Event Based Characterization of Hydrologic Change in Urbanizing Southern Ontario Watersheds via High Resolution Stream Gauge Data

by

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I hereby declare that I am the sole author of this thesis except where noted. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

P.J. Thompson

Declaration of Co-Authorship

The report entitled “ArkWSC: Automating the Extraction of Instantaneous Data from archived STREAM Formats” included as Appendix A within this thesis was prepared in collaboration with Tom Arsenault, Water Survey of Canada, Weather and Environmental Monitoring Directorate, Meteorological Service of Canada, Environment Canada. The included report was prepared by myself with the guidance of Mr. Arsenault, who’s insights and knowledge were key to processing the data employed in this study. I certify, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

Abstract

Tracking and quantifying hydrologic change in urbanizing watersheds is a complex problem which can vary spatially and temporally throughout the effective catchment area as change occurs. Hydromodification due to urbanization usually results in a larger peak event stream discharge, a change in typical event volume, a reduced lag time between rainfall and stream discharge events, and a more complex falling hydrograph. Recently extracted Environment Canada data have allowed the creation of a high resolution instantaneous stream flow dataset dating to the late 1960s for many Ontario gauge stations. Hydrometric data were obtained for fifteen urban and semi-urban catchments within Southern Ontario ranging in size from 50km^2 to 300 km^2 with urbanized land use assemblages varying from <5% to 80%. Utilizing automated methods, each individual runoff event from the hydrographic record was identified and characterized. Temporal changes to urban land area, land use, and road length were quantified for each watershed from aerial photography spanning the period of record at approximately 8 year intervals allowing identified trends in event hydrograph parameters to be correlated quantitatively with the alteration of the catchment over time.

Increasing trends in event peak discharge were identified in all but one study catchment. Event volume was found to be consistently increasing in most of the urban watershed, while trends in event duration were observed but with no clear increasing or decreasing trend. The lack of consistent trends in the timing and distribution of flow during runoff events suggest that build-out, drainage network design, and stormwater management systems play differing roles in the neighbouring urban catchments. Changes to flood recurrence intervals through the period of urbanization were also investigated; peak magnitude of high frequency events is affected to a greater extent than low frequency or flood events. The relative change in return frequency distribution is not consistent between catchments, also the degree of alteration can differ between various recurrence intervals at a gauge. Peak discharge of some return periods appeared to decrease with urban development suggesting that the increased detention brought with urban stormwater management systems have effectively offset the increased runoff due to additional impervious area and improved drainage efficiency. A consistent relationship defining the change in geomorphically significant return periods (i.e. channel forming flow) with urbanization was identified in neighbouring urban catchments.

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Chapter 1

Introduction

"Of all land-use changes affecting the hydrology of an area, urbanization is by far the most forceful."

— Luna Bergere Leopold

1.1 Background

"Urban stream syndrome" (Walsh *et al.*, 2005) describes the characteristic ecological impacts of urban development upon stream networks. Symptoms include degraded water quality, altered stream morphology, and reduced biological diversity (Everard & Moggridge, 2012). These symptoms are in part a causal effect of urbanization on the hydrologic response altered watersheds. Prime drivers of hydrologic change include: increasing paved area by covering permeable soils with impermeable streets, parking areas, roofs; and the construction of hydraulically efficient channels through which storm runoff can flow at rapid speeds (Hare, 1970). This results in flashier stream systems with larger, more frequent storm events interspersed by periods of reduced low flow conditions (Everard & Moggridge, 2012).

Hydrologic processes occur at disparate temporal scales (Blöschl & Sivapalan, 1995); for example, peak flood conditions may last only minutes while subsurface groundwater flow may take years or decades to reach its destination. This is an important consideration in urban watersheds, where runoff events are short and intense. Spatially, processes and conditions are also different at the reach, watershed, or synoptic scale. Understanding complex hydrological mechanisms requires observations that reflect both the spatial and temporal scales at work. Figure 1.1 compares a range of hydrological problems with the temporal and spatial scale of the data required to analyze the problem. Understanding processes that over years or decades at a large spatial scales can be understood with relatively coarse, low frequency datasets. Analyzing problems at short temporal scales, for example, erosional or runoff processes, require finer resolution data. The need for hydrometric data at a high resolution also becomes more critical as the size of the basin decreases and runoff travel time shortens.

