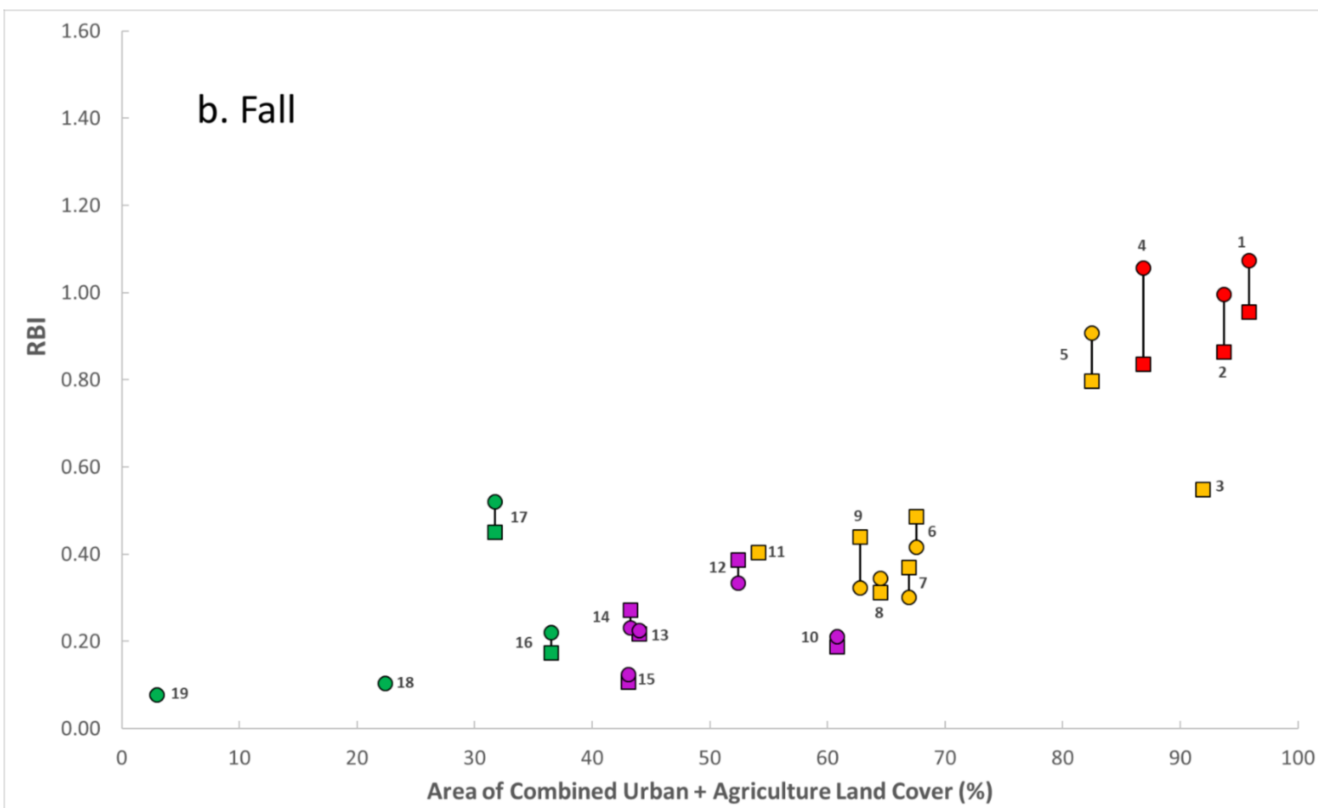
| *Land Cover* | **DUR3** | | | | | **DUR5** | | | | | **Tqmean** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Fall | Winter | Spring | Summer | Total | Fall | Winter | Spring | Summer | Total | Fall | Winter | Spring | Summer |
| **Urban** | 0.43 | 0.34 | 0.13 | 0.23 | 0.31 | **0.55** | 0.35 | 0.24 | 0.32 | 0.45 | **-0.70** | **-0.57** | -0.38 | **-0.58** | **-0.49** |
| **Agriculture** | 0.38 | 0.37 | **0.59** | 0.41 | 0.38 | 0.37 | 0.38 | **0.49** | 0.34 | 0.15 | -0.06 | 0.07 | 0.33 | 0.24 | -0.14 |
| **Agriculture (n-3)** | **0.80** | **0.86** | **0.73** | **0.84** | **0.85** | **0.87** | **0.89** | **0.81** | **0.90** | **0.83** | **-0.55** | -0.40 | 0.06 | -0.10 | **-0.64** |
| **% Row Crop** | **0.83** | **0.82** | **0.79** | **0.89** | **0.75** | **0.88** | **0.86** | **0.89** | **0.93** | **0.73** | **-0.60** | -0.40 | -0.02 | -0.16 | **-0.61** |
| **% Pasture** | 0.08 | 0.14 | 0.44 | 0.35 | 0.32 | 0.17 | 0.16 | 0.31 | 0.42 | 0.32 | -0.09 | 0.08 | 0.14 | -0.38 | -0.34 |
| **Disturbance** | **0.82** | **0.86** | **0.55** | **0.79** | **0.84** | **0.87** | **0.87** | **0.67** | **0.86** | **0.88** | **-0.72** | **-0.64** | -0.32 | -0.45 | **-0.76** |
| **Natural** | **-0.78** | **-0.83** | **-0.53** | **-0.75** | **-0.82** | **-0.85** | **-0.84** | **-0.64** | **-0.84** | **-0.86** | **0.71** | **0.61** | 0.31 | **0.49** | **0.75** |

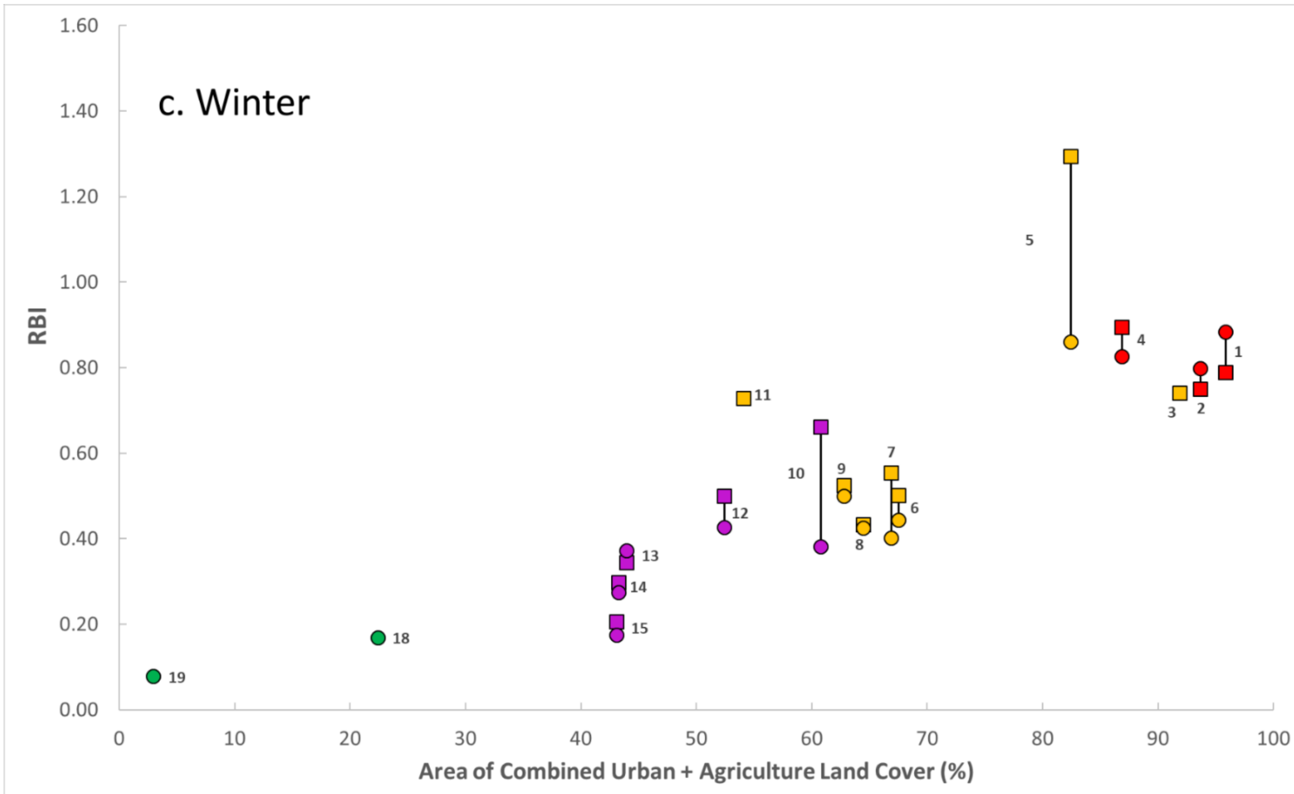
*RBI Analysis of Annual and Seasonal Variation*

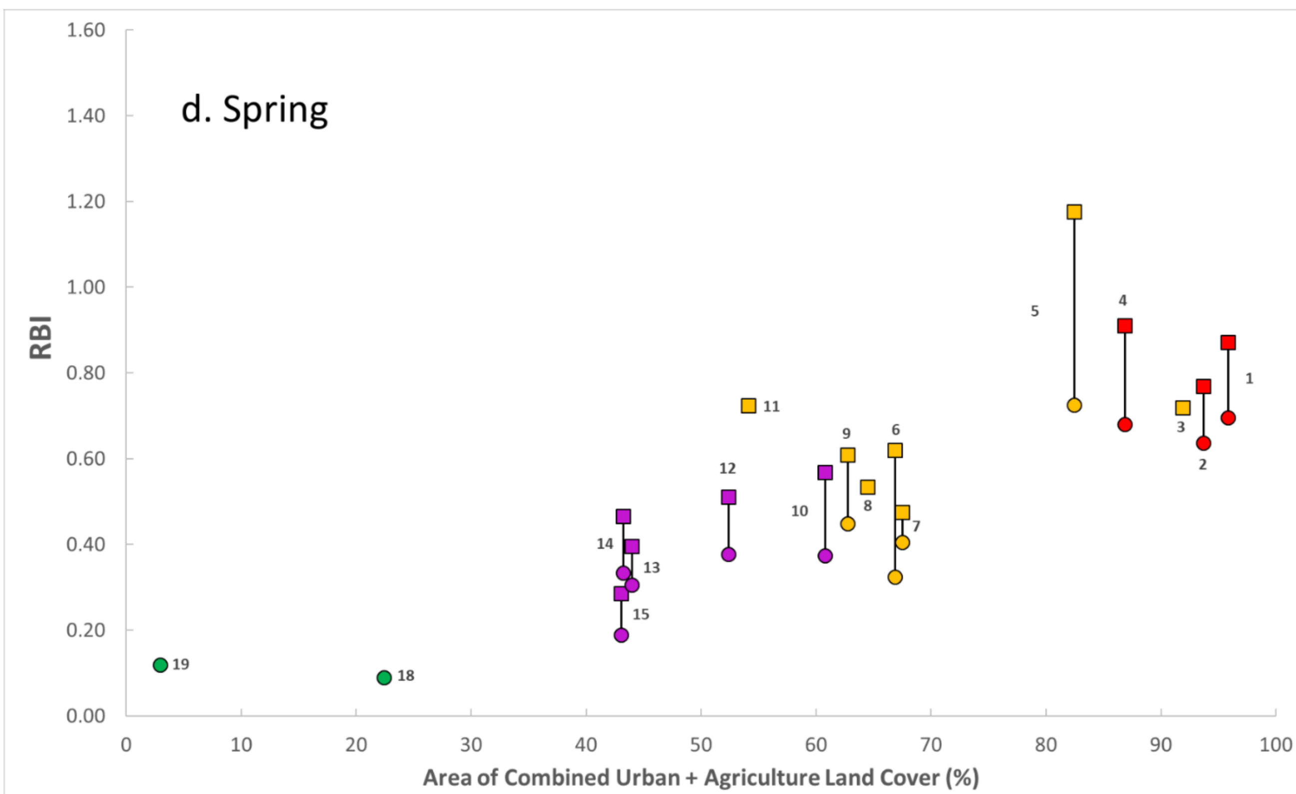
Very different precipitation inputs between the two years of study allowed the relative influence of climate on hydrologic response to be explored. Only the RBI metric was contrasted between the two years since it was the most consistently sensitive metric (i.e., at annual and seasonal scales; see Table 2.7) to both intensive agriculture and urban cover. Interestingly, the three most urbanized catchments had very similar annual RBI values in the two years despite an ~20% difference in precipitation between 2018-19 and 2019-20. Of the three urban watersheds, Gage Urban varied the most with RBI values of 0.91 and 0.83 in 2018-19 and 2019-20, respectively, whereas RBI was nearly constant at Highland Creek (Figure 2.5 a). In contrast, agricultural watersheds were more variable between years, especially Brand Creek, which ranged from 0.80 to 1.20 between the two water years (Figure 2.5 a, e). Inconsistent record lengths across the 19 streams make it difficult to statistically compare year-to-year differences, although overall, flashiness tended to be higher in 2018-19 compared with 2019-20 consistent with greater precipitation in that year (863 mm vs. 724 mm).

Seasonal RBI values were more variable and were not always higher in seasons with greater precipitation. The two falls were nearly identical in terms of total precipitation and temperature (Table 2.5), and similarly fall RBI values were similar between the two years for most watersheds (Figure 2.5 b). In contrast, differences in average RBI values between the two years in summer (0.53 vs 0.35), spring (0.64 vs 0.46) and winter (0.60 vs 0.52) were generally larger, likely due to greater inter-annual differences in precipitation within these seasons (Table 2.5).


a. Annual
RBI
Area of Combined Urban + Agriculture Land Cover (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19


b. Fall
RBI
Area of Combined Urban + Agriculture Land Cover (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19


c. Winter
RBI
Area of Combined Urban + Agriculture Land Cover (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
18
19


d. Spring
RBI
Area of Combined Urban + Agriculture Land Cover (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
18
19

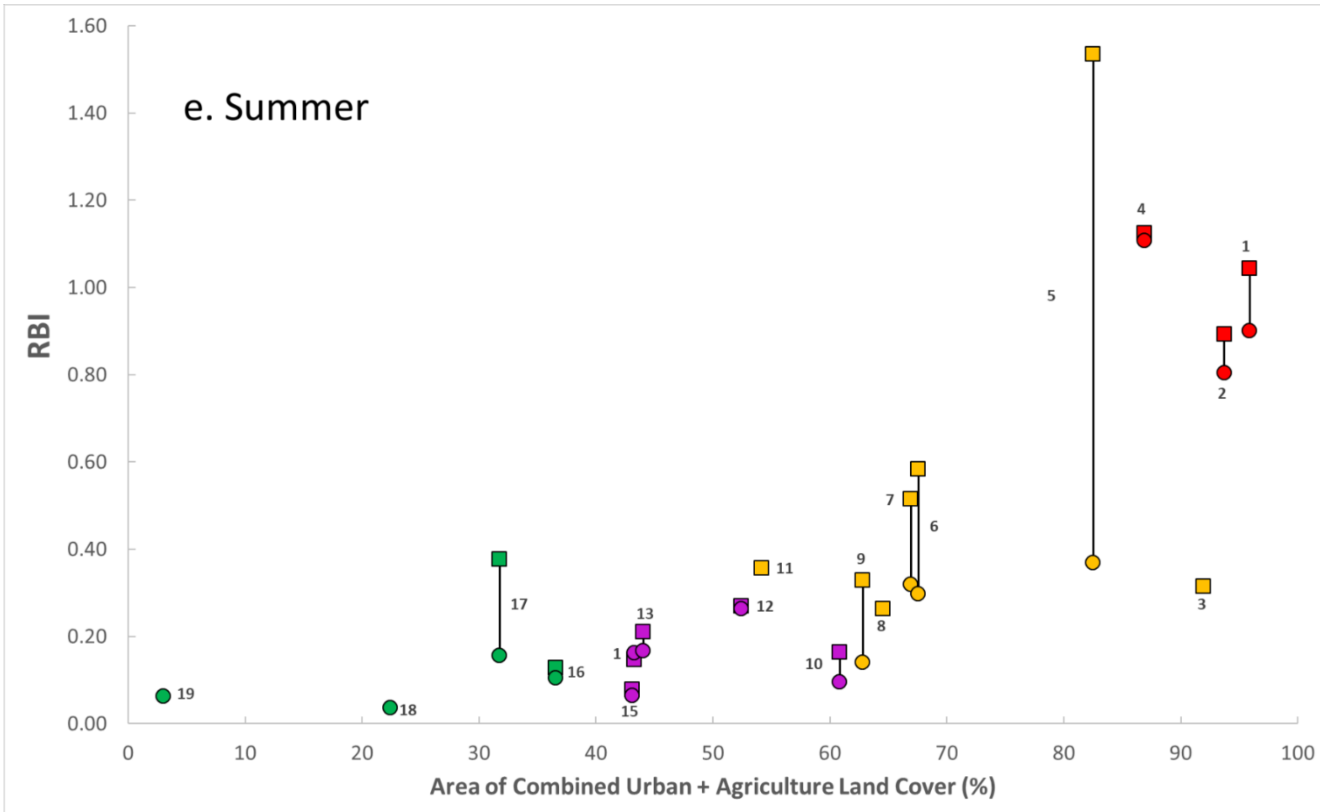



Figure 2.5 a, b, c, d, e. RBI values plotted against total area of developed land cover as % of watershed area. Red points = urban watersheds, yellow = agriculture, purple = mixed, green = natural. Squares represent 2018-2019 WY, and circles represent 2019-2020 water year. Numbers on points represent watersheds from Table 2.1.

A Principal Components Analysis (PCA) was used to evaluate the influence of landscape physiography as well as land cover on stream flashiness using all metrics (Figure 2.6). Overall, the PCA showed that while land cover is correlated with flashiness, other physiographic characteristics may play a role. It is also important to note that some aspects of catchment physiography might 'offset' anticipated land cover influence. More specifically, natural cover was strongly associated with the ORM, but was also associated with steeper slopes and coarser soils. Coarse-textured, well-drained soils should lower flashiness in streams by promoting infiltration of precipitation, yet steeper slopes may enhance flashiness by routing water more rapidly to recipient streams. Conversely, the more urban and agricultural watersheds located beyond the ORM toward the Lake

Ontario shoreline generally had flatter topography, which should reduce flashiness. However, they were also dominated by fine textured soils which would reduce soil infiltration capacity and thereby enhance flashiness. Despite these opposing patterns, very clear associations between developed land area and flashiness metrics (see above) indicate that land cover has a larger effect on flashiness than physiographic characteristics. Watershed area was also not a major influence on watershed flashiness and was not strongly associated with any type of land cover or physiography. Examples of this are Highland Down, which is the third largest watershed (91 $km^2$) but one of the flashiest (Figure 2.5) and Gan Nat 1, which is the fifth smallest (9.3 $km^2$) but usually the least flashy (Figure 2.5). Notably, Highland Down and Wilmot Down are similar in watershed area (91 $km^2$ vs 81 $km^2$, respectively), but have very different hydrologic behaviours as indicated by almost every flow metric (Figure 2.5). Overall, these observations suggest that land cover has a stronger influence on hydrologic behaviour compared with watershed physiography or size, and that flashiness is greater during wetter periods.