Hydrometric data, typically the form of stream stage or discharge, are usually processed at the daily time step (Environment Canada, 1999a); this limits the analysis of processes that occur at sub-daily time steps. For example, when assessing the volume of sediment transported by a stream, 15 minute streamflow data can provide a significant improvement in the estimation over daily data in some river channels (Chen *et al.*, 2012). Transport processes are sensitive to small changes in discharge, and streamflow can vary dramatically over hours or minutes. When undertaking any hydrologic study, it is necessary to obtain data at a temporal frequency that reflects the nature, spatial scale, and sensitivity of the processes under investigation.

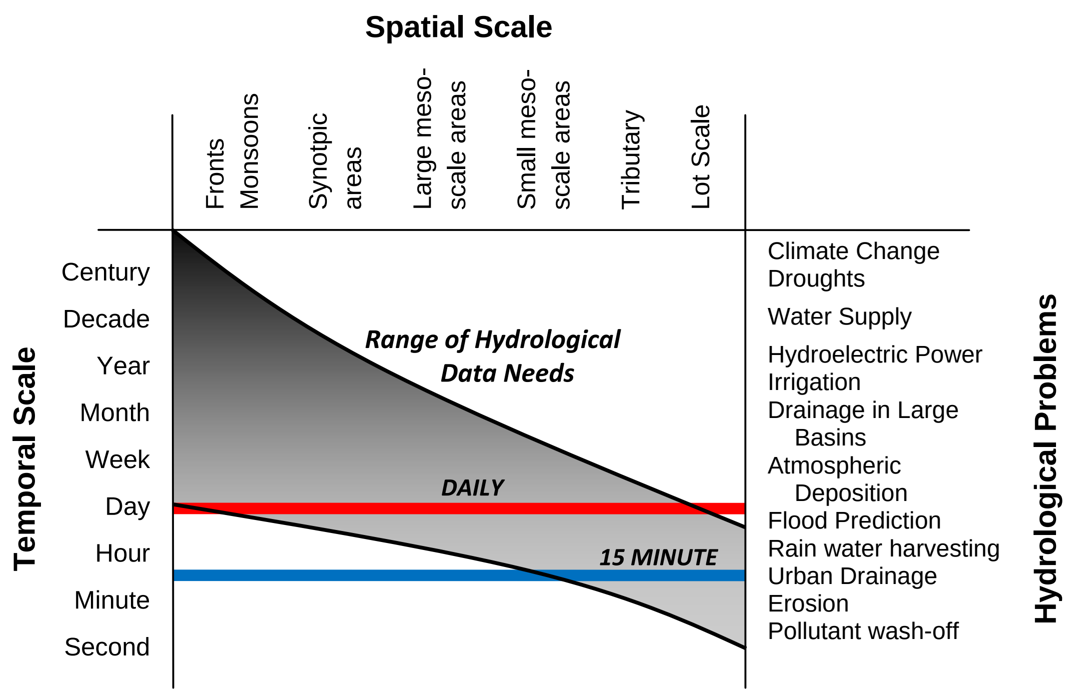

Figure 1.1: Data requirements for typical hydrological problems compared with temporal and spatial scale (modified from Arnbjerg-Nielsen (2008))

The Water Survey of Canada (WSC), a division of the Weather and Environmental Monitoring Directorate, Meteorological Service of Canada, Environment Canada, has been collecting hydrometric data since 1908, and currently operates over 2500 gauging stations across the country (Environment Canada, 2013). Figure 1.2 presents a typical gauge station at a mountain stream. WSC processes and publishes both mean daily stage and discharge for most active stream gauges. Higher resolution stream data, sampled on an hourly or 15 minute basis, are used to generate the published mean daily dataset. These instantaneous data, while not an official hydrometric product, are available upon request from WSC.

Availability of WSC instantaneous data varies from region to region, and depends on the quality of archived paper and electronic records. As daily streamflow data may not provide the resolution to describe relevant hydrological processes, the analysis of instantaneous data can provide valuable insight into the hydrologic regime.

(a) October 1971

(b) May 1977

Figure 1.2: Glacially-fed stream gauge station (Peyto Creek at Peyto Glacier, Banff National Park, Alberta, Canada) (Photo credit: Water Survey of Canada)

The relevance of the increase in resolution provided by instantaneous data is illustrated on Figure 1.3. These hydrographs provide a comparison of daily and instantaneous 15-minute streamflow data at a glacially-fed stream (Figure 1.2) during a summer month. Large, diurnal fluctuations in instantaneous discharge can be observed. Incoming solar radiation varies during the day producing higher meltwater flows during the afternoon and evening; these processes are averaged away at the daily time step. Additionally, precipitation events are masked at the daily time scale by the diurnal melt events. The total daily runoff volume is captured at this gauge yet the sub-daily variation is obscured.

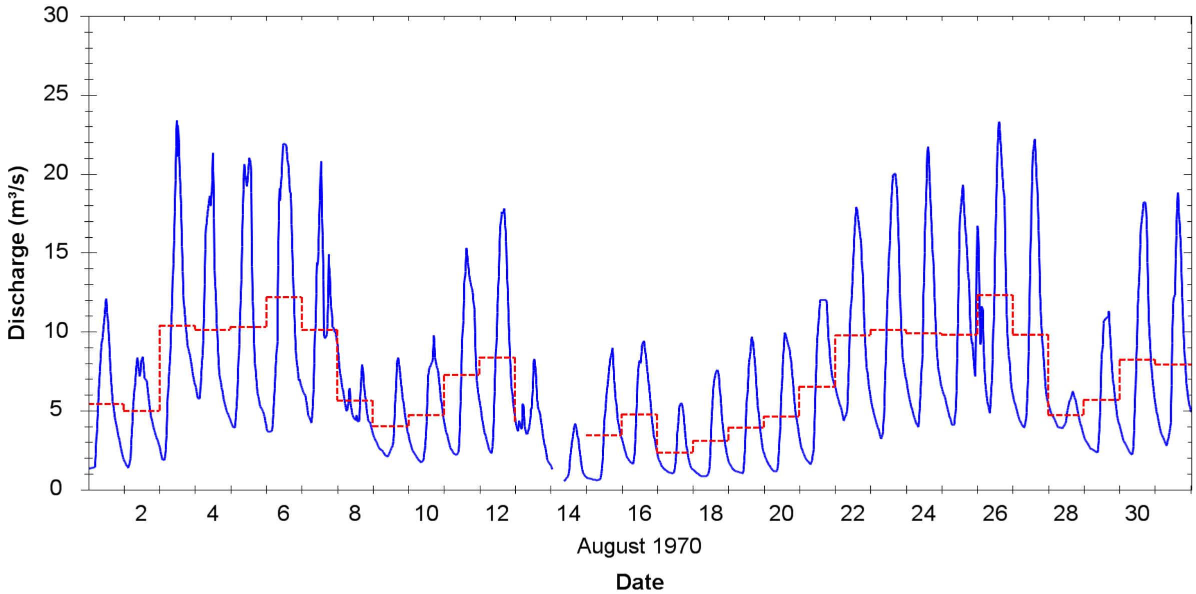

Figure 1.3: Daily (red) vs. 15 minute Instantaneous (blue) stream discharge data at Peyto Creek (Peyto Glacier, Banff National Park, Alberta, Canada)