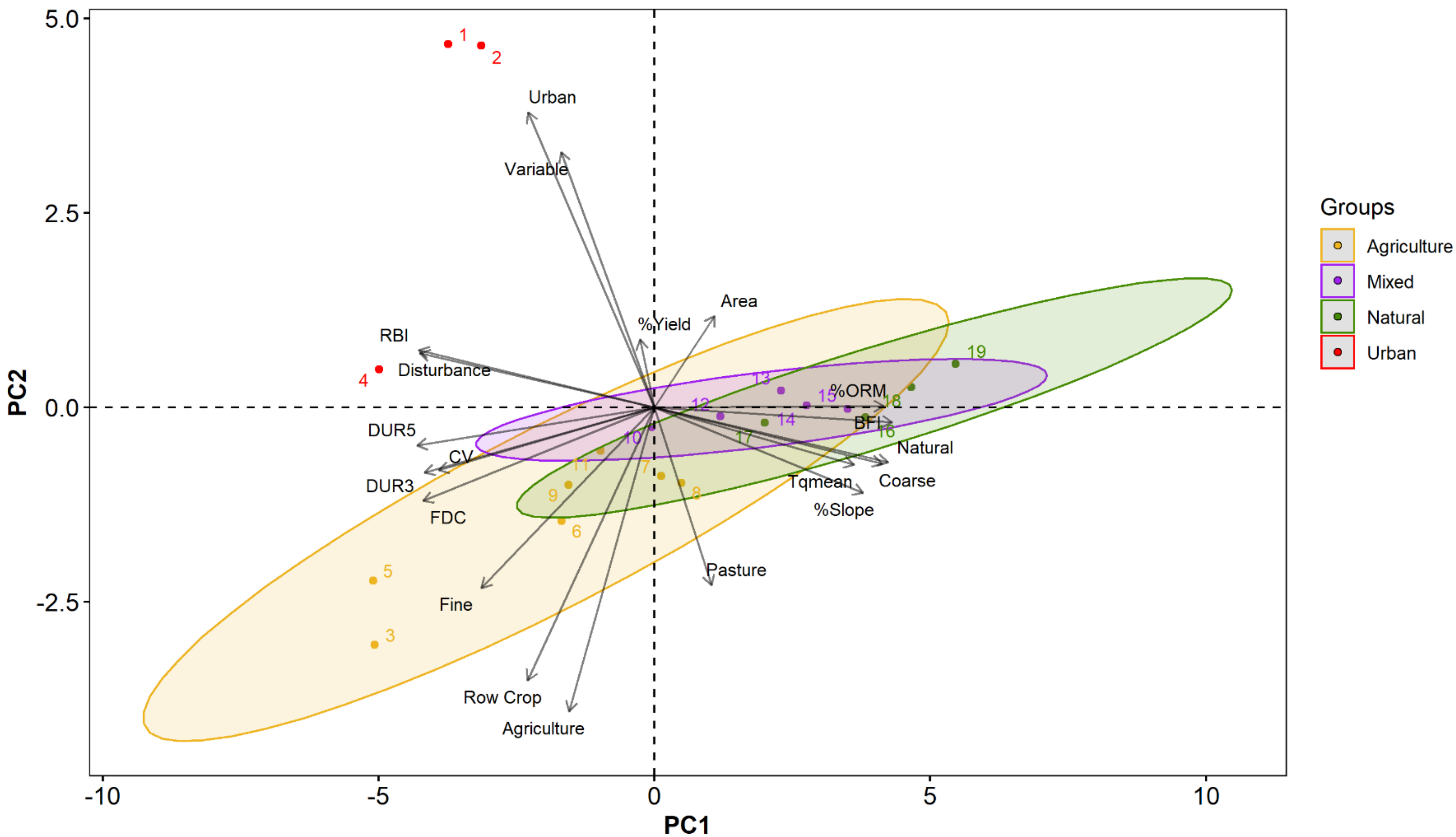



Figure 2.6. Principal Component Analysis biplot of flashiness metrics correlated against land cover and physiographic characteristics. Numbers on points represent watersheds found in Table 2.1.

*Hydrograph Comparison of Tile Drainage versus other Land Covers*

To gain greater insight into land cover controls on stream flashiness, three watersheds that represent the ‘end members’ of land cover in this region, including Mystery Creek (87% agriculture; 89% watershed area tile-drained), Gage Urban (64% urban, 0% TD), and Gan 2 (46% natural; 50% agriculture, 1% TD), were selected for further analysis at the event-scale. These three watersheds are appropriate comparators due to their proximity (Figure 2.1) and thus similar weather conditions, plus similar size (2.6 – 21 $km^2$). The three watersheds were compared between September 2018 and November 2019, when their records were continuous.

A cursory examination of hourly flow patterns at the three watersheds indicates that Gage Urban responded consistently to precipitation inputs throughout the year regardless of season, whereas Mystery and Gan 2 showed a less consistent response (Figure 2.7). More specifically, Mystery Creek responded modestly or not at all to precipitation inputs during the summer and early fall (June to October) when conditions were relatively dry but showed a much larger and more consistent response to precipitation and snow melt events in the late winter and spring months, when conditions were generally wetter (Figure 2.7). In contrast, the more natural watershed, Gan 2, had frequent but small peak events throughout the year, especially during the winter and spring months. Unlike Mystery Creek, streamflow at Gan 2 was maintained throughout the summer (Figure 2.7).

These differences in flow response may be attributed to differences in antecedent soil moisture conditions across the three watersheds, and more specifically the influence of TD.  For example, the almost-completely tiled Mystery Creek watershed responded very modestly to rain events during the summer, including a record-breaking storm (67mm) on July 17, 2019 which caused extensive flooding in the GTA (Figure 2.7). The relatively modest flow response at Mystery to this extremely large precipitation event in the summer may be due to enhanced soil moisture storage created by tile drainage. In contrast, peak flows at Gage Urban and Gan 2 were 3.99 and 0.88 mm/hr, respectively, following the July 17 event, suggesting much greater translation of precipitation input to runoff in these watersheds (Table 2.8).

In contrast, numerous rain events in the winter and spring ‘wet period’ resulted in a much larger response at Mystery compared with the other two watersheds. For example, a 26 mm rain-on-snow event on March 10, 2019 elicited the highest peak flow response (3.2 mm/h) recorded at Mystery over the study period, whereas runoff peaks at Gage Urban and Gan 2 were much smaller (2.4 mm/h and 1.4 mm/h, respectively; Figure 1-7). RBI values at Mystery remained higher (0.152) through the winter than at Gage Urban (0.138) or Gan 2 (0.088, Table 2.8), indicating that tile drained watersheds can be flashier than urban systems, depending on antecedent moisture conditions. This is further supported by larger depths of runoff at Mystery compared with the other two rivers during ‘wet’ periods, whereas runoff at Mystery during dry periods was generally lower (Table 2.9).

Overall, this comparison suggests that TD helps to mitigate the runoff response to large precipitation events by lowering the water table and enhancing soil moisture storage. In contrast, when soils are wet, as in Feb-March (Figure 2.7), tiles may enhance flashiness by increasing hydrologic connectivity and delivering precipitation more rapidly to streams.

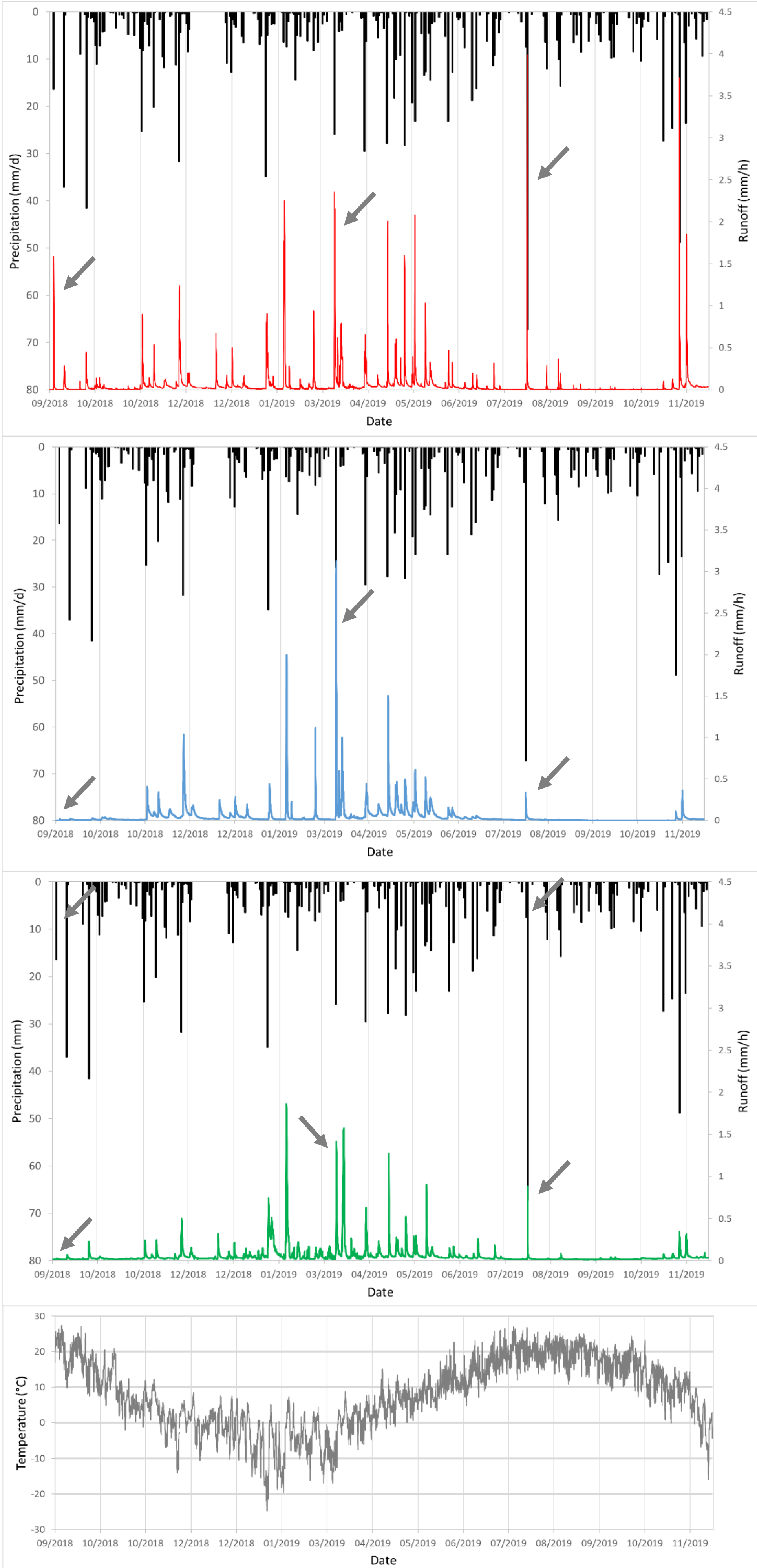



Figure 2.7. Top three graphs: hourly average runoff at Gage Urban, Mystery and Gan 2 between September 1, 2018 and November 15, 2019 along with sum of daily precipitation. Arrows indicate peak flow examples noted in text above. Bottom Figure is hourly average air temperature over the same period.

Table 2.8. Hourly RBI analysis of “dry” and “wet” periods.

| | | SEP 1 - OCT 31 (2018) | | NOV 1 (2018) - JUN 1 (2019) | | JUN 2 - AUG 31 (2019) | | SEP 1 (2018)- AUG 31 (2019) |
|---|---|---|---|---|---|---|---|---|
| Watershed | % TD | **RBI** | **% of Annual Runoff** | **RBI** | **% of Annual Runoff** | **RBI** | **% of Annual Runoff** | **Total Runoff (mm)** |
| Mystery | 85.0 | 0.035 | 3% | 0.083 | 91% | 0.034 | 6% | 494 |
| Gan 2 | 1.0 | 0.029 | 6% | 0.072 | 83% | 0.057 | 10% | 543 |
| Gage Urban | 0 | 0.197 | 6% | 0.134 | 86% | 0.294 | 8% | 499 |

Table 2.9. Hourly RBI analysis of the months that include peak flow examples indicated in Figure 2.7.

| Watershed | SEP 1 - Sep 31 (2018) | | February 22 - March 26 (2019) | | July 1 - July 31 (2019) | | SEP 1 (2018)- AUG 31 (2019) |
|---|---|---|---|---|---|---|---|
| | **RBI** | **% of Annual Runoff** | **RBI** | **% of Annual Runoff** | **RBI** | **% of Annual Runoff** | **Total Runoff (mm)** |
| Mystery | 0.047 | 1.1 | 0.152 | 16.7 | 0.067 | 2.2 | 494 |
| Gan 2 | 0.043 | 3.2 | 0.088 | 18.5 | 0.110 | 3.1 | 543 |
| Gage Urban | 0.259 | 3.9 | 0.138 | 17.9 | 0.408 | 4.3 | 499 |

## 2.4 Discussion

*Land cover effects on hydrologic regime*

Like previous studies, results of this work suggest that urbanization has a strong influence on hydrology as the three most urbanized streams (Highland Creek watersheds and Gage Urban) had the highest peaks flows ($T_{Qmean}$), the smallest fraction of baseflow (BFI), and the most variable flow (RBI, CV, FDC) of the 19 study watersheds. However, unexpectedly, flashiness, baseflow and peak flows at the two most heavily tile-drained watersheds (Mystery and Brand) were comparable to the urban streams. Flashiness values measured in this study at the three most urbanized watersheds are similar to values reported in the literature. For example, Mogollón et al. (2016) reported RBI values of 0.80-1.25 at similarly sized, predominantly urban watersheds (ranging from 40% to 100%

coverage) using data collected over a 22-year period in North Carolina and Virginia, United States. Relatively high values of flashiness including larger peak flows and longer periods of low flow are expected in urban watersheds due to their altered water balance. While this study did not estimate ET or storage, patterns of runoff in the urban watersheds suggest that there is little temporary storage as streams respond rapidly to precipitation inputs. Previous studies have estimated the water balance of urban watersheds and have shown that reduction of vegetation and construction of impermeable surfaces together reduce temporary storage resulting in higher flashiness (Lull & Sopper, 1969).

While agricultural watersheds were typically less hydrologically altered compared with urban streams, they were significantly different from the most natural watersheds. For example, the average annual RBI at the seven agricultural watersheds was 0.58 ± 0.21, which was more than double the average at the four natural watersheds of 0.23 ± 0.15, indicating more frequent and larger peak flows. Interestingly, while total agricultural area was strongly correlated with most flow metrics (after the three urban watersheds were removed), separation of agriculture into its two constituent categories of row crop and pasture showed that row crop area (much of which is tile-drained; see Table 2.1) is the primary driver. While agriculture is considered to have a smaller influence on hydrology compared with urban development, numerous studies have reported hydrologic differences between agriculture and natural cover. For example, annual row crops alter the water balance by reducing ET losses compared with naturally vegetated (perennial) grasslands, resulting in more annual runoff (Schilling et al., 2008). Results from this study are consistent with Schomberg et al. (2005) who showed that streams with greater row crop cover had more variable flow using the coefficient of variation flow metric. Pasture appeared to have a smaller influence on hydrology compared with row crops, although the range in pasture cover across the study watersheds was also smaller (0 to 37% of watershed area compared with 0 to 85% row crop coverage), which may be too narrow to detect the effects of pasture on the hydrologic regime. Previous research has similarly shown that pasture has a smaller hydrologic impact compared with row crops. For example, Udawatta et al. (2002) and Gilley et al. (2000) reported 1% - 52% declines in surface runoff (surface runoff contributes to flashiness) when annual row crops (corn/soy) were replaced by perennial vegetation commonly found in pasture.

The two most intensively agricultural watersheds (Mystery and Brand) were flashier than any of the other agricultural or more natural watersheds and in some cases were even flashier than the urbanized streams. There is no clear consensus in the literature on the hydrologic impacts of TD and some studies suggest an increase in flashiness and peak flow, whereas others report the opposite, and differences appear to be related to soil type, antecedent moisture and topography (Gramlich et al., 2018). We hypothesized that TD would increase stream flashiness, although other studies have shown the opposite and have reported that TD can augment baseflow which should decrease peak flow (Schilling & Helmers, 2008; Schilling et al., 2012) since more water is being released slowly from soils into drains instead of during flow events. Contradictions exist even in the same geographical area, as Miller and Lyon (2021) recently showed that tile-drained corn-soy dominated watersheds in Iowa were flashier and had 21% less base flow volume compared with watersheds with less extensive tile drainage, in stark contrast to Schilling and Helmers (2008). These contradictions suggest that there may be a threshold of TD coverage before hydrologic impacts are detected, which Miller & Lyon (2021) showed to be ~ > 40% coverage. Our watersheds suggest a similar threshold response, as Brand (47% TD coverage) and Mystery (87% TD coverage) are both clearly flashier than other less intensive (less tiled) agricultural watersheds including Gage West (25% TD; Figure 2.5).

Watersheds with the most natural coverage were the least flashy and forest is the most abundant natural cover in this region. At the watershed scale, forests remove more water via ET than annual crops or urban areas and ET losses extend over a longer period of the year (Liu et al., 2003) resulting in less annual runoff that ultimately reduces peak flow events and diminishes flashiness. Other processes such as canopy and leaf litter interception of precipitation likely also contribute to lower runoff generation in forests compared with agricultural cover, as agricultural soils are often bare during parts of the year following crop removal. Furthermore, more mature forests promote slower snowmelt, which reduces runoff peaks as well as daily average streamflow (Winkler et al., 2005).

*Annual and Seasonal Differences in Flashiness*

Inter-annual differences in flashiness were observed amongst most watersheds at the annual scale, and flashiness was generally higher in the first year (2018-2019) when precipitation was greater (863 mm). Previous studies have reported differences in flashiness caused by differences in precipitation, suggesting that land cover can amplify the hydrologic response to weather events (Bezak et al., 2015; Saharia et al., 2021).

The three most urbanized watersheds showed the lowest inter-annual variability, which contradicted the premise that more annual precipitation results in higher flashiness.

Urban cover has been shown to consistently produce high peak flow events regardless of season by impervious surfaces reducing the variability of soil-water interactions (Konrad & Booth, 2005) which may explain the similar flashiness values between years with differing amounts of precipitation. Smaller inter-annual differences in certain seasons, like winter, may be due to the homogenizing effect of snow and frozen soils as discussed by Eimers & McDonald (2015). Nevertheless, when RBI values were compared by season, differences between the two water years were clearer and more consistent with precipitation, especially during the summer.

*Effects of Watershed Physiographic Characteristics on Flashiness*

Other factors can influence hydrologic regime, including watershed size, soil texture, slope, and hydrologically significant landforms like the ORM. Principal Component Analyses showed that several of these landscape factors were correlated with land cover and hydrology, but the results suggest that land cover is the primary driver.