High resolution discharge data is of particular importance when studying urban watersheds. Figure 1.4 provides a comparison of daily and instantaneous streamflow data at a typical urban gauge (Figure 1.5) within southern Ontario. Due to urbanizing processes runoff events increase in magnitude but shorten in duration (Leopold, 1968). Frequent convective storms during the summer months produce intense events (Gingras *et al.*, 1994; Glaves & Waylen, 1997) which may last only hours. Individual events can be identified from the instantaneous data, and the magnitude of the peak of these events far exceed the observed mean daily discharge. Isolated events which occur on different days may also appear as one event on the daily hydrograph. While the daily mean dataset provides a good representation of the total event volume, a large amount of information concerning the shape, form, and magnitude of the event is obscured at the daily time scale. The annual instantaneous peak forms an important metric for flood frequency analysis; however, in urban catchments there may be several large events per year which approach the magnitude of the annual event. Temporal resolution clearly is important when characterizing these short, dynamic storm events.

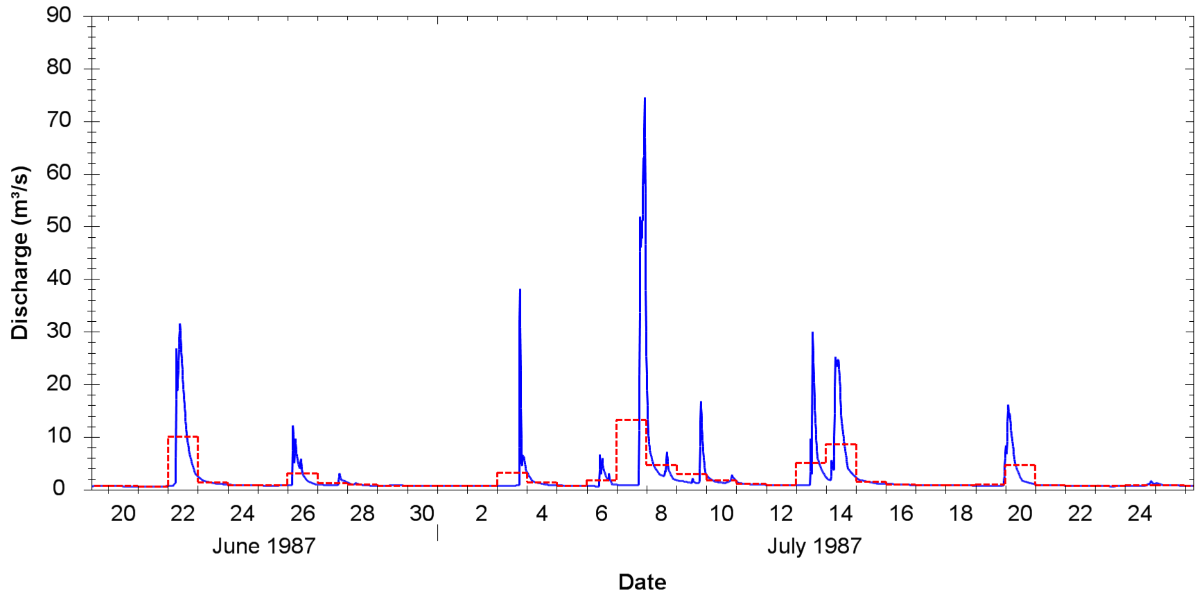

Figure 1.4: Daily (red) vs. 15 minute Instantaneous (blue) stream discharge data at a typical urbanized southern Ontario catchment

(a) Concrete channel with control

(b) Concrete channel with storm drain

Figure 1.5: Channelized urban river course (Don River, Toronto, Canada) (Photo credit: Water Survey of Canada)

Instantaneous streamflow data offers a substantial improvement in resolution over mean daily data. Even in heavily urbanized areas, previous studies in southern Ontario analyzing changing land-use patterns have reached inconclusive results when employing daily stream gauge data (Morgan *et al.*, 2004). When considering the urban instantaneous hydrograph (Figure 1.4), individual runoff events can be clearly identified. While techniques considering the analysis of individual flood hydrographs have been proposed (Yue *et al.*, 2002), most applications have focused on annual or larger events (Sauquet *et al.*, 2008; Mediero *et al.*, 2010; Chebana *et al.*, 2012). By considering every event observed on a hydrograph, not just large floods, subtle hydrologic changes over time can be investigated. This work attempts to better understand and explain the changing hydrologic regime in urbanizing watersheds by characterizing the change in individual event characteristics.

1.2 Scope and Objectives

While instantaneous data from the mid-1990s onward are readily available, a long period of hydrometric record is preferable when investigating hydrologic change. Early investigations revealed the availability of instantaneous data dating back to the late-1960s archived in electronic formats and preserved by the WSC. Working closely with WSC staff, this data was extracted and vetted for quality. These efforts, only briefly summarized within this manuscript, produced a 40 year period of instantaneous record.

To characterize individual events, automated methodologies were developed to isolate and parse runoff events from the hydrometric record. Event parameters describing magnitude, volume, duration, etc. can be then calculated. To capture spatial change in urban form with time, an analysis of aerial photography was undertaken to track temporal changes to urban land area, land use, and road length. Aerial and satellite imagery spanning a period of 50 years was scanned, digitized, and analyzed to produce temporal and spatial mapping. This allows identified hydrological trends to be correlated quantitatively with the alteration of the catchment over time. Utilizing these methods, 15 urban and agricultural watersheds in southern Ontario, Canada have been analyzed over a 40 year period of record.

The objective of this research was two fold. Firstly, to determine if trends exist within the identified event parameters. If trends exist within the series of isolated events, to then correlate these trends with urbanization. Secondly, to better understand changes to event recurrence intervals caused by urban build-out. While it is understood that urbanization preferentially affect smaller events (Hollis, 1975), an analysis considering all runoff events in a catchment has not been undertaken. Isolating the peaks for every event observed on the hydrometric record should allow an assessment of recurrence intervals for small weekly or monthly events to large flood magnitude events. Events of a geomorphically significant return interval, such as bankfull or channel forming discharge, can also then be analyzed and compared to urbanizing influences.

1.3 Thesis Organization

The remaining body of this thesis is organized into the following chapters:

- **Chapter 2** provides a review of the literature relevant to this work.
- **Chapter 3** discusses the hydrometric data utilized in this study. The methodology employed to process and analyse the data are also presented.
- **Chapter 4** presents the results of the event based analysis conducted in each of the study watersheds. Hydrologic trends are identified and compared with changes in urban influence. Changes to event frequency are also considered.
- **Chapter 5** summarizes this research and offers recommendations for future work.

Chapter 2

Background

The hydrologic cycle provides a baseline paradigm for considering the many hydrologic processes that may occur in the urban environment. In the case of surface water hydrology, precipitation represents the driving process of the cycle, falling in the form of rain or snow. Precipitation may enter a water body directly or via overland flow to a stream or lake. Some portion may be stored in surface depressions while other portions may be intercepted by vegetation. Some water may be evaporated back into the atmosphere, while other fractions may infiltrate into the ground, percolating to the water table or removed by vegetation via evapotranspiration. From each precipitation event, no water is lost; it is partitioned to the surface water system, groundwater or returned to the atmosphere. All of these processes occur simultaneously but at different temporal scales.

In the built environment, the same basic hydrologic cycle exists, however, the interdependencies of the above processes may be significantly altered both spatially and temporally. With urbanization comes change in land use, removal of soil and vegetation, regrading and levelling of topography, and the introduction of buildings, pavement and other impervious surfaces. As the form of the watershed is altered, the function is also changed; impervious surfaces reduce the potential for groundwater infiltration, while man made drainage increases the velocity and magnitude of surface runoff (Hare, 1970). Storage in the system is altered by stormwater management systems, reduction of depression storage, and changes to vegetation patterns. Urban services such as water supply, flood protection, and wastewater collection and management provide additional complex pathways for water flow. A simplified schematic of the urban hydrologic cycle is presented in Figure 2.1 illustrating the labyrinthine nature of these processes and interactions. Introducing these processes to a watershed through urbanization leads to dramatic alternations of the hydrology, geomorphology, and ecology of urban stream channels (Paul & Meyer, 2001).