More specifically, watersheds located on the ORM (7 of 19 had > 50% of their watershed area within the ORM) had coarse textured, well drained soils and more sloped topography, while watersheds outside of the ORM, closer to the shore of Lake Ontario, had finer textured soils and flatter topography (Buttle et al., 2015). The ORM has two contradicting characteristics that affect the flashiness of streams: steeper sloped topography that should increase the rate of water delivery to streams, and predominance of well-drained soils that should instead favor infiltration. These opposing patterns of physiography and flow regime also occur south of the ORM, where watersheds are flatter (less surface runoff/flashiness), but also have finer textured soils (more surface runoff/flashiness). The fact that physiographic influences are expected to ‘cancel each other out’ suggests that land cover is the primary driver of hydrologic differences across watersheds. Watershed area was also taken into consideration as a modifier of flashiness. However, watershed size did not appear to be important in this case, as watershed area was not correlated with any of the flow metrics (see Figure 2.7) despite most metrics not using area adjusted flow values. Baker et al. (2004) found that flashiness was lower in larger watersheds (> 1000 $km^2$) whereas size was less impactful on flashiness in watersheds of the size considered in this study. For example, in this study RBI was similar at Highland Down, which is 30 times larger in size than Gage Urban. Furthermore, the RBI was calculated at the daily time sale in order to reduce the effect of basin size on time of travel.

*Metrics*

One of the objectives of this study was to identify the most sensitive hydrologic metric(s) to human development, and to determine whether some metrics are better indicators of urban vs. agricultural expansion. Most flow metrics were correlated with urban cover, with the RBI, CV, BFI and, to a lesser extent, the $T_{Qmean}$ showing the strongest correlations. Poff et al. (2006) showed that the $T_{Qmean}$ and a similar metric to the RBI were statistically correlated with urban cover across watersheds in the U.S.A, whereas the CV was not significantly correlated with urban cover at any of the watershed regions considered, contrary to the results of this study. This difference may be attributed to the location of urban areas further upstream in the larger watersheds considered by Poff et al. (2006; range 17 – 242 $km^2$; mean area = 107 $km^2$) which may lessen the effects of impervious cover on flashiness (Roodsari & Chandler, 2017). The %Yield metric generally did not have strong correlations with urban cover, which is contrary to the idea that urban watersheds translate a greater fraction of incoming precipitation into runoff. This coincides with other research that also found that urbanization does not always produce more runoff relative to precipitation (Rose & Peters, 2001). From this study, it was easier to determine which metrics performed poorly than to determine the best metric considering most metrics were correlated with developed land area. Poor performers include %Yield, which did not show clear distinctions between land covers, and DUR3 and DUR5 that did not perform as expected, even though they showed significant correlations with land cover (Table 2.7).

*Conclusions*

This research chapter evaluated the hydrologic effects of land cover change using eight different hydrologic metrics in 19 watersheds that encompass a gradient of agricultural and urban development in east-central Ontario. Watersheds with the greatest extent of human disturbance (i.e., urban and intensive agriculture) had the most variable and flashiest flow regimes, whereas watersheds with more natural land cover and/or less intensive agriculture were less flashy. Most of the eight metrics considered in this study responded as expected and were sensitive to land cover change at both the annual and seasonal time scales. The hydrologic effects of agriculture became clearer when the tile-drained watersheds were examined separately. The two most tile-drained watersheds were even flashier than the most urbanized watersheds in some seasons, and the effect of tile drainage was most clearly observed during the late winter and spring months when soils are likely saturated with water. In contrast, tile drainage may minimize the hydrologic response to extreme precipitation events during the summer, when antecedent moisture conditions are low and soil storage is enhanced by TD. Physiographical characteristics undoubtedly play an important role in modifying hydrologic response, particularly for watersheds located on the ORM; however, these results suggest that land cover 'trumps' physiography. A recommendation from this study would be to protect natural areas within the headwaters of the ORM to prevent flooding in downstream agricultural fields and urban areas. Likewise, tile drainage within agricultural headwaters may increase the potential for downstream flooding in urban areas during wet seasons and reduce runoff in summer months. With increasing popularity of tile drainage in southern Ontario and changing climate, further research on the hydrologic effects of tile drainage may be useful to farmers and downstream cities.

# 3.0: Long Term Response of Streamflow to Changes in Landcover

## 3.1 Introduction

The population of southern Ontario is expected to increase by approximately 30% between 2017 and 2041 along with urban expansion (Ontario Ministry of Finance, 2018). As urban centers are built, agricultural lands are the primary targets for development (Hofmann, 2001). Urbanization can alter the hydrologic regime by increasing the magnitude of peak flows, and increasing the frequency of flooding (Hollis, 1975; Burges et al., 1998; Rosburg et al., 2017).

Hydrologic metrics, like those assessed in the first research chapter, can be used to determine how the hydrologic regime has been altered by land cover change over time. The Richards Baker Index (RBI) quantifies stream 'flashiness' and is commonly used to evaluate hydrologic response to urbanization (Rosburg et al., 2017; Diem et al., 2018; Roodsari & Chandler, 2016). The RBI has been found to have low intra-annual variability compared with other hydrologic metrics and is therefore preferable for long-term analyses (Baker et al., 2004). The RBI can be useful for evaluating changes in flashiness at the decadal time scale, although the majority of previous analyses of long-term flow response have computed the RBI metric using annual time series and have not indicated which season(s) are driving flashiness response (Booth & Konrad, 2017).

Another metric frequently used in longer-term analyses of flow response as well as precipitation change is the Flow Duration Curve (FDC) (Rosburg et al., 2017; Brown et al., 2005). Flow percentiles in FDCs can be contrasted at the inter-annual or decadal scale to evaluate flow response to land cover change. Typically, land cover changes from natural to agriculture or from natural to urban have a larger impact on high percentiles (i.e., peak flows), whereas the response of lower percentiles (i.e., baseflows) can vary, and both increases and decreases in low flows have been reported (Rosburg et al., 2017).

While comparative studies often report that land cover has a larger impact on hydrologic regime than variations in precipitation (Schoonover et al., 2006; Cuo et al., 2011), long-term shifts in precipitation changes are important to consider in longer term analyses of hydrologic regime. Precipitation has generally increased in southern Canada due to climate change with one study reporting a 5 to 35% increase of annual precipitation between 1900 and 1998 (Zhang et al., 2000). Furthermore, statistically significant increases in precipitation have been reported in southern Ontario beginning between the 1960s and early 1970s that resulted in more streamflow between 1954 and 2008 (Nalley et al., 2012). Another more recent study found significant increases of flow in the winter months because of increasing amounts of winter rainfall between 1968 and 2017 in southern Ontario (Azarkhish et al., 2021).

Building on results of the first chapter of this thesis, the objective of this chapter was to use historical data to evaluate the effect of shifts in land cover change on watershed hydrologic regime across a range of streams in southern Ontario. Two hydrologic metrics, the RBI and FDC, were used to characterize the hydrologic response to changes in land cover and precipitation. Results of Section 2.0 indicated that both the RBI and FDC were sensitive to urban land cover, although the FDC was more sensitive to agricultural intensification; thus, these two metrics were selected for long-term analyses. Specific hypotheses tested in this research chapter include: i) urban expansion has increased stream flashiness (i.e., higher RBI values) leading to higher flow magnitudes, and ii) land cover change over time has a greater impact on the hydrologic regime than changes in the timing and amount of precipitation.

## 3.2 Methods

*Study Area*

Ten long-term (43-71 years) Water Survey of Canada (WSC) watersheds were selected to encompass a gradient of land cover from predominantly urban (e.g. Highland Creek, 91%) to substantial amounts of natural (e.g., Gan NW, 61%) and agricultural cover (e.g., Bowmanville Creek, 63%). The ten study watersheds are located in east-central Ontario, between Scarborough and Cobourg (Figure 2.1), range in size from 46 to 255 $km^2$ (Table 2.1) and drain into Lake Ontario. The physiography and climate of the region is similar to that described in Section 2.2 and is characterized by relatively flat slopes near Lake Ontario and more undulating topography in the headwaters, characteristic of the Oak Ridges Moraine. Surficial geology closer to the lake shore is mixed, and is composed of both silt-textured material with pockets of clay as well as areas of well-drained sand deposits, although these deposits are more widespread in the watersheds east of Oshawa (Ontario Ministry of Northern Development, Forestry and Mines, 2010).

*Land Cover*

Watershed areas were calculated using OFAT, identical to Section 2.2, whereas land cover change was calculated using several spatial layers that together record land cover in the region over a period of 50 years (1966 – 2016). The Canadian Land

Inventory (CLI; Agriculture and Agri-food Canada, 2013) layer and the Canadian Land Usage Monitoring Program (CLUMP; Natural Resources Canada, 1999) layers are the oldest available digitized land cover layers, and both were created through manual digitization of air photos from 1966. The CLI layer was used to reconstruct 1966 land cover because the CLUMP layer only covered Highland Creek and Rouge River, whereas the CLI covered all watersheds. Resolution is identical between the CLUMP and CLI. The CLUMP layer only considers dense urban areas near Toronto, and as such only the Rouge and Highland Creek watersheds were included in the 1971-1986 land cover analysis. The Southern Ontario Land Resource Information System (SOLRIS) was used to estimate land cover in 2000 (version 1), 2010 (version 2) and 2016 (version 3). SOLRIS has a much higher resolution compared with CLI and CLUMP using 30m x 30m cells collected by satellite and LiDAR. There were also differences in classification method amongst the three land cover sources that needed to be addressed prior to analysis. More specifically, the SOLRIS classification system includes 30 categories of land cover including four types of wetlands and four types of forest. For the purpose of this study, these ‘natural’ land covers were summed (Table 3.2). In contrast, SOLRIS (versions 1-3) describes agricultural cover very simply as ‘crops’ or ‘idle/undifferentiated’ land. The CLUMP and CLI used either pastureland or horticulture/crops as the categories for ‘agriculture’. Urban cover is very simply described in the CLI/CLUMP layers as land with buildings and/or lawns/parks, which differs from the SOLRIS layers that separate urban into either permeable or impermeable surfaces. To remain consistent across all layers, the impermeable and permeable categories in the SOLRIS layers were summed as one category to be in line with the

CLI/CLUMP category. Another noteworthy difference is that SOLRIS includes major roads within urban coverage whereas the CLI/CLUMP likely did not have high enough resolution to include roads (see Figure 3.1).

Table 3.1. Study watershed areas.

| Watershed | Area ($km^2$) |
|---|---|
| Highland Creek | 90.5 |
| Rouge River | 187.0 |
| Lynde Creek | 100.2 |
| Duffins Creek | 255.6 |
| Bowmanville Creek | 80.0 |
| Shelter Valley Creek | 63.4 |
| Wilmot Creek | 80.9 |
| Gan Osaca | 72.3 |
| Gan Sylvan | 239.7 |
| Gan NW | 46.0 |

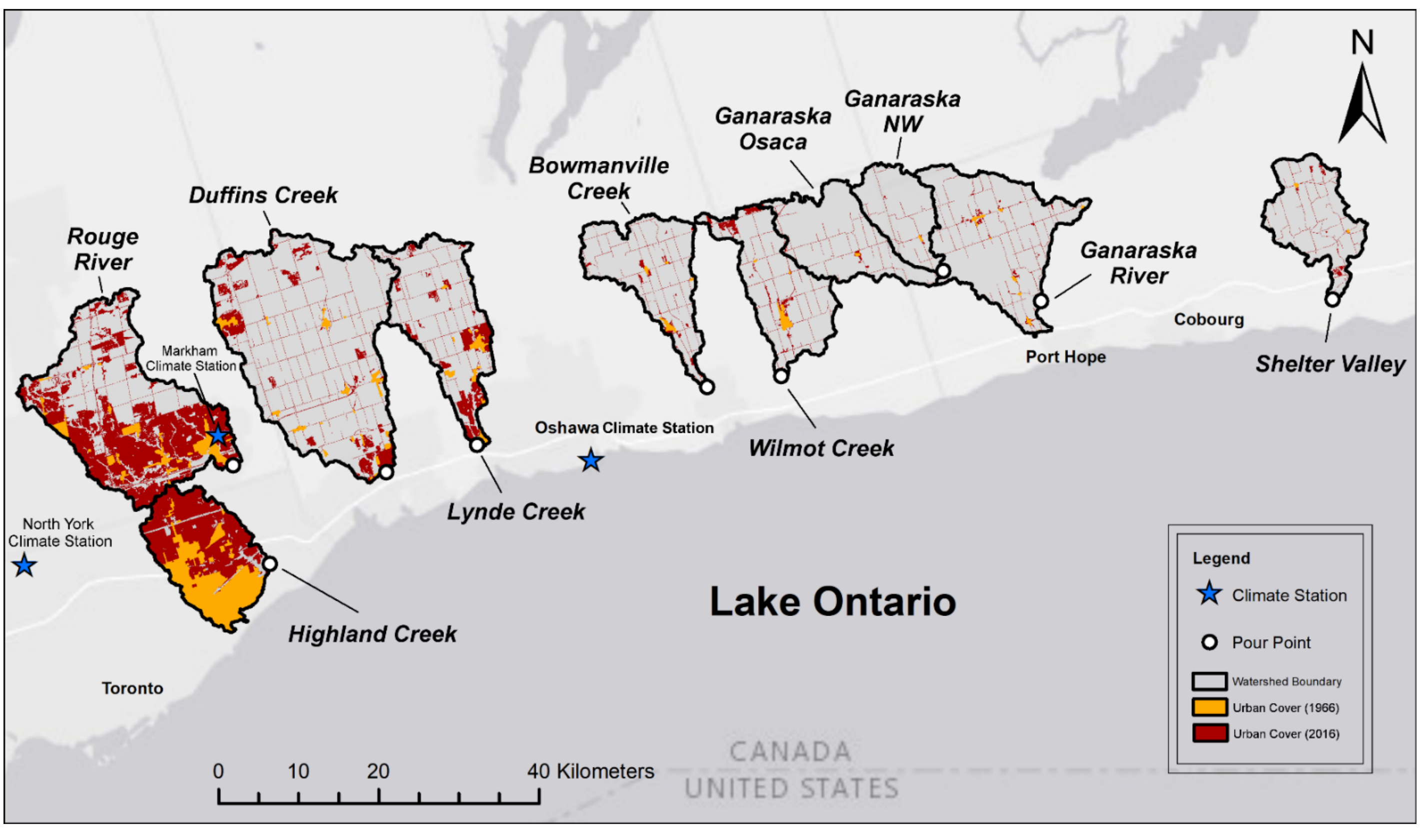



Figure 3.1. Urban land use change (% coverage) in watersheds selected for long term hydrologic analysis.

Table 3.2. Land cover attributes that were classed into urban, agriculture and natural coverage from the CLI/CLUMP layers, SOLRIS 1.0 and SOLRIS 2.0/3.0.

| Landuse Class | CLI/CLUMP (1966 – 1986) | SOLRIS 1.0 (2000) | SOLRIS 2.0/3.0 (2010 – 2016) |
|---|---|---|---|
| Urban | Built Up Areas<br>Mines, Quarries<br>Outdoor Recreation | Transportation<br>Built Up Area - Pervious<br>Built Up Area - Impervious | Transportation<br>Built-Up Area - Pervious<br>Built-Up Area - Impervious |
| Agriculture | Horticulture<br>Orchards and Vineyards<br>Cropland<br>Improved Pasture and Range Land<br>Unimproved Pasture and Range Land | Idle Land<br>Tree Plantations<br>Undifferentiated | Tree Plantations<br>Tilled<br>Undifferentiated |
| Natural | Productive Woodland<br>Non-productive Woodland<br>Swamp<br>Marsh<br>Bog | Sand Dunes<br>Open Tallgrass Prairie<br>Tallgrass Woodland<br>Forest<br>Coniferous Forest<br>Mixed Forest<br>Deciduous Forest<br>Hedge Rows<br>Swamp<br>Fen<br>Bog<br>Marsh<br>Open Water<br>Shallow Water | Forest<br>Coniferous Forest<br>Mixed Forest<br>Deciduous Forest<br>Treed Swamp<br>Thicket Swamp<br>Fen<br>Bog<br>Marsh<br>Hedge Rows<br>Open Water |

*Flow and Precipitation Analysis*

Daily flow records ($m^3$/sec) were obtained from the Water Survey of Canada (wateroffice.ec.gc.ca) for each of the selected watersheds. Record length ranged from 43 years (Gan Sylvan) to 71 years (Duffins Creek). Because both urban and agricultural land cover have changed over time, two metrics were used to identify changes to the hydrologic regime. First, the Richards-Baker Index (RBI) was used to evaluate differences in flashiness amongst watersheds and changes over time based on results from the first research chapter. The RBI was calculated for every complete (or nearly complete) year of record as well as seasonally (fall: Sept-Nov; winter: Dec-Feb; spring:

Mar-May; summer Jun-Aug). Annual flow records were not always complete, and some years had many weeks of missing flow data. Also, older records often included one value of flow that was repeated for several days or sometimes weeks during winter months when there was likely ice on the streams. To avoid potential inaccuracies, years with more than 30 days of missing data or having 30 or more days of repeated daily averages were excluded from the analysis. Furthermore, if a season had 14 or more days with the same issue, then that season was not included in further analyses.

The second metric used was the flow duration curve (FDC), which evaluates decadal shifts in flow. Flow duration curves separate the entire flow record into percentiles and results from the first research chapter indicated that FDCs were especially sensitive to agricultural change. Daily streamflows were normalized by watershed area and split into decades using the earliest flows available (starting in the 1960s) and ending in 2018. FDCs were calculated using the entire record at each watershed. Years with > 30 days of missing data were excluded from the analysis to avoid inaccurately weighting flow due to missing data.

To create the longest record possible at Duffins Creek, two flow records (1945 – 1989 and 1989 – 2018) had to be combined together. These two records exist because of a minor change in the location of the WSC gauging station. The old site was moved 500 m downstream, adding approximately 2 $km^2$ of new watershed coverage to the original watershed area of 257 $km^2$. There was no distinguishable difference in the combined hydrograph.

Daily precipitation data were gathered from three weather stations: Markham (station ID 6154987), Oshawa (station ID 6155875), and North York (station ID

615S001; Environment Canada, 2020) and were obtained from Environment and Climate Change Canada (https://climate.weather.gc.ca/). Due to incomplete records at each individual station, observations from the three stations were combined together to form a complete record. Markham's records were used from 1960-1979, Oshawa between 1970-1999, and North York between 2000-2019. These climate stations were selected because they were close to the center of the study area near Lake Ontario and were relatively close in proximity to one another. A fourth station (Pearson Airport, station ID 6158733) with complete records between 1960 and 2019 was used to visually check whether combining multiple records biased the trend analysis, assuming that any 'real' directional trends in precipitation observed in the combined record should also be observed at Pearson. Years with complete daily precipitation records were summed to calculate annual and seasonal totals (mm). A variety of different precipitation metrics were calculated for each decade of record (Table 3.3) and were selected because they are considered good indicators of weather conditions that result in flashy streamflow (Nastos & Zerafos, 2009).

Table 3.3. Descriptions of precipitation metrics.

| Precipitation Metrics | Description |
|---|---|
| Sum Precip | Total sum of precipitation |
| < 2mm | Sum of daily precipitation less than 2mm |
| ≥ 10mm | Sum of daily precipitation equal to or greater than 10mm |
| ≥ 20mm | Sum of daily precipitation equal to or greater than 20mm |
| ≥ 30mm | Sum of daily precipitation equal to or greater than 30mm |
| Wet | Counts of daily precipitation ≥ 1mm three days consecutively |
| Dry | Counts of daily precipitation < 1mm seven days consecutively |

*Statistical Analyses*

The Mann-Kendall test was used to determine temporal trends in RBI values and precipitation using the packages ‘trend’ and ‘mk.test’ in the statistical program R (R Core Team, 2017; Pohlert & Kendall, 2016). All complete years and seasons were used in trend tests and p-values < 0.05 were considered statistically significant, except for Table 3.7 that additionally used p-values < 0.10. Spearman correlations were used to evaluate correlations between precipitation metrics (units in mm/year and mm/season) and RBI values after first testing for normality (Shapiro-Wilk tests).