Urbanization cannot be considered a single state, nor is it the result of a change to a single environmental function (Konrad & Booth, 2005). Urbanization is a process resulting from a series of cumulative actions within a watershed, and the change in observed hydrologic response may be confounded by these many alterations. Leopold (1968) suggests

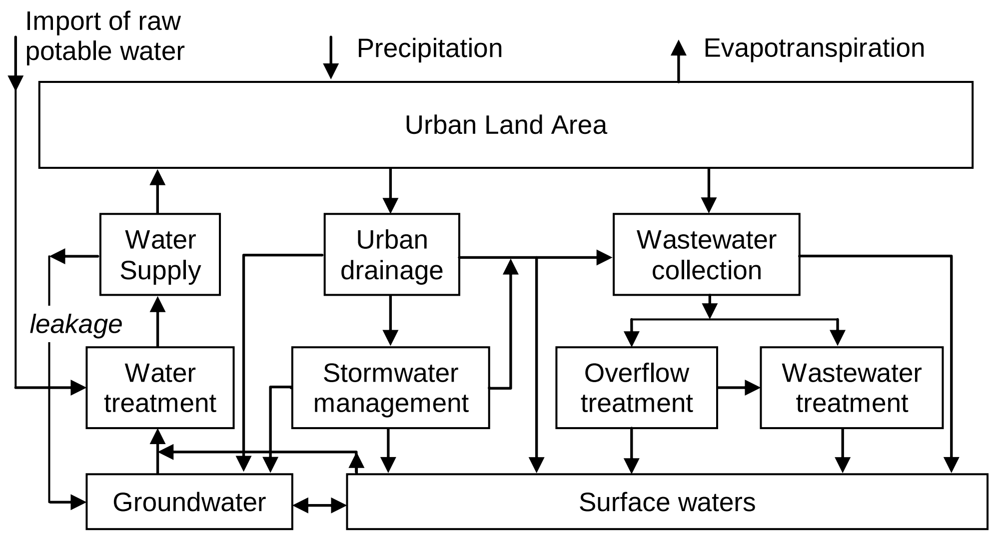

Figure 2.1: Urban water cycle - main components and pathways (after Marsalek *et al.* (2008))

four interrelated but separable effects on the hydrology of a catchment with urbanization: change in peak flow characteristics, changes in total runoff, changes in quality of water, and change in the hydrologic amenities. Urban water quality is often poor (Weibel *et al.*, 1964; Duda *et al.*, 1982; Tong & Chen, 2002; De la Cretaz & Barten, 2007), and worsens as a catchment builds outwards (Brabec, 2002; Bishop *et al.*, 2000; Ren *et al.*, 2003). Urban catchments also frequently lack natural stream buffers which can help attenuate pollutants (Vought *et al.*, 1995). Hydrologic amenities refers to the appearance of the catchment, and to the impression that the channels, streams, and valleys (the hydrologic system) impart to the observer. While water quality and natural aesthetics are important watershed features, this work primarily focuses on the change in hydraulic response due to urbanization.

2.1 Event Response

The change in hydraulic response with urbanization can be illustrated by comparing pre and post urbanization hydrographs. Figure 2.2 presents a hypothetical unit hydrograph and the direct runoff response observed in a typical catchment from a given rainfall event. Also illustrated is the change in event response typically observed with urbanization; an increase in peak discharge and total event volume, and a shorter duration of storm runoff (Leopold, 1968; Seaburn, 1969; Burns *et al.*, 2005; Chang, 2007).