## 3.3 Results

*Land cover*

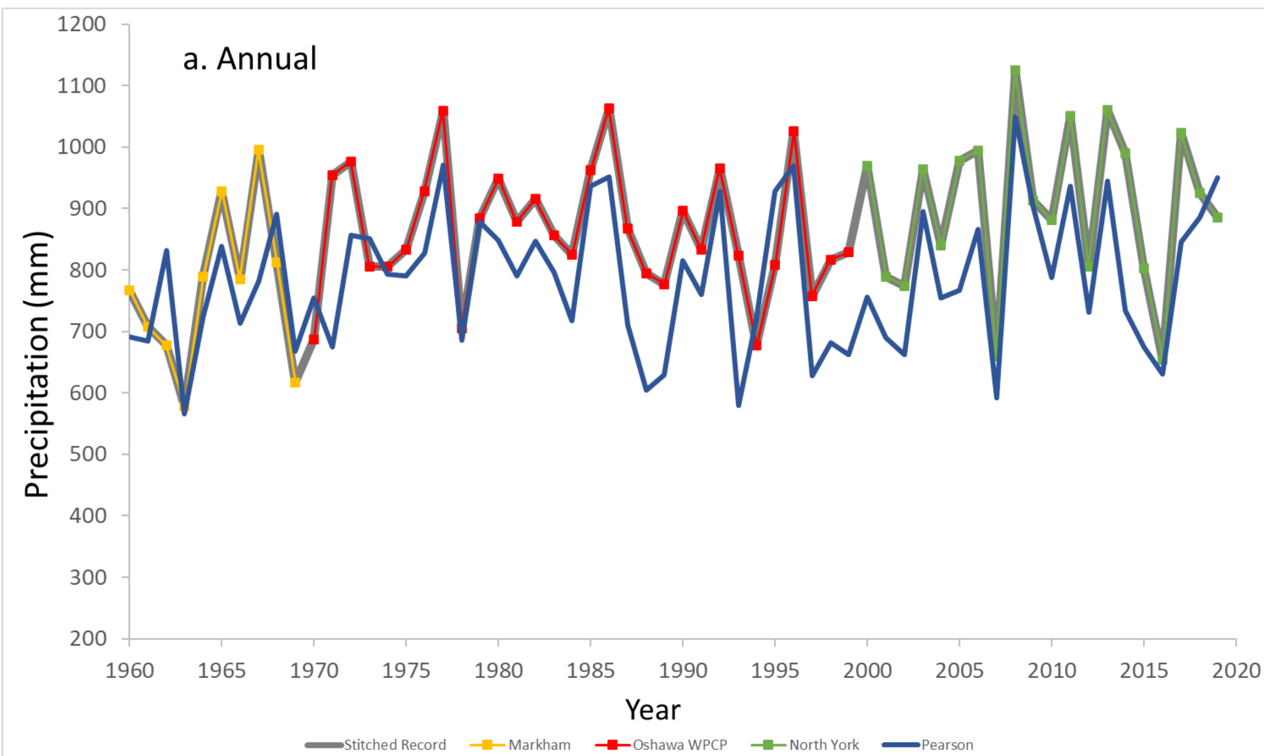
Across the ten study watersheds, urban cover changed the most over time, and increases in urban cover were primarily at the expense of agricultural land (Table 3.4). Urban increases were particularly large at Highland, Rouge and Lynde, whereas others showed relatively small changes over time (Gan 4, Gan Sylvan and Shelter Valley; Table 3.4). For example, Highland Creek was 53% agriculture in 1966, and this was almost entirely replaced by urban cover by 2016, when only 6% of the watershed area remained as agriculture (see Figure 3.1). The Rouge River had similar urban expansion rates as Highland but had little urban cover in the 1960s and the greatest increase in urban cover occurred between 1986 and 2000 (Table 3.4). By contrast, Shelter Valley and the Ganaraska watersheds (Gan Sylvan, Gan NW, and Gan Osaca) had very little urban growth and instead showed slight increases in natural cover since the 1960s. Urban increases were slightly higher at other watersheds, ranging from 4-13% between 1966 and 2016 (Table 3.4).

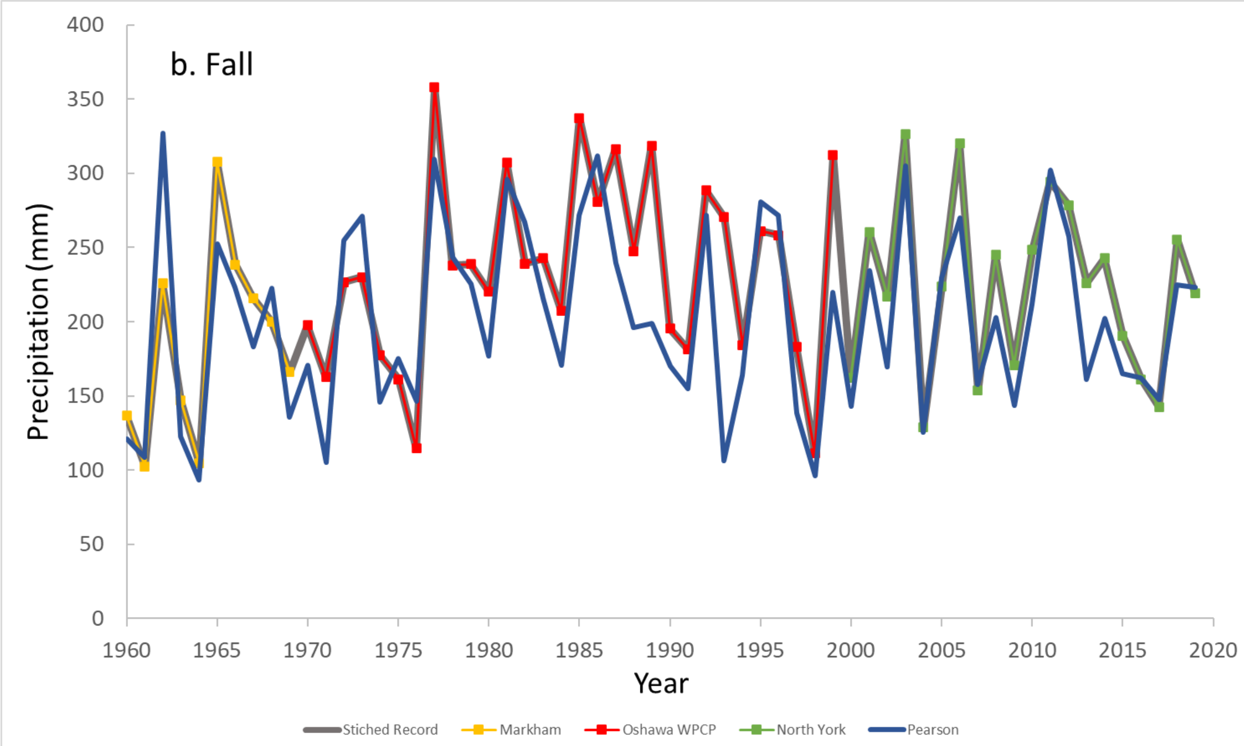
Table 3.4. Land cover (as % of watershed area) at the 10 study watersheds over time. Watersheds are ordered from largest to smallest percentage change within the three major land cover classifications.

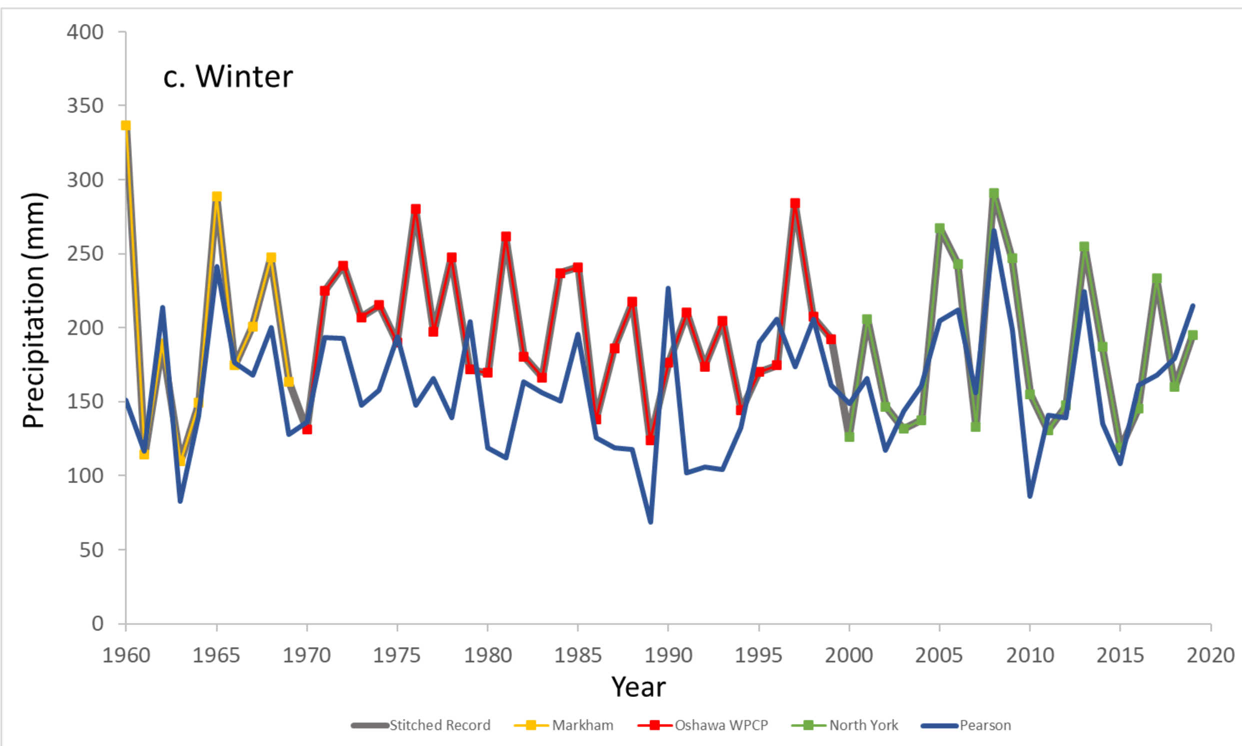
| Land Cover | Landcover Layer | CLI | CLUMP | CLUMP | CLUMP | CLUMP | SOLRIS 1.0 | SOLRIS 2.0 | SOLRIS 3.0 | %Δ 1966 - 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Year** | **1966** | **1971** | **1976** | **1981** | **1986** | **2000** | **2010** | **2016** | |
| **Urban** | Highland Down | 42 | 69 | 73 | 77 | 83 | 91 | 91 | 91 | +49 |
| | Rouge | 8 | 13 | 16 | 15 | 22 | 45 | 51 | 51 | +43 |
| | Lynde Down | 5 | | | | | 13 | 18 | 18 | +14 |
| | Duffins | 4 | | | | | 8 | 10 | 10 | +6 |
| | Bowmanville | 1 | | | | | 6 | 7 | 7 | +5 |
| | Shelter Valley | 0 | | | | | 4 | 4 | 4 | +4 |
| | Wilmot Down | 3 | | | | | 6 | 7 | 7 | +4 |
| | Gan Osaca | 0 | | | | | 3 | 3 | 3 | +3 |
| | Gan Sylvan | 1 | | | | | 3 | 3 | 3 | +3 |
| | Gan NW | 0 | | | | | 2 | 2 | 2 | +2 |
| **Agriculture** | Highland Down | 53 | 27 | 23 | 19 | 13 | 6 | 7 | 6 | -47 |
| | Rouge | 82 | 76 | 74 | 73 | 65 | 41 | 36 | 35 | -46 |
| | Lynde Down | 80 | | | | | 65 | 61 | 60 | -19 |
| | Gan Osaca | 58 | | | | | 41 | 42 | 42 | -17 |
| | Wilmot Down | 77 | | | | | 64 | 63 | 63 | -14 |
| | Bowmanville | 76 | | | | | 63 | 63 | 63 | -13 |
| | Duffins | 76 | | | | | 64 | 63 | 63 | -12 |
| | Gan Sylvan | 60 | | | | | 48 | 49 | 49 | -11 |
| | Shelter Valley | 69 | | | | | 55 | 58 | 58 | -11 |
| | Gan NW | 46 | | | | | 37 | 37 | 37 | -9 |
| **Natural** | Wilmot Down | 20 | | | | | 28 | 27 | 27 | +7 |
| | Bowmanville | 23 | | | | | 30 | 30 | 30 | +7 |
| | Gan NW | 54 | | | | | 61 | 61 | 61 | +7 |
| | Duffins | 19 | | | | | 25 | 26 | 26 | +7 |
| | Shelter Valley | 30 | | | | | 37 | 37 | 37 | +7 |
| | Lynde Down | 15 | | | | | 21 | 21 | 21 | +6 |
| | Rouge | 9 | 9 | 9 | 13 | 12 | 14 | 13 | 13 | +4 |
| | Gan Osaca | 41 | | | | | 46 | 45 | 45 | +4 |
| | Gan Sylvan | 39 | | | | | 39 | 39 | 39 | 0 |
| | Highland Down | 5 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | -1 |

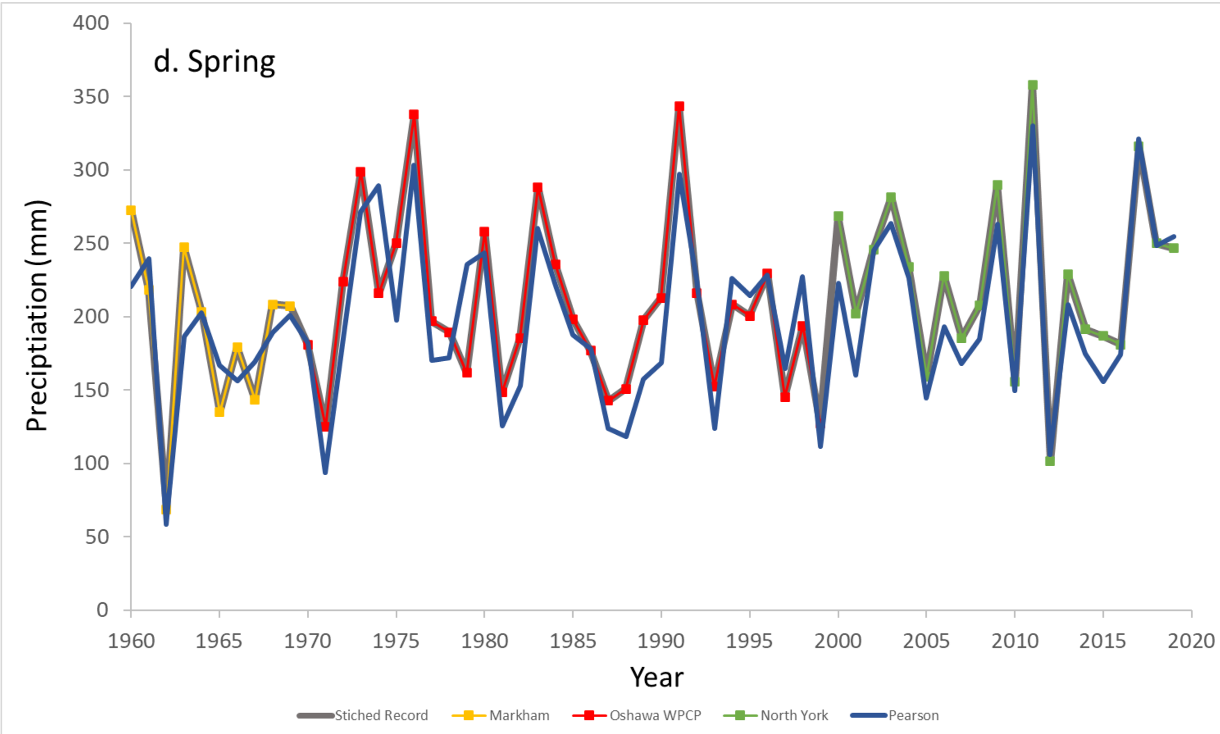
*Precipitation*

Total annual precipitation increased significantly between 1960 and 2019 in the combined record ($p$ = 0.03) whereas no trend was detected at Pearson airport ($p$ = 0.33; Figure 3.2 a), suggesting the blending of three climate station records may have influenced the result. The fraction of snowfall at Pearson airport ranged from 4 - 24% across all years and declined significantly over the period of record ($p < 0.05$) such that 19% fell as snow in the 1960s, compared with only 12% in the 2010s. The seasonal distribution of precipitation changed slightly in the combined record, with summer being the only season to increase significantly ($p < 0.05$) according to the Mann-Kendall trend test. Fall precipitation increased by 24% between the 1960s and 2010s, although the trend was not significant, whereas winter precipitation was relatively stable over the period of study (Figure 3.2 b, c). Spring was the only season when precipitation was lower in the 2010's compared with the 1960s, although differences were not significant. Overall, these results suggest relatively modest directional changes in precipitation, but large inter-annual variability.




b. Fall
Precipitation (mm)
Year
Stiched Record
Markham
Oshawa WPCP
North York
Pearson


c. Winter
Precipitation (mm)
Year
Stitched Record
Markham
Oshawa WPCP
North York
Pearson



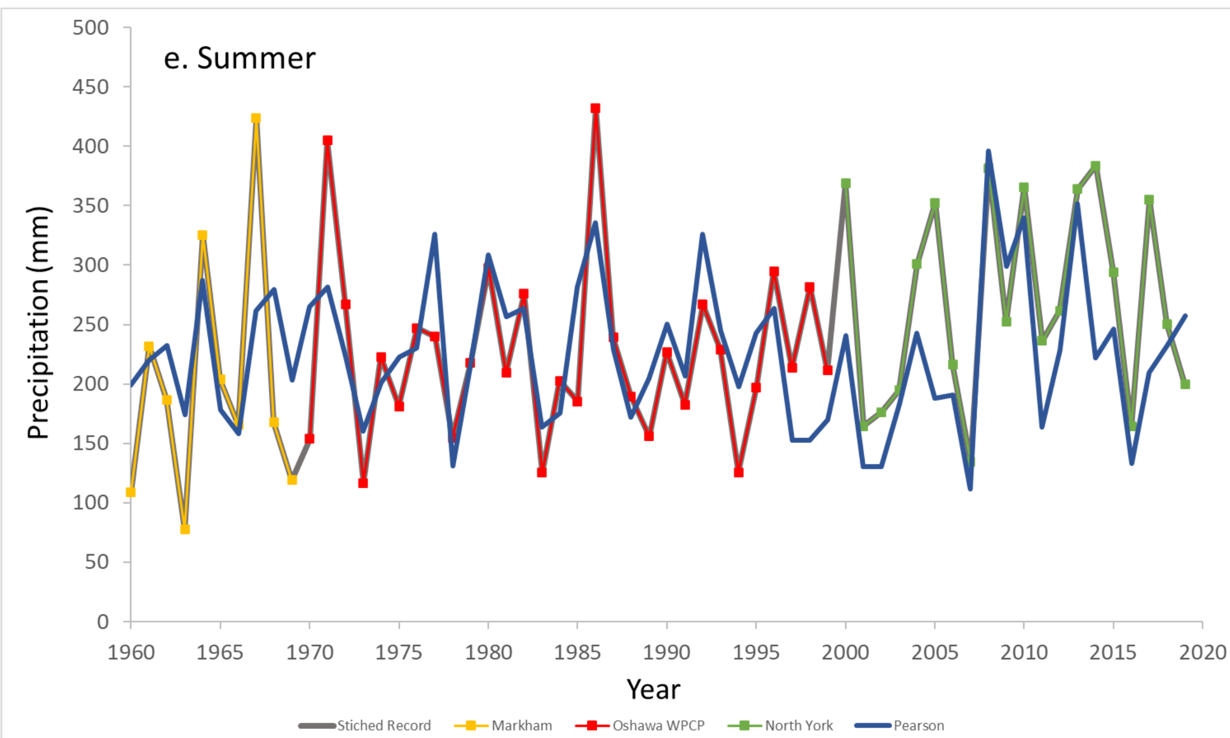
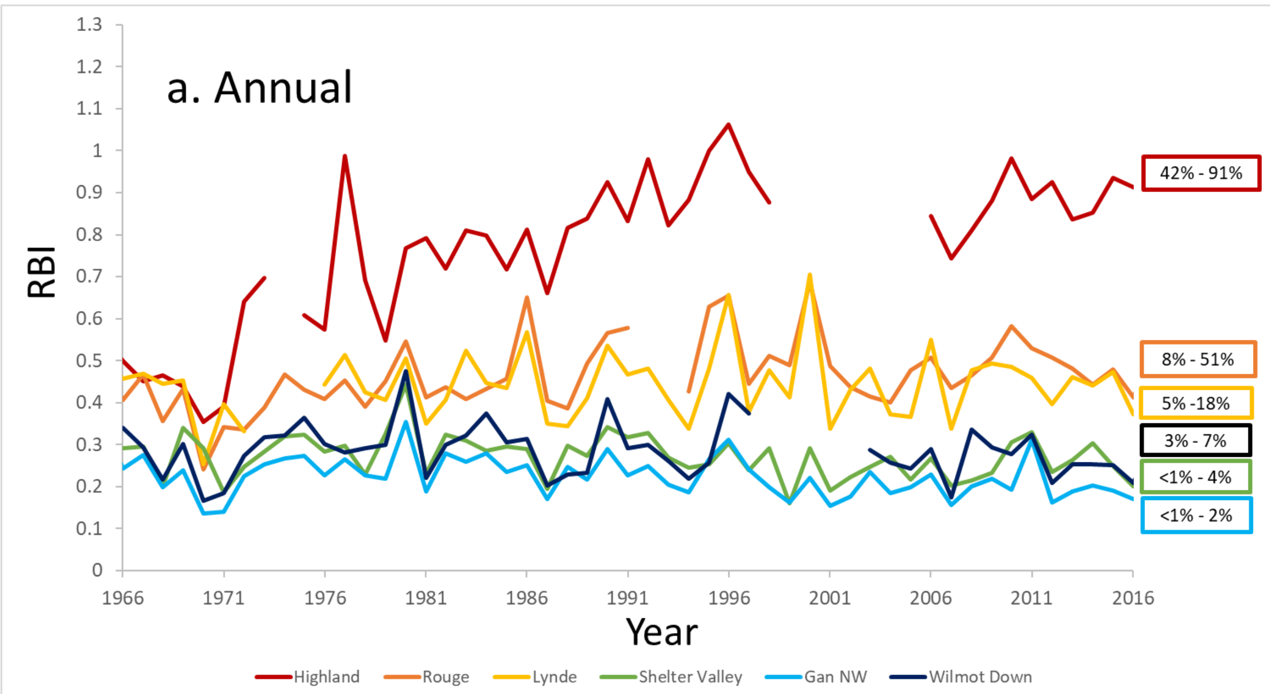



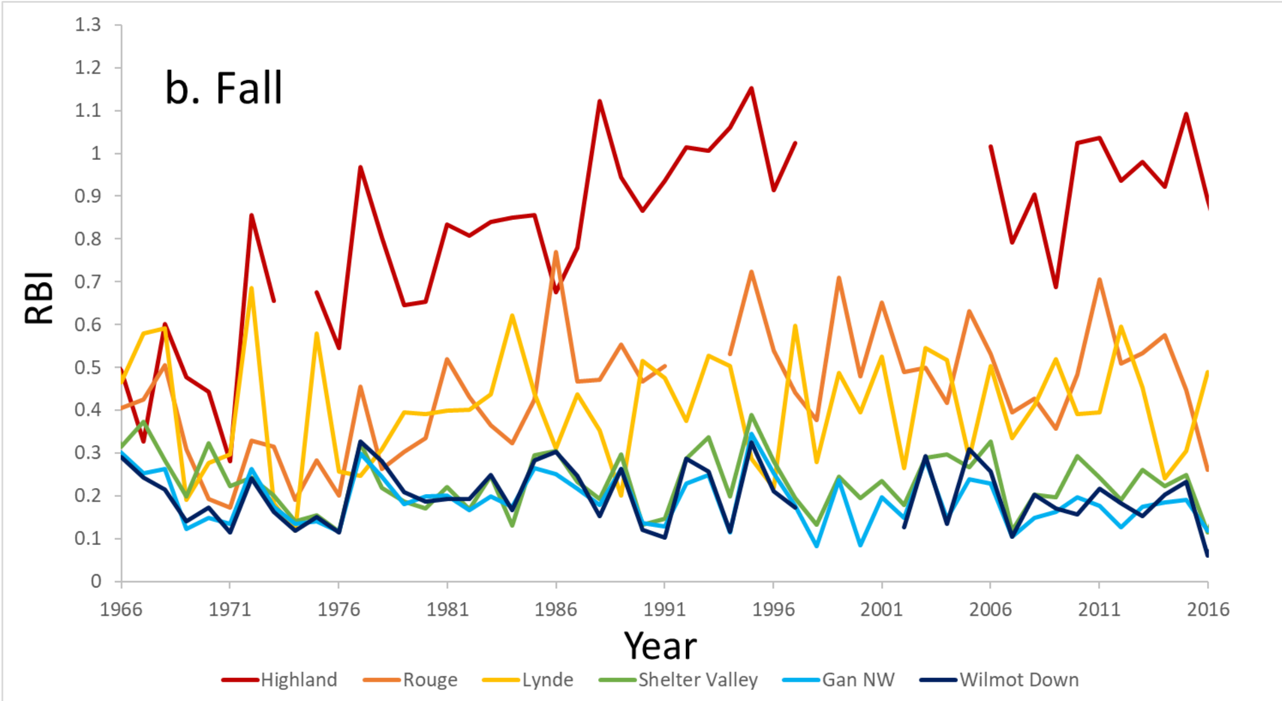

Figure 3.2 a, b, c, d, e. Total annual and seasonal precipitation between 1960 and 2019. Coloured lines indicate different climate stations.

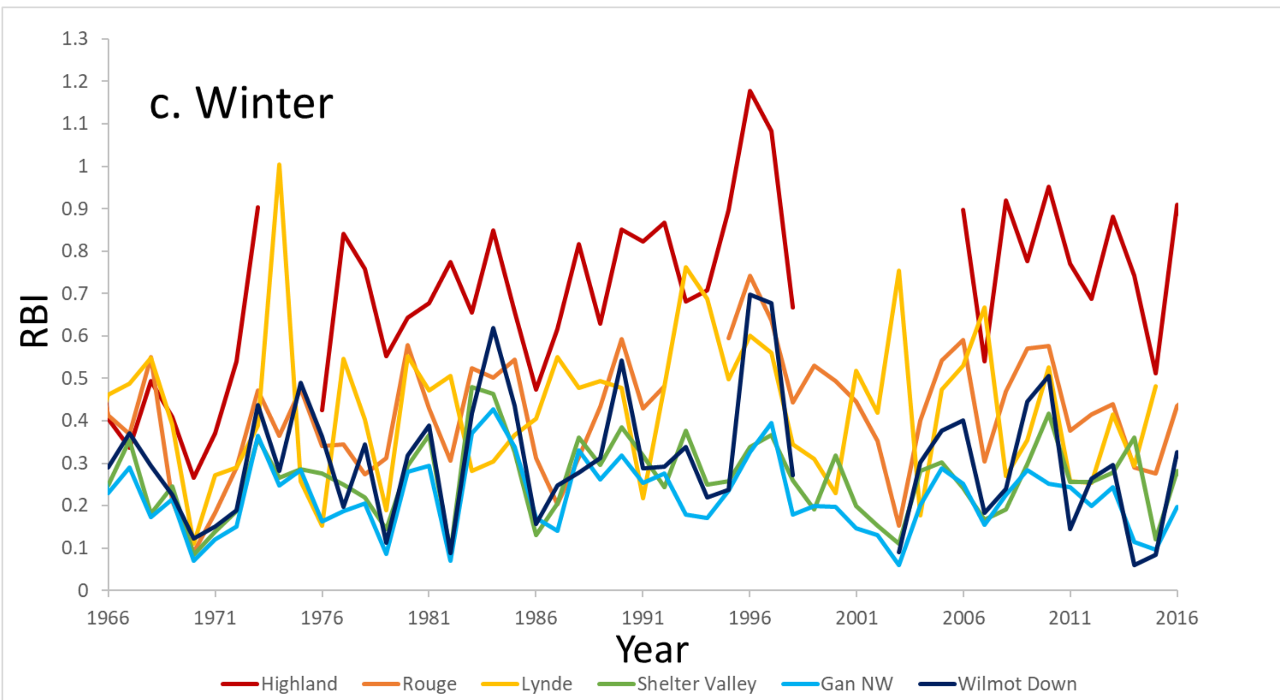
*Land cover-Flow Relationships*

While there was substantial inter-annual variability, significant increases in flashiness were identified at the three watersheds that urbanized the most between 1966 and 2016, including Highland Creek, Rouge River and Lynde Creek. Over the period of record, average RBI doubled from 0.45 to 0.90 over 50 years at Highland and increased from 0.37 to 0.49 at Rouge River. In contrast, annual RBI values were generally more stable at Gan NW, Shelter Valley, and Wilmot Down (~0.25 to 0.27), where urban increases were only 1% to 4% of watershed area since 1966. It should be noted that only these six watersheds are plotted in Figure 3.3 because the other four watersheds had either gaps in flow data or similar RBI values and because these six encompass the end members of land use change (urbanizing vs. rural). Interestingly, flashiness at the Rouge River did not increase as much as at Highland Creek, despite their similar rates of urbanization and presumably similar precipitation inputs. Instead, the Rouge River had a similar RBI value (0.49) in the 2010s as Lynde Creek (0.44), a much less urbanized watershed (Figure 3.3 a). RBI values were fairly consistent across the more rural watersheds over the 50 years of record, although there was substantial inter-annual variability (e.g., range 0.14-0.47 at Wilmot Down; Figure 3.3 a).

Seasonal RBI patterns were also evaluated. Like the annual scale, significant increases in RBI occurred in the fall, spring, and summer seasons at the three most urbanized watersheds. These increases were greatest during the 1970s and 1980s and patterns became distinct from the more rural watersheds during these decades (Figure 3.3). Notably, RBI values in the 1960s 'pre-urbanization' period were more similar in 1966 (0.24 to 0.50) across most watersheds, at both the annual and seasonal scales compared with 2018 (0.25 to 0.88; Figure 2.5). There was no clear distinction between the urbanizing and stable watersheds during the winter season (apart from Highland) over the period of record.




b. Fall
RBI
Year
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011
2016
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Highland
Rouge
Lynde
Shelter Valley
Gan NW
Wilmot Down


c. Winter
RBI
Year
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011
2016
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
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1
1.1
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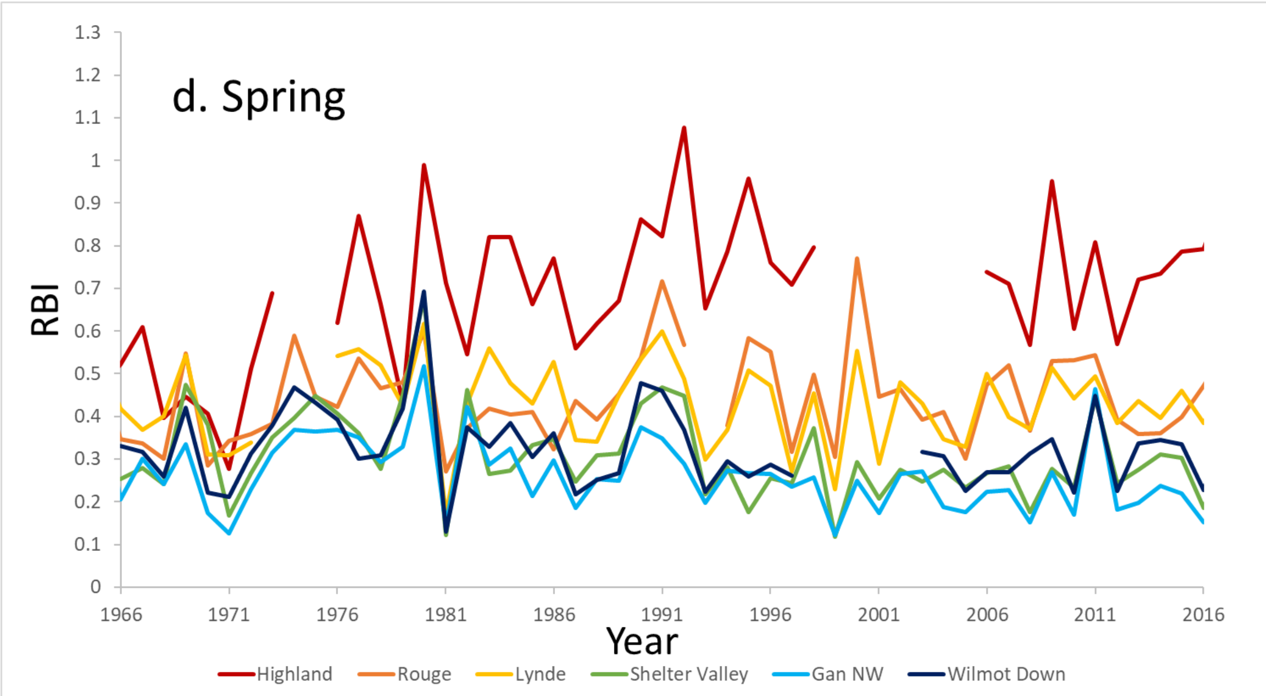
1.3
Highland
Rouge
Lynde
Shelter Valley
Gan NW
Wilmot Down



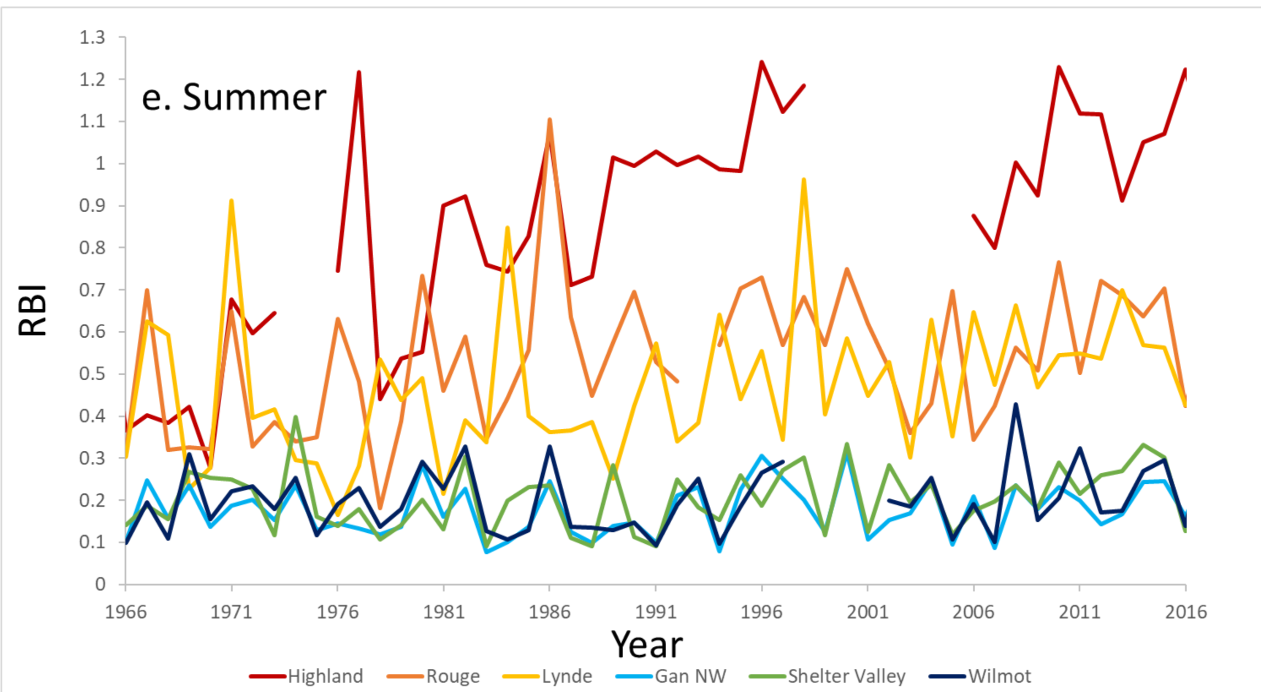




Figure 3.3 a, b, c, d, e. Annual and seasonal RBI values at urbanized and rural watersheds between 1966 and 2018. Highland, Rouge and Lynde are considered urbanized, and Shelter Valley, Gan NW and Wilmot Down are considered rural. Values to right of graph in panel ‘a’ are percentages of urban cover relative to watershed area beginning in 1966 until 2016.

Changes in RBI over time were evaluated using the Mann-Kendall trend test (Table 2.6). The two most urbanized watersheds (Highland Creek and Rouge River) showed significant increases in flashiness (*p* values usually < 0.001) at the annual scale and across all seasons. Lynde Creek, where urban cover increased by 13% over the period of record, had statistically significant increases in flashiness at the annual scale and during the winter and summer seasons, but not in the fall or spring. RBI values at the other mostly rural watersheds were largely stable. In fact, Gan NW had statistically significant decreasing flashiness values in the annual, fall and spring periods. Interestingly, flashiness at Gan Sylvan increased in the summer months despite relatively stable land cover, although its shorter flow record (starting in 1977) may influence this result. A closer look at the summer RBI values at four of the stable watersheds (Gan Osaca, Wilmot Creek, Bowmanville Creek, and Shelter Valley) during the most recent 10 years indicates slight increases in flashiness in the summer months which may be caused by increases in precipitation (Figure 3.3 a, e).