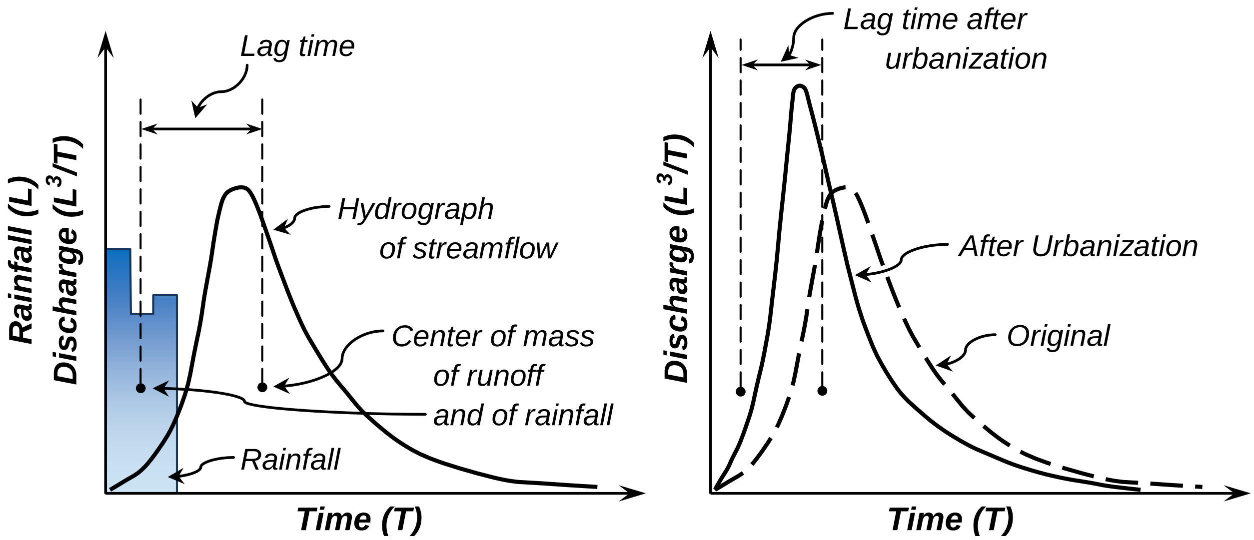

Figure 2.2: Hypothetical unit hydrographs relating runoff to rainfall with urbanization (after Leopold (1968))

Several landform changes combine to increase the total runoff volumes in urban systems. An increase in impervious area results in less infiltration to the groundwater system and therefore greater runoff (Shuster *et al.*, 2005). Decreasing the vegetative coverage results in less interception (canopy) storage and yields more runoff. Changes in topography and drainage result in less depression storage (which also may reduce groundwater infiltration) leading to greater runoff volumes.

Changes in the distribution of event runoff with urbanization can be directly related to the alteration of the drainage network (Graf, 1977; Meierdiercks *et al.*, 2010a). Figure 2.3 illustrates the watershed scale construction of an artificial drainage network which serves to route runoff directly to the natural system. Stormwater systems are constructed to manage rainfall by collecting and routing runoff away from impervious areas. The construction of road networks and the accompanying drainage channels also lead to an increase in stream drainage or network density (Bannister, 1979). Road ditching and storm drain construction can dramatically alter the dendritic nature of natural catchments, truncating natural drainage channels, increasing runoff in lower order streams, and creating additional pathways for flow. Artificial ditches and drainage pipes also provide capacity to move a larger volume of water more efficiently (i.e., faster) than the natural system. Shorter pathways combined with more efficient drainage results in a decreasing lag time and produce shorter events.