Table 3.5. Statistical increases or decreases of the RBI according to the Mann Kendall Test. Percentage of urban increase is between 1966 and 2016.

| **Watersheds** | # of Complete Yearly Flow Records | % Increase of Urban Cover | Annual | Fall | Winter | Spring | Summer |
|---|---|---|---|---|---|---|---|
| Highland Down | **54** (1957 - 2018) | 49 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Rouge | **56** (1960 - 2018) | 43 | <0.001 | <0.001 | 0.038 | 0.035 | <0.001 |
| Lynde Down | **55** (1962 - 2018) | 13 | 0.048 | 0.109 | 0.032 | 0.385 | <0.001 |
| Duffins | **49** (1964 - 2018) | 6 | 0.314 | 0.078 | 0.105 | 0.831 | 0.040 |
| Bowmanville | **38** (1967 - 2018) | 5 | 0.152 | 0.451 | 0.814 | 0.052 | 0.702 |
| Wilmot Down | **48** (1966 - 2018) | 4 | 0.360 | 0.587 | 1.000 | 0.333 | 0.384 |
| Shelter Valley | **53** (1966 - 2018) | 4 | 0.076 | 0.738 | 0.521 | 0.078 | 0.194 |
| Gan Osaca | **48** (1959 - 2016) | 3 | 0.124 | 0.369 | 0.511 | 0.450 | 0.843 |
| Gan NW | **55** (1962 - 2016) | 3 | 0.013 | 0.044 | 0.931 | 0.009 | 0.496 |
| Gan Sylvan | **42** (1977 - 2018) | 2 | 0.558 | 0.762 | 0.897 | 0.095 | 0.006 |

*Correlations between Annual Precipitation Metrics and RBI Values*

Correlation analysis was used to evaluate associations between flashiness and precipitation vs. land cover change (Figure 3.4). There was evidence from the first research chapter that years with higher total or seasonal precipitation were flashier (Figure 2.5) and so increases in precipitation over time might be expected to likewise increase RBI values. Between 1970 and 1998, there was no statistically significant trend of increasing or decreasing total annual precipitation according to the Oshawa climate record (p value = 0.41 using Mann-Kendall test; Figure 3.4). Evaluating changes in flashiness over this period of stable precipitation can be used to isolate the effects of land cover on flashiness. To that end, Shelter Valley, one of the most rural watersheds, and Highland Creek, the most urbanized watershed, were compared (Figure 3.4, Table 3.7). Shelter Valley had consistent RBI values and had no increasing or decreasing trend using the Mann-Kendall test, usually ranging from 0.19 to 0.44 between 1970 and 1998 (Figure 3.4). In contrast, Highland Creek had an average RBI of 0.61 between 1970 – 1979 which increased significantly to an average of 0.93 between 1990 – 1998 using the Mann-Kendall test (p value < 0.001).

Correlations were further used to identify if extremes in precipitation (using the precipitation metrics from Table 3.5) affected interannual variability in the RBI values at Shelter Valley and Highland Creek (Table 3.7). It was expected there would be fewer or weaker correlations between Highland Creek flow and precipitation because urbanization has a stronger influence on flow, whereas Shelter Valley's flow patterns were expected to be more correlated with precipitation due to its relatively stable land cover.

As predicted, RBI values at Shelter Valley had overall more seasonal correlations with precipitation metrics compared with Highland Creek, signaling that land cover was the primary driver of increased stream flashiness at the latter (Table 3.6). The total amount of rainfall was especially important for explaining interannual variations in flashiness at Shelter Valley, and correlations were especially strong in the fall (r = 0.63; Table 3.6). Conversely, the number of days when daily precipitation was less than 2mm was negatively correlated with flashiness in spring at Shelter Valley. Similar correlations were not observed at Highland Creek despite presumably similar precipitation patterns between the two watersheds.

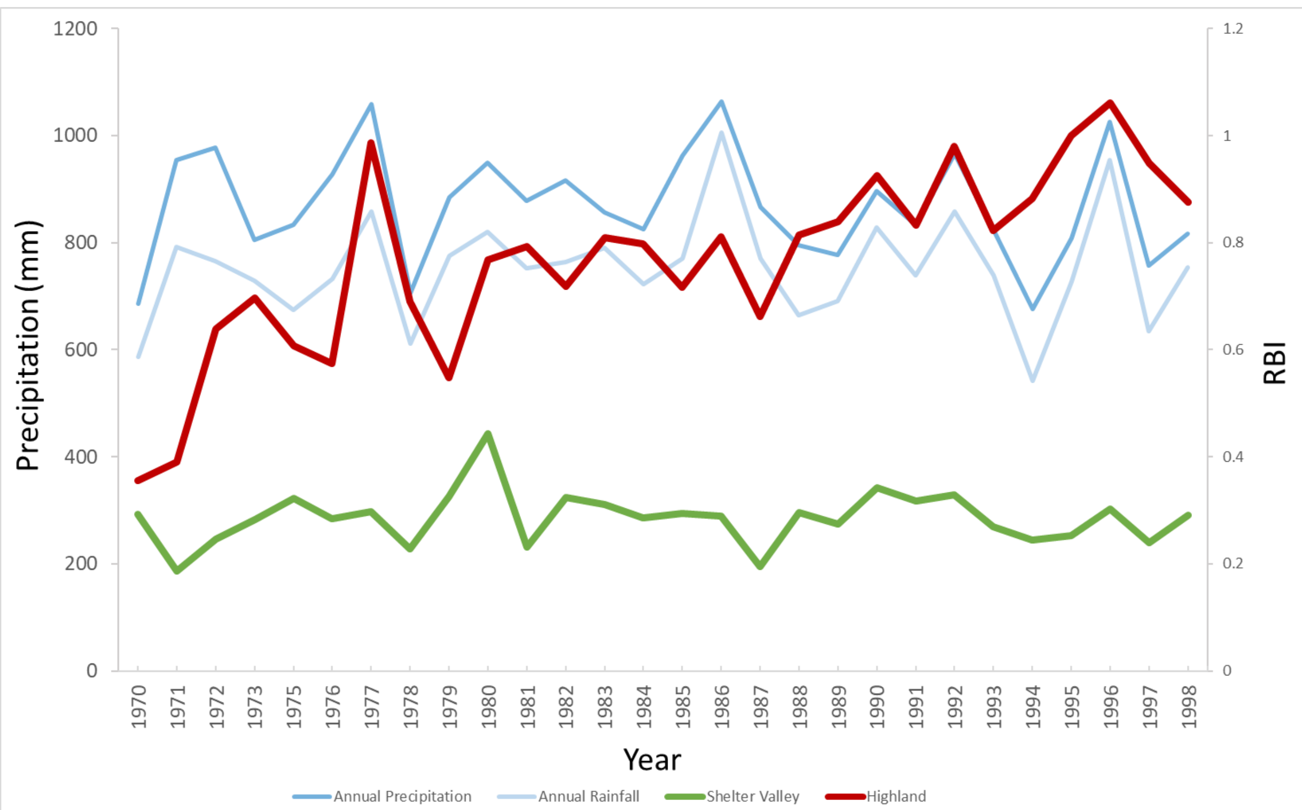



Figure 3.4. Annual RBI values at Highland Creek and Shelter Valley Creek plotted with total annual precipitation and rain.

Table 3.6. Spearman correlation coefficients between RBI and seasonal and annual precipitation at Highland Creek (top) and Shelter Valley (bottom). Statistically significant correlations ($p < 0.05$) are bolded. The 'Dry' metric is the count of days when there was less than 1mm of precipitation for seven days in a row, and 'wet' metric is the count of days when precipitation exceeded 1mm of rain for three days in a row.

| | | | | | Highland | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Precipitation** | *Count <2mm* | *Count >10mm* | *Count >20mm* | *Count >30mm* | *Sum Rain* | *Sum <2mm* | *Sum >10mm* | *Sum >20mm* | *Sum >30mm* | *Dry* | *Wet* |
| Annual | -0.087 | 0.346 | 0.215 | 0.072 | 0.253 | 0.175 | 0.321 | 0.182 | 0.081 | 0.155 | 0.093 |
| Fall | -0.114 | 0.106 | **0.384** | **0.528** | 0.314 | 0.311 | 0.319 | 0.362 | **0.495** | 0.097 | 0.344 |
| Winter | -0.041 | 0.023 | -0.089 | -0.128 | 0.129 | 0.292 | -0.016 | -0.067 | -0.159 | 0.098 | **0.397** |
| Spring | 0.054 | **0.418** | **0.535** | **0.440** | **0.512** | 0.104 | **0.536** | **0.583** | **0.427** | -0.058 | 0.102 |
| Summer | -0.087 | 0.346 | 0.215 | 0.072 | 0.253 | 0.175 | 0.321 | 0.182 | 0.081 | 0.155 | 0.093 |
| **Rainfall** | | | | | | | | | | | |
| Annual | 0.099 | 0.221 | 0.302 | 0.133 | 0.167 | 0.316 | 0.210 | 0.237 | 0.116 | -0.013 | 0.264 |
| Fall | -0.049 | 0.095 | **0.389** | **0.528** | 0.280 | 0.276 | 0.284 | 0.367 | **0.495** | 0.097 | 0.217 |
| Winter | -0.041 | 0.183 | -0.075 | -0.171 | 0.308 | 0.236 | 0.115 | -0.077 | -0.221 | -0.245 | 0.174 |
| Spring | 0.004 | **0.571** | **0.538** | **0.440** | **0.628** | 0.068 | **0.628** | **0.591** | **0.427** | -0.086 | 0.211 |

| | | | | | Shelter Valley | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Precipitation** | *Count <2mm* | *Count >10mm* | *Count >20mm* | *Count >30mm* | *Sum Precip* | *Sum <2mm* | *Sum >10mm* | *Sum >20mm* | *Sum >30mm* | *Dry* | *Wet* |
| Annual | -0.259 | **0.378** | 0.012 | 0.101 | 0.344 | 0.082 | 0.267 | 0.005 | 0.035 | -0.098 | **0.378** |
| Fall | -0.304 | **0.478** | **0.516** | **0.670** | **0.669** | **0.410** | **0.689** | **0.673** | **0.694** | -0.296 | 0.252 |
| Winter | -0.034 | 0.001 | 0.207 | 0.108 | 0.257 | 0.038 | 0.104 | 0.195 | 0.055 | -0.131 | 0.018 |
| Spring | **-0.455** | 0.372 | 0.294 | 0.318 | **0.414** | 0.192 | **0.398** | 0.279 | 0.321 | -0.207 | **0.472** |
| Summer | 0.033 | 0.243 | **0.482** | **0.633** | **0.386** | -0.064 | **0.460** | **0.494** | **0.606** | 0.014 | -0.341 |
| **Rainfall** | *Count <2mm* | *Count >10mm* | *Count >20mm* | *Count >30mm* | *Sum Rain* | *Sum <2mm* | *Sum >10mm* | *Sum >20mm* | *Sum >30mm* | *Dry* | *Wet* |
| Annual | -0.335 | **0.416** | -0.056 | 0.148 | **0.422** | 0.048 | **0.379** | 0.003 | 0.087 | -0.092 | 0.362 |
| Fall | -0.252 | **0.476** | **0.516** | **0.670** | **0.630** | **0.387** | **0.681** | **0.670** | **0.694** | -0.296 | 0.069 |
| Winter | -0.261 | 0.323 | 0.194 | 0.040 | 0.512 | 0.209 | 0.332 | 0.139 | -0.002 | **-0.427** | 0.254 |
| Spring | **-0.431** | **0.399** | 0.269 | 0.318 | **0.480** | 0.145 | **0.469** | 0.247 | 0.321 | -0.208 | 0.258 |

*Decadal Shifts in Precipitation and Flow*

Over the past 60 years, total annual precipitation appeared to increase slightly, but differences between decades were usually not statistically significant. The exception was fall precipitation, which was significantly higher in the 1980s compared with the 1960s ($p < 0.05$). In contrast, there were significant increases in the frequency of extreme precipitation events over the period of record. Specifically, there were significant increases in the number of events > 30 mm between the 1970s and 2010s, which occurred on average 1.7 times per year in the 1970s, compared with an average of 4.6 times per year in the 2010s (Table 3.7). The total sum of precipitation ≥30mm also increased significantly ($p < 0.05$) between the 1970s and 2010s. Increases in extreme events occurred primarily in the summer months, which drove increases in extremes at the annual scale. The only season with significant declines in extreme precipitation was the winter, which had significantly less total precipitation ≥30mm in the 1990s and 2000s than the 1960s (Table 3.7).

Table 3.7. Precipitation metrics by decade. Tukey Post Hoc tests were used to determine significant differences. Bolded values represent differences between decades that are significant at $p < 0.05$ and underlined values represent $p < 0.10$.

| Decade (Annual) | Counts of Days | | | | Sum of Daily Precipitation | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | <2mm | ≥10mm | ≥20mm | ≥30mm | Annual Avg | <2mm | ≥10mm | ≥20mm | ≥30mm |
| 1960s | 285 | 23.9 | 8.2 | 2.7 | 766 | 45.4 | 451 | 234 | 104 |
| 1970s | 272 | 29.6 | 7.5 | **1.7** | 864 | 47.9 | 521 | 214 | **75.9** |
| 1980s | 279 | 29.1 | 7.4 | 3.2 | 889 | 55.5 | 534 | 236 | 133 |
| 1990s | 283 | 27.6 | 8.3 | 2.6 | 843 | 56.0 | 510 | 238 | 101 |
| 2000s | 279 | 28.7 | 10.0 | 3.2 | 901 | 56.9 | 552 | 292 | 128 |
| 2010s | 281 | 29.5 | 9.5 | **4.6** | 908 | 55.1 | 588 | 307 | **190** |
| Decade (Fall) | <2mm | ≥10mm | ≥20mm | ≥30mm | Annual Avg | <2mm | ≥10mm | ≥20mm | ≥30mm |
| 1960s | 73.3 | 5.5 | 2.3 | 0.6 | **184** | 11.7 | 106 | 59.6 | 20.0 |
| 1970s | 70.5 | 7.1 | 2.2 | 0.5 | 210 | 13.4 | 125 | 58.6 | 17.8 |
| 1980s | 66.5 | 9.6 | 2.3 | 1.1 | **271** | 13.6 | 180 | 80.7 | 51.5 |
| 1990s | 70.3 | 7.1 | 2.3 | 1.1 | 225 | 15.9 | 140 | 73.0 | 45.7 |
| 2000s | 69.7 | 7.2 | 2.6 | 0.7 | 221 | 13.4 | 134 | 69.8 | 23.5 |
| 2010s | 69.8 | 7.7 | 2.4 | 0.9 | 226 | 13.4 | 144 | 69.9 | 33.2 |
| Decade (winter) | <2mm | ≥10mm | ≥20mm | ≥30mm | Annual Avg | <2mm | ≥10mm | ≥20mm | ≥30mm |
| 1960s | 69.6 | 5.9 | 2.0 | 0.9 | 197 | 14.5 | 108 | 56.7 | <u>29.1</u> |
| 1970s | 62.7 | 6.3 | 1.3 | 0.3 | 211 | 12.6 | 104 | 35.5 | 11.4 |
| 1980s | 69.8 | 6.0 | 1.5 | 0.4 | 192 | 15.3 | 101 | 41.1 | 14.0 |
| 1990s | 69.0 | 6.0 | 1.3 | 0.2 | 194 | 16.0 | 101 | 34.9 | <u>6.9</u> |
| 2000s | 68.9 | 5.8 | 1.3 | 0.2 | 193 | 19.5 | 96 | 35.1 | <u>6.7</u> |
| 2010s | 70.3 | 5.1 | 1.1 | 0.2 | 173 | 16.8 | 85 | 28.3 | 7.4 |
| Decade (spring) | <2mm | ≥10mm | ≥20mm | ≥30mm | Annual Avg | <2mm | ≥10mm | ≥20mm | ≥30mm |
| 1960s | 72.2 | 6.0 | 1.6 | 0.4 | 188 | 11.2 | 103 | 44.8 | 16.0 |
| 1970s | 67.2 | 8.1 | 1.8 | 0.3 | 218 | 10.6 | 137 | 46.2 | 11.1 |
| 1980s | 71.1 | 6.7 | 1.0 | 0.4 | 198 | 15.5 | 108 | 28.6 | 14.2 |
| 1990s | 71.5 | 7.2 | 1.5 | 0.4 | 203 | 12.8 | 120 | 40.3 | 14.2 |
| 2000s | 68.9 | 7.1 | 2.3 | 0.8 | 230 | 12.7 | 137 | 70.1 | 33.3 |
| 2010s | 70.9 | 7.6 | 1.9 | 0.9 | 222 | 12.5 | 141 | 61.1 | 35.5 |
| Decade (summer) | <2mm | ≥10mm | ≥20mm | ≥30mm | Annual Avg | <2mm | ≥10mm | ≥20mm | ≥30mm |
| 1960s | 69.1 | 7.0 | 2.6 | 0.9 | 201 | 8.0 | 141 | 80.1 | 38.6 |
| 1970s | 71.8 | 7.8 | 2.1 | **0.6** | 221 | 10.5 | 149 | 70.6 | 35.7 |
| 1980s | 71.6 | 6.9 | 2.7 | 1.3 | 231 | 11.4 | 149 | 88.3 | 53.6 |
| 1990s | 72.1 | 7.4 | 3.2 | <u>0.9</u> | 223 | 11.1 | 151 | 89.5 | **34.0** |
| 2000s | 71.5 | 8.4 | 3.6 | 1.5 | 254 | 11.7 | 181 | 113 | 64.9 |
| 2010s | 71.2 | 9.1 | 4.0 | <u>**2.6**</u> | 287 | 11.3 | 219 | 148 | **116** |

Flow duration curves were constructed to evaluate shifts in other aspects of the hydrologic regime including baseflow and high flows. All watersheds showed increases in flow across nearly all flow percentiles since the 1960s, apart from some extreme flows in the 95-99$^{th}$ percentiles. These increases of flow must be explained by precipitation, since landcover changes were variable over time. More specifically, the 1960s had the lowest average precipitation (average of 766 mm/year) and the lowest overall magnitude of flow in the FDCs, whereas the 2010s had the greatest precipitation (average of 908 mm/year) and some of the highest flows (Figure 3.5). Nevertheless, the magnitude of increase differed between the urbanizing and rural watersheds. Figure 3.6 shows how the magnitudes of flow have changed for each percentile between the 1960s and the 2010s for the previously mentioned rural vs. urbanizing watersheds. These two decades show the largest differences in average annual precipitation amongst the decades studied. Highland Creek was the only watershed where the 80$^{th}$ flow percentiles (i.e., highest flows) increased more than the lower flow percentiles. These high flow percentiles doubled since the 1960s. The other urbanizing watersheds (Rouge and Lynde) exhibited larger increases in low flow compared with higher flow percentiles, although percentiles greater than the 80th also increased by 20% to 100% (Figure 3.6). The more rural watersheds (Gan NW, Shelter Valley, Wilmot Creek) underwent very modest increases across all flow percentiles between the 1960s and 2010s which are most likely associated with changes in precipitation, although agricultural change cannot be strictly ruled out. The higher flow percentiles either increased slightly (maximum of 22% at Wilmot Creek) or even declined (ranging from -3% to -29% at Gan NW). Furthermore, the average flow at Shelter Valley increased by 20% between the 1960s and 2010s, which coincides with a

19% increase in precipitation over the same time period. Increases in the frequency and sum of intense daily precipitation (e.g., ≥20mm; see Table 3.7) did not appear to increase the higher flow percentiles as much as expected.

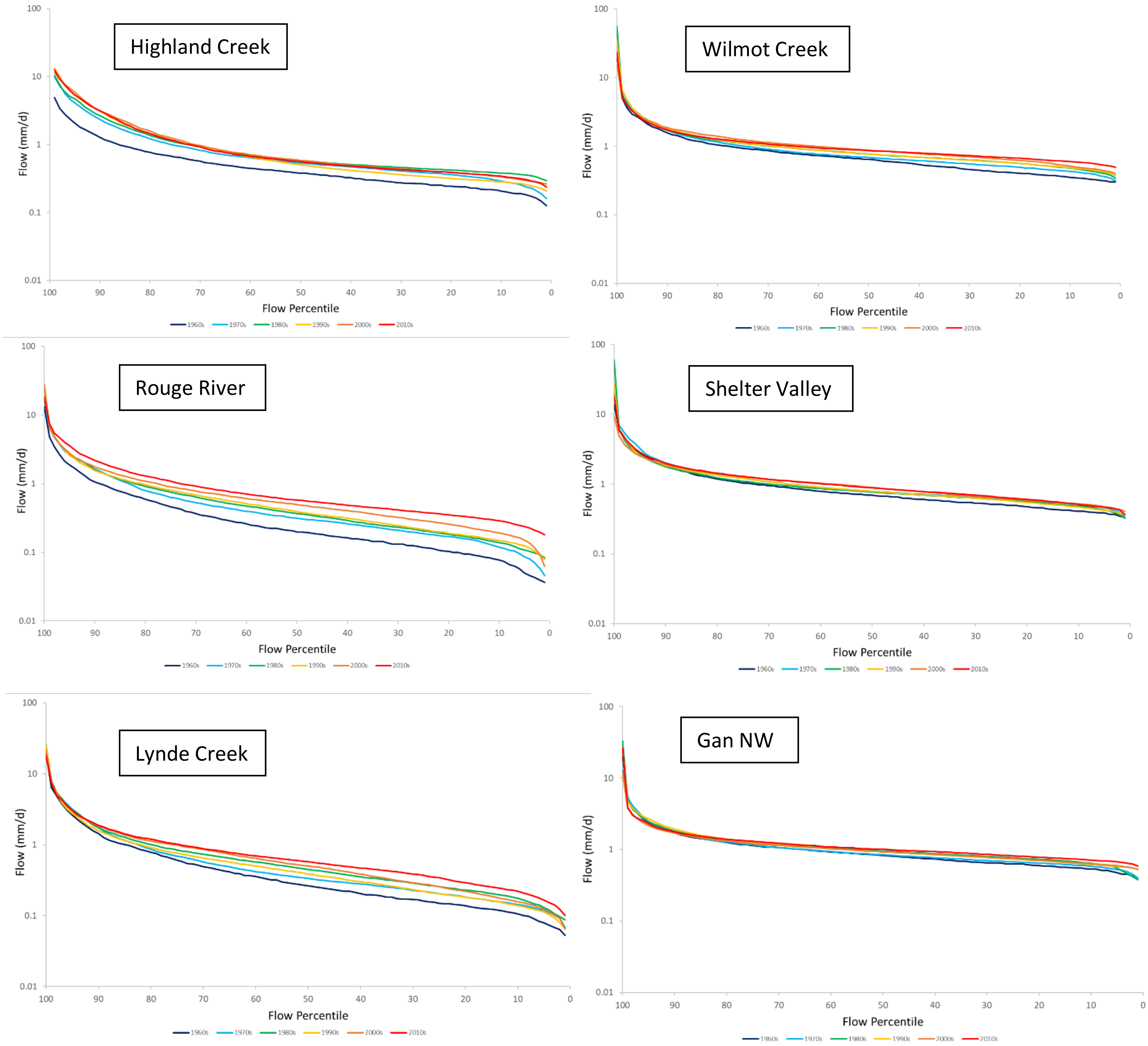



Figure 3.5. Flow-duration curves for rural and urbanizing watersheds. Flow is area-normalized, converted from daily average $m^3/s$ to daily runoff as mm/d. Urbanizing watersheds are on left side, rural on the right.

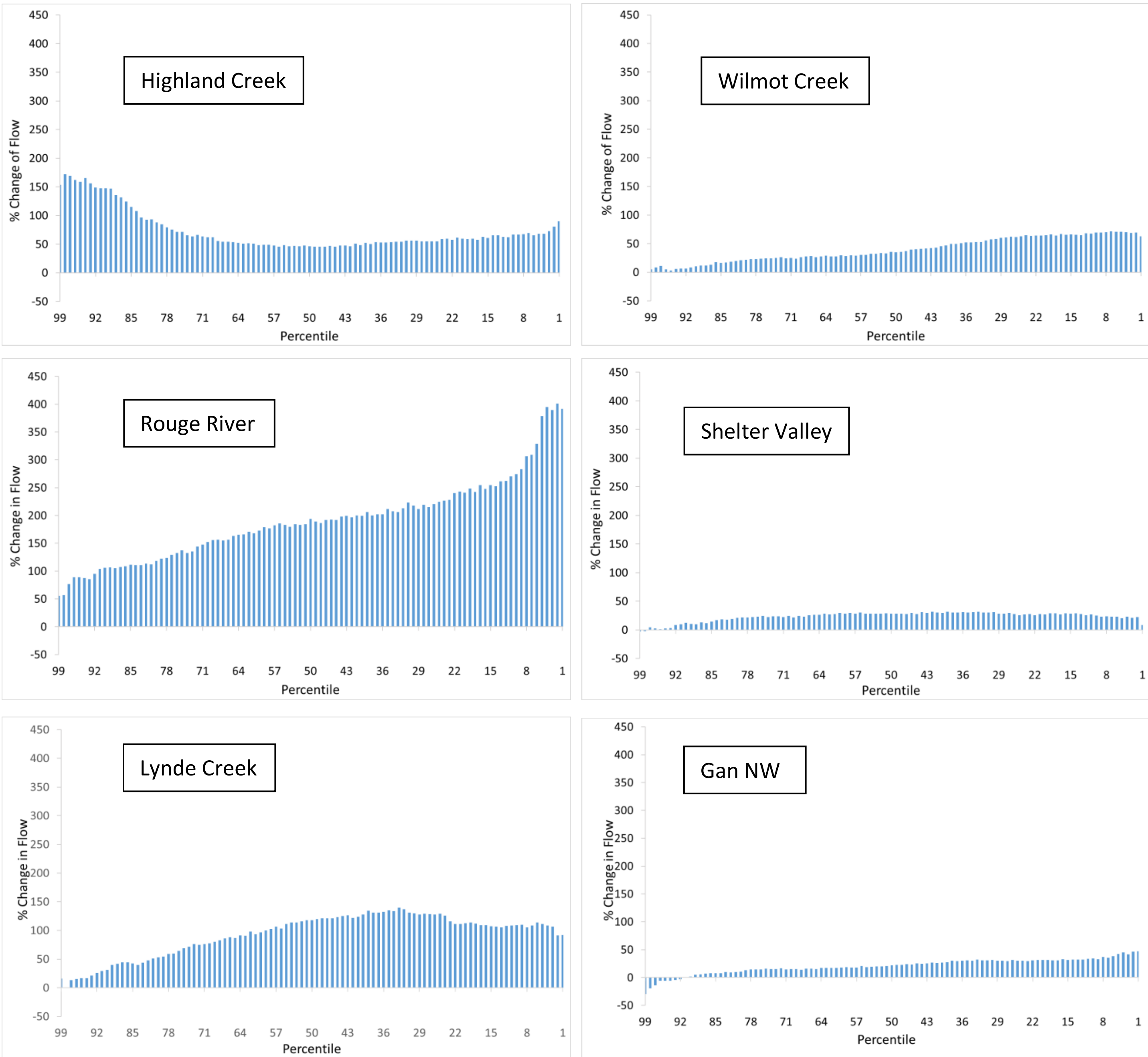



Figure 3.6. Percentage changes of flow percentiles between 1960s and 2010s.

## 3.4 Discussion

Urbanization and expansion of impervious cover within watersheds impact the hydrologic regime by increasing the amount and velocity of runoff resulting in higher peak flows and increased flashiness (Rosburg et al., 2017; Usinowicz et al., 2017). The ten study watersheds were selected to encompass a broad range in urban cover (2 to 91% in 2010) as well as urban growth over time (2 to 49% change between 1960 and 2010) and increases in urban cover were especially large at Highland Creek (49%) and the Rouge River (43%). Precipitation also changed over the period of record, with higher total annual and fall precipitation and increases in extreme precipitation during the summer months, especially during the latter two decades. Urban cover expansion appeared to be primarily responsible for increasing RBI over time at Highland, Rouge and Lynde, although increases in summer extreme precipitation during the most recent two decades may have contributed as well (Table 3.7). The effect of precipitation was more apparent when comparing the FDCs between the urbanizing watersheds and more rural watersheds. Precipitation was significantly lower in the 1960s whereas the 2010s had the highest average precipitation and usually the highest flows. All the study watersheds received similar precipitation, which suggests that land cover was the primary driver of changes in RBI and FDC over time.

*Annual Changes of RBI*

Flashiness at the study watersheds was affected by two main factors: land cover and precipitation changes over time. Other factors that can affect the hydrologic regime such as water extraction for drinking water, dams (Baker et al., 2004) and treated wastewater inputs were considered during site selection and were mostly avoided across the study streams. Total precipitation and rainfall were important factors for determining stream flashiness within a given year or season, but increases in RBI over time could not be explained by precipitation alone. This agrees with Saharia et al. (2017), who reported only slight increases in flashiness with more annual precipitation across a few hundred watersheds in the United States ranging in size between ~8 $km^2$ and 10 000 $km^2$. Total annual precipitation and RBI were significantly correlated between 1970 and 1998 at Shelter Valley in the fall, spring, and summer, while total rainfall was significantly correlated with RBI in all seasons (Table 3.7). This indicates that rainfall may be more important for explaining interannual variation in seasonal RBI values than total precipitation. However, despite significant increases in summer rainfall ($p < 0.05$) and annual precipitation over 60 years in the combined precipitation record, there was no trend in RBI at Shelter Valley. To contrast, the gap-free record at Pearson airport showed no increases of precipitation at either the annual or summer time scales ($p > 0.05$) which further indicates that precipitation is likely not drastically affecting RBI patterns. Since precipitation did not significantly affect flashiness at the rural watersheds, land cover must be more influential for changing RBI trends. This result agrees with Rosburg et al. (2017) who found that precipitation-normalized RBI values increased at four urbanizing watersheds in Seattle, Washington (ranging between 12 – 31 $km^2$), while three of four rural watersheds showed no change in RBI values.

Much of the expansion of urban area in southern Ontario has been at the expense of surrounding agricultural land (Hoffman, 2001), and as a result, the area of agriculture decreased at Highland, Rouge and Lynde Creek while total agricultural area at the other watersheds remained relatively stable (Table 3.4). During and after the 1960s, RBI values increased at Highland Creek, Rouge River, and Lynde, but the amount of increase varied by watershed (Figure 3.3, Table 3.6). The hydrologic regime at Highland Creek appeared to be the most severely impacted, while Lynde Creek and Rouge River showed more modest effects of urbanization (see Figures 3.3 and 3.6). Diem et al. (2018) reported that RBI values increased by ~0.25 after ~1/3 of watershed area was developed at urbanizing watersheds in Atlanta, Georgia. Similarly, the RBI at Highland Creek increased by 0.21 after ~30% of watershed area was developed between 1966 and 1976. In contrast, RBI values at the Rouge River did not change as drastically, despite an approximate 40% increase in urban cover, perhaps due to better runoff management practices implemented beginning in the early 1990s (Toronto Region Conservation Authority, 2007). Likewise, stormwater ponds and more distributed runoff controls in urban developments post 1990 (Bradford & Gharabaghi, 2004) may have mitigated the hydrologic response of Lynde Creek to more recent urban development.

While storm water management may have helped avoid increases in stream flashiness at the more recently urbanized Rouge River and Lynde Creek, both watersheds still showed statistically significant increases in RBI over time. In this study, RBI values increased significantly at both the annual and seasonal scales above a threshold of total urban cover of ~ 13% (Table 3.6). This threshold agrees with Booth and Jackson (1997), who found that the hydrologic regime was altered above an impervious surface threshold of ~10%. While urban cover in this study was calculated as the sum of impervious plus pervious cover due to limitations of older map layers, more recent estimates using new land cover layers (i.e., SOLRIS 1.0, 2.0 and 3.0; Table 3.4) suggest that impervious cover represents approximately 2/3 of total urban cover. This suggests that a threshold of impervious surface cover of ~10% is associated with increased flashiness, which agrees with Booth & Jackson's (1997) threshold for hydrologic alteration from land cover.

Statistically significant decreases in stream flashiness over time were only observed at Gan NW (a headwater tributary of the Ganaraska River) at the annual, fall and springtime scales, despite overall increases in flow at this river (see FDC in Figure 3.6). Afforestation initiatives may explain declining RBI at this river as previous studies have reported decreases in peak flows and lower runoff ratios in response to forest cover expansion (Buttle, 1994). Furthermore, slower snow melt in the forested headwaters during spring and increased baseflow contribution (Buttle et al., 2015) likely contributed to decreasing RBI values after forest growth.

*Decadal Changes of FDC*

The effects of land cover change on the watershed hydrologic regime are commonly evaluated using FDCs, as these can be calculated over different time periods to identify before-and-after effects of land development (Rosburg et al., 2017; Lane et al., 2005, Philip et al., 2022). All watersheds exhibited higher flow magnitudes in decades that had more precipitation; however, increases were always greater at the more urban compared with the rural watersheds (Figure 3.6).

Urbanization typically increases the rate of runoff delivery to streams, leading to higher high flows and a lower proportion of baseflow. However, the latter is not always the case, and some studies have reported inconsistent baseflow responses depending on topography, climate, and best management practices (Hopkins et al., 2015; Walsh et al., 2005). In this study, only Highland Creek demonstrated the hypothesized FDC response to urbanization, whereby high flow percentiles increased more than baseflow percentiles between the 1960s and 2010s, although baseflow did not decline (Figure 3.5, 3.6). Interestingly, the other urbanizing watersheds, Rouge and Lynde, had larger increases in baseflow than peak flows. While not typical of urbanizing watersheds, Rosburg et al. (2017) also found large increases in baseflow at an urban watershed where the base flow percentiles (Q10-Q20) increased by an average of ~90% while peak flow percentiles (Q80 – Q100) increased by ~80%. To compare, base flow percentiles at Lynde Creek increased by 110% whereas peak flows only increased by 35% (Figure 3.6). Rosburg et al. (2017) further elaborates that the increase in baseflow was likely from a groundwater well system leaching into the urban stream they studied and other urban streams are subject to leaking storm sewers and water distribution.

The rural watersheds' FDCs showed smaller increases in flow across all percentiles compared with the urbanizing streams between the 1960s and the 2010s. High flow percentiles (Q > 90) increased by a maximum of 11% at Wilmot Creek and decreased at Gan NW by 29% between the 1960s and 2010s (Figure 3.6). Declines in high flow magnitudes at Gan NW are consistent with decreases in RBI, since flashiness is associated with peak flow events (Roodsari & Chandler, 2017; Baker et al., 2004). Similar increases in low flow between the "newer" urbanizing watersheds (Rouge and Lynde) and rural watersheds may indicate that urban water retention practices are effective by catching rapid surface runoff in retention ponds and releasing slowly into streams.

The rural watersheds (e.g., Wilmot, Shelter Valley) examined in this study underwent relatively small changes to their hydrologic regime compared with the urbanizing basins (e.g., Highland Creek and Rouge River), as evidenced by their relatively low and stable RBI values and increases in lower flow percentiles. Despite relatively modest shifts at the rural watersheds, some aspects of their flow regime changed, especially at Wilmot Creek (Figure 3.6) which lost 14% of agricultural land that was mostly replaced by natural cover (Table 3.4). Higher runoff values in Wilmot Creek's FDC may be the result of agricultural intensification that could not be quantified using available spatial data layers (i.e., SOLRIS; CLUMP). Many of the WSC sites were established in the 1960s when there was a rapid increase of corn and soy production that primarily replaced pasturelands in Ontario (Smith, 2015). These shifts could have increased the amount of runoff generated in agricultural watersheds (Dons, 1987) although this could not be evaluated in this study. Likewise, the effect of expansions in tile drainage over time could not be evaluated in this chapter due to poor historical records of tile installation (Eimers et al., 2020). Overall, results of this thesis suggest that there is substantial scope for further agricultural intensification, especially as urban cover expands, and so tile drainage may become more influential in the future.

# 4.0: Conclusions

Of the metrics considered in this study, the RBI and FDC were the most sensitive and useful for detecting the hydrologic effects of land cover change, particularly at the urbanizing watersheds. The RBI trend analysis showed clear differences between urban and rural watersheds and the FDC indicated that high flows were especially sensitive to urban expansion at the 'old urban' Highland Creek, whereas storm water management practices at Rouge and Lynde may have muted their peak flow response to more recent urban increases. Urban watersheds are clearly more flashy than rural watersheds; however, results of the first research chapter indicated that heavily tile-drained watersheds are as flashy or even flashier than urban systems, suggesting a threshold in response (> ~40% of watershed tiled). The first research chapter also indicated that years with greater precipitation were 'flashier' and likewise results of this chapter confirmed that differences in precipitation contribute to inter-annual variation in streamflow. Nevertheless, clear increases in flashiness over time at the urbanizing watersheds cannot be solely explained by increases in precipitation and are most likely associated with expansions of impervious cover and stormwater drainage.

Recommendations to avoid significant hydrologic regime change based on the results of this thesis would be to maintain higher levels of natural cover to reduce or offset the effects of urban development on flashiness and runoff. Modern water retention practices, namely retention ponds, appear to be reducing flashiness as demonstrated by relatively small increases of RBI at the Rouge River despite almost half of the watershed becoming urbanized in the past 50 years. Land use planners should be aware that agricultural land is primarily being replaced by urban cover, which puts pressure on remaining agriculture land to increase productivity. Techniques to increase agricultural productivity (i.e., 'agricultural intensification') including expansions in tile drainage may alter the hydrologic regime, and urban water managers should be aware that shifts in upstream agricultural areas may have substantial impacts on downstream flow regime. In particular, flood events may become more common during wet periods of the year, as tile drainage effectively transfers water from fields to streams, whereas flood risk during dry periods may be lower.

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# Appendix

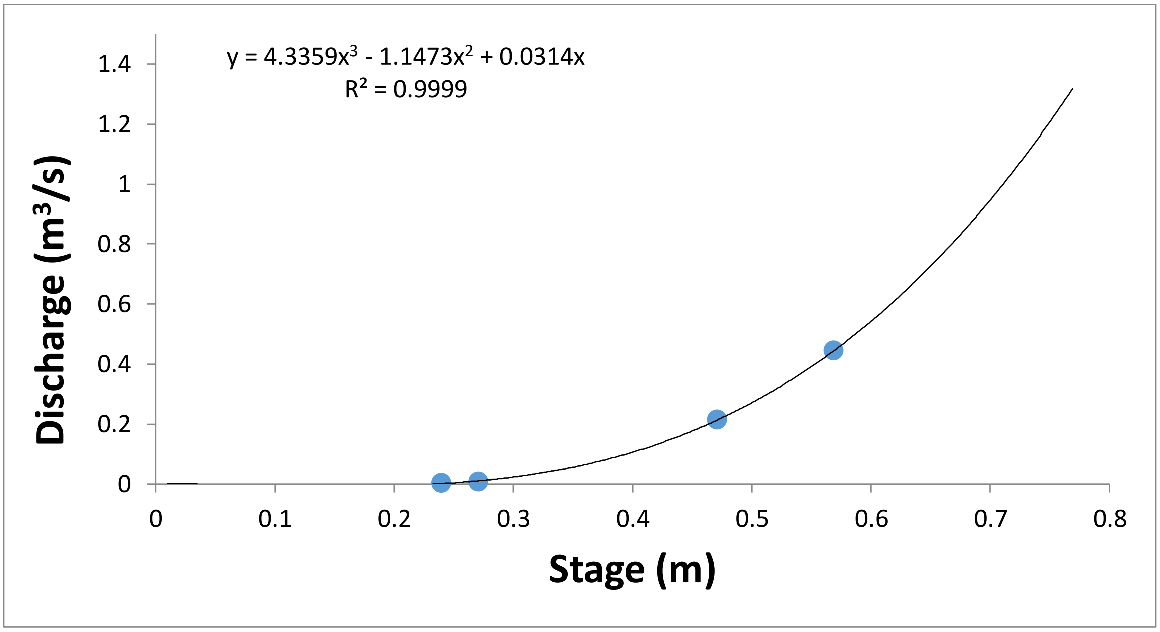


Figure A1. Rating curve for Gage Urban.

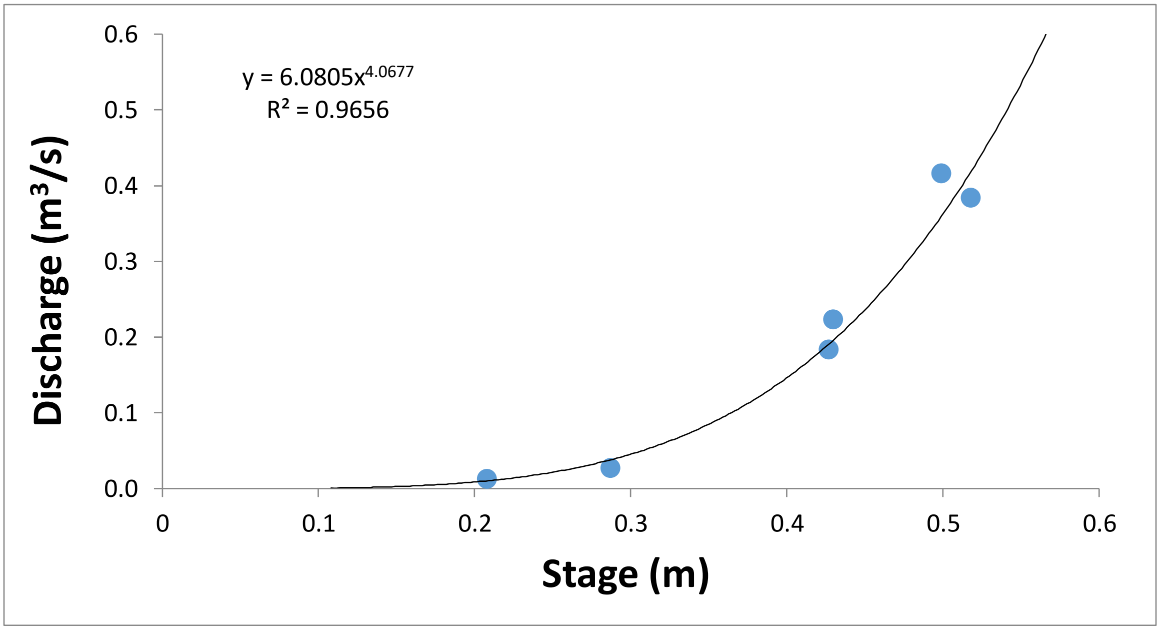


Figure A2. Rating curve for Mystery Creek.

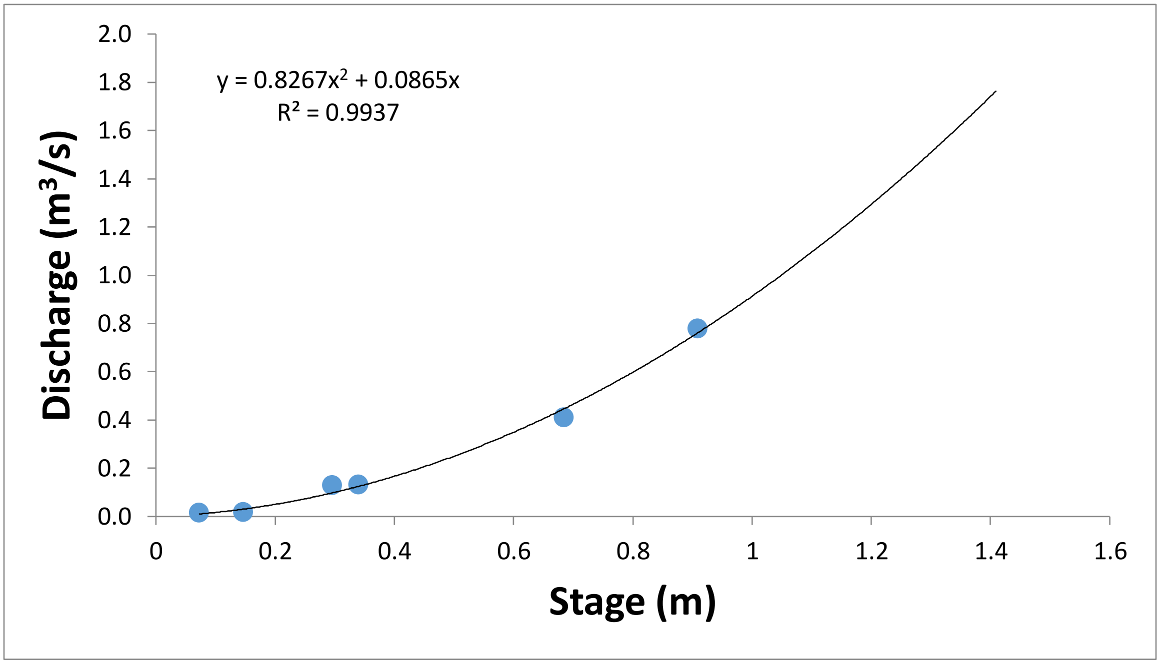


Figure A3. Rating curve for Gage West.

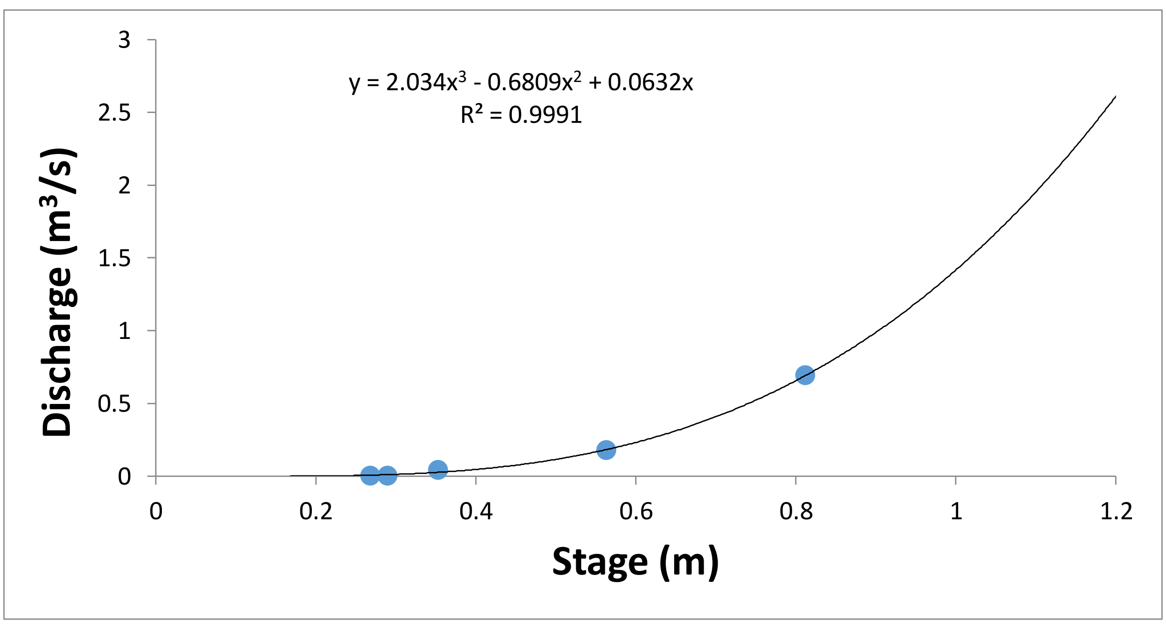


Figure A3. Rating curve for Brand Creek.

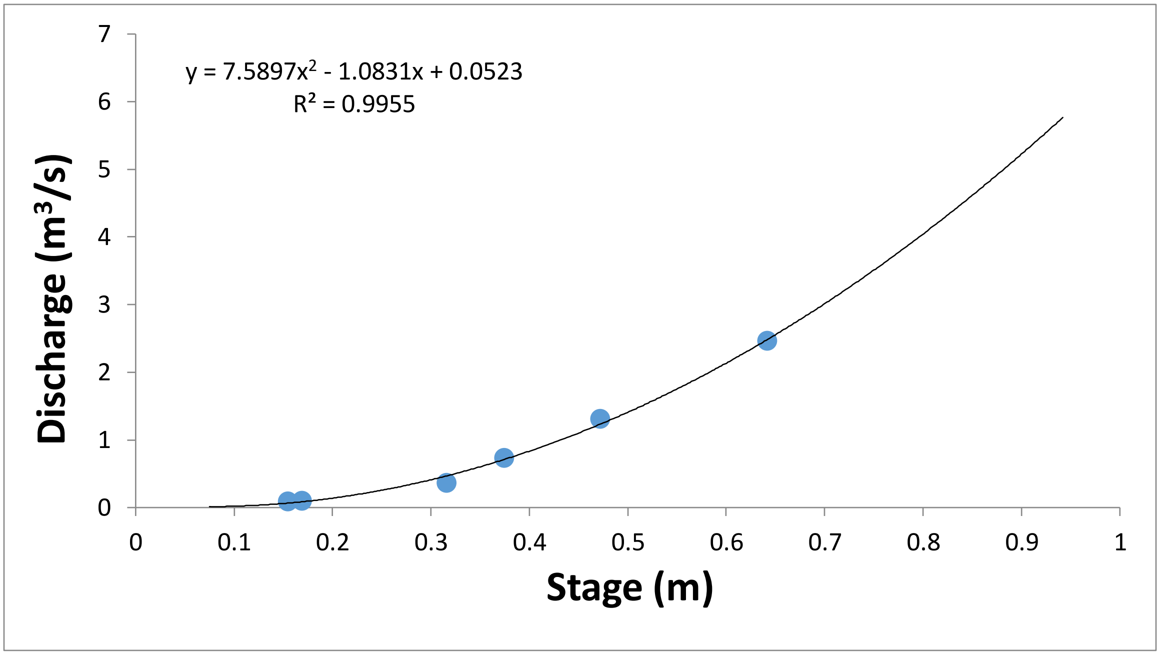


Figure A4. Rating curve for Gan 2.

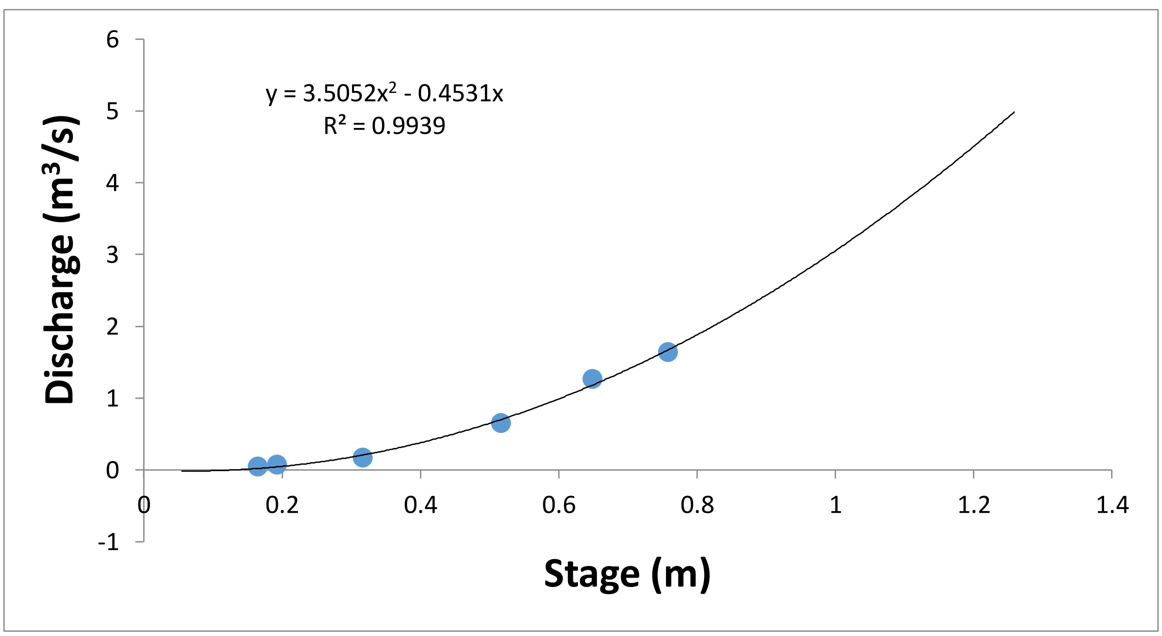


Figure A5. Rating curve for Gan 1.

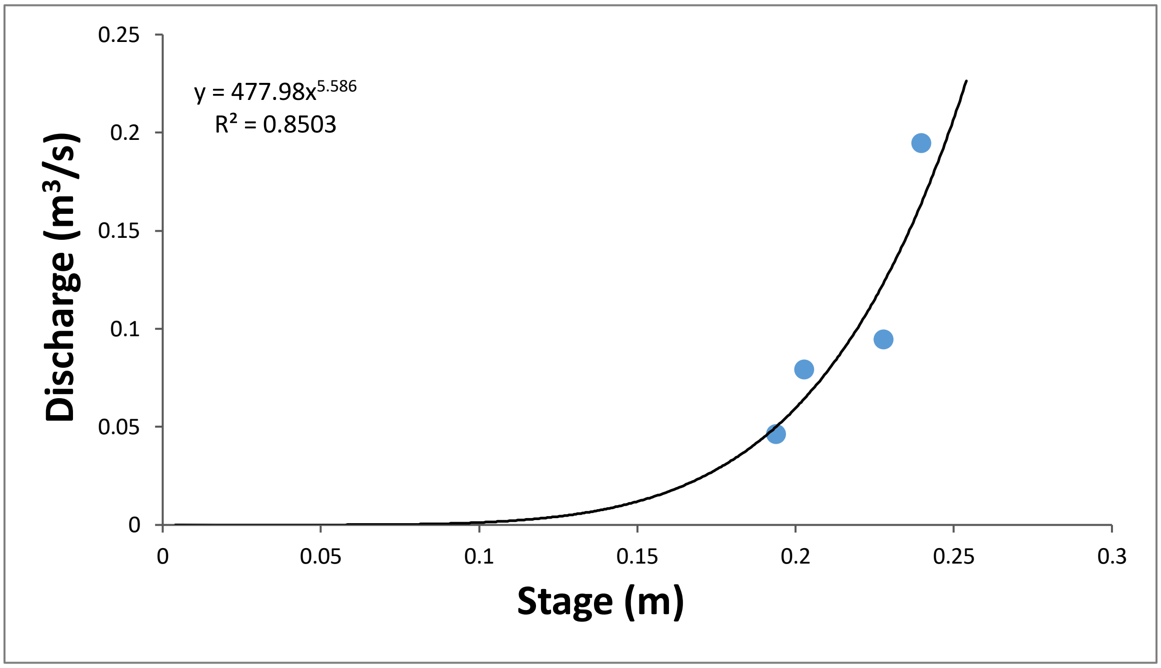


Figure A6. Rating curve for Gan Nat 1.

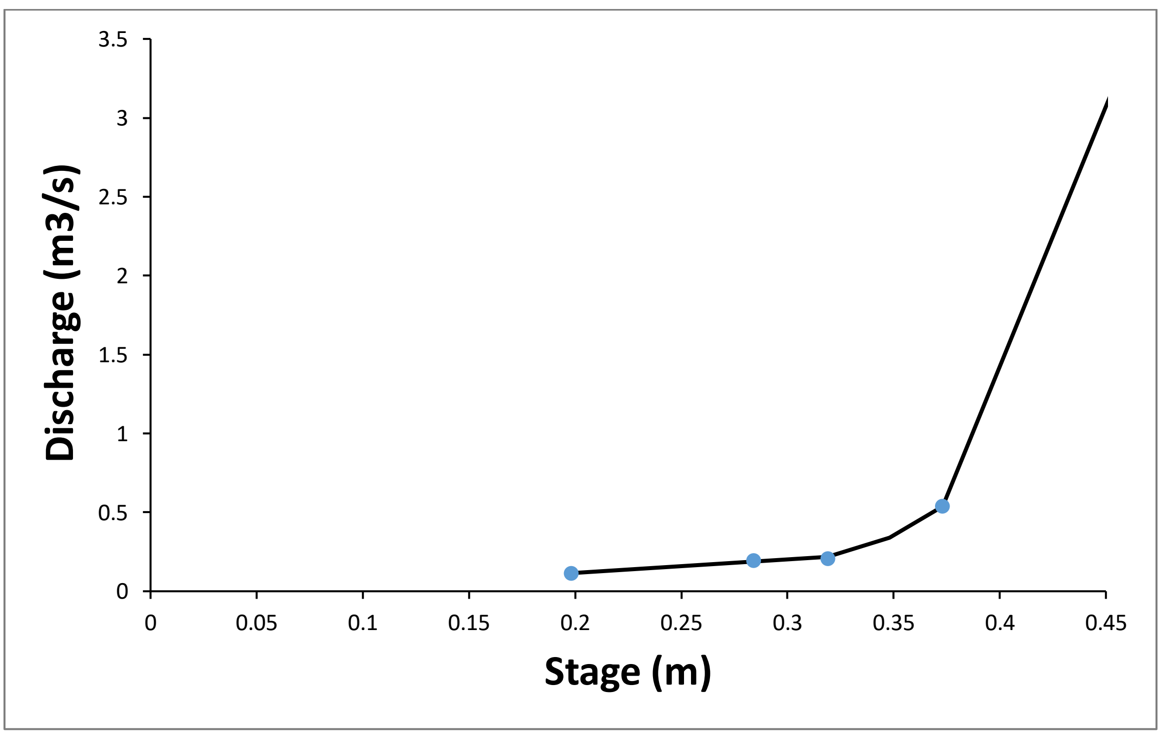


Figure A7. Rating Curve for Gan Nat 2. Slopes were manually calculated due to Excel curves not representing relationship between discharge and stage accurately.