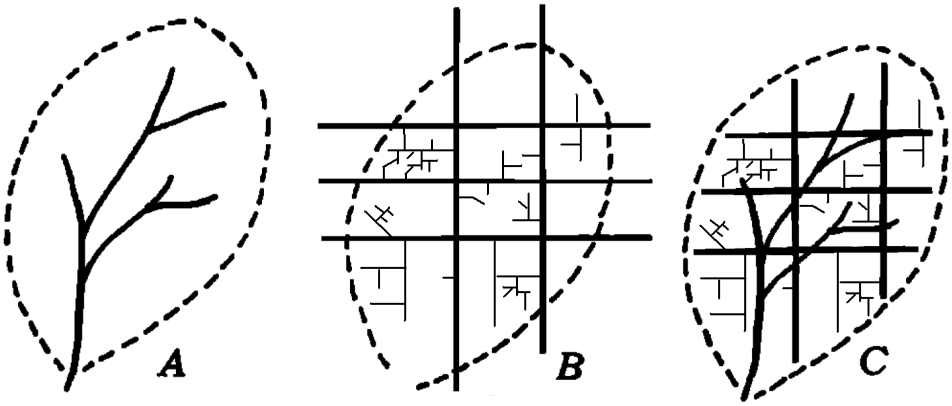

Figure 2.3: Hypothetical change in catchment drainage network; a)natural system b)artificial drainage c)combined network (modified from Graf (1977))

The decrease in lag time between rainfall and storm runoff with urban development is well documented (James, 1965; Leopold, 1968; Booth *et al.*, 2002). The hydrologic regime can vary significantly with the type of stormwater management system employed (Meierdiercks *et al.*, 2010b). Additionally, the degree of sewering has been shown to directly affect lag time (Dunne & Leopold, 1978); Figure 2.4 illustrates change in lag time between undeveloped and heavily sewered basins within the same hydroclimatic region.

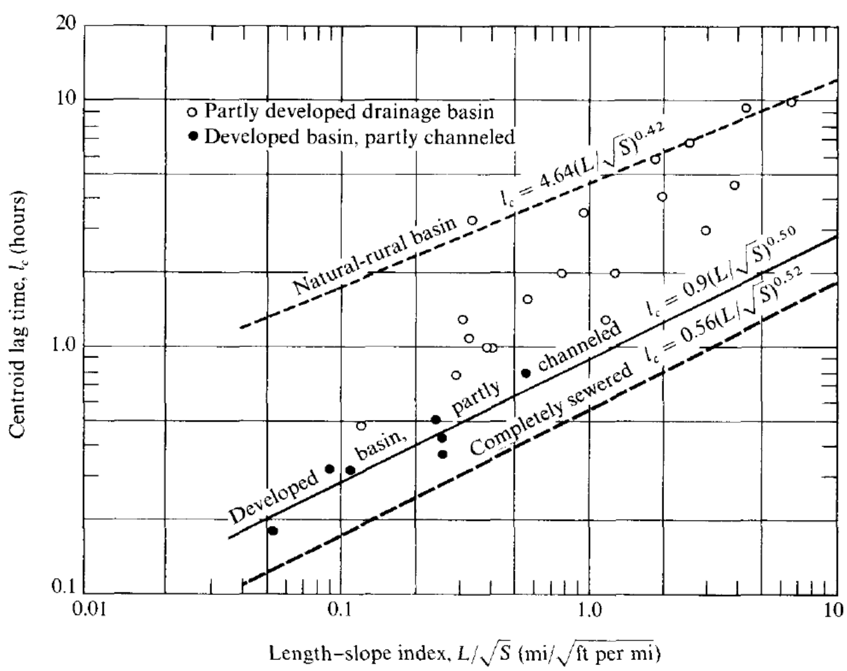

Figure 2.4: Relationship between lag time and Length-Slope for catchment with varying degrees of development (Dunne & Leopold (1978))

The peakedness or kurtosis of the observed urban hydrograph is a result of shorter detention times combined with an increase in total runoff; urban streams convey more water, more quickly, than in an unaltered state. The rate of change in discharge during the event is larger, the slope of both the rising and falling limbs of the hydrograph is steeper. Urban systems are termed ‘flashy’ due to this rapid rise and fall of the runoff hydrograph (McMahon *et al.*, 2007). Locally within a catchment, flashiness may be affected by stormwater management infrastructure. Where impervious surfaces decrease the residence time of runoff, stormwater management ponds act to detain and retain flow to prevent flooding downstream. These structures are typically designed for high intensity events, with the 2 to 5-year storm considered as a design target in Ontario by many municipalities (Cumming Cockburn Limited, 2000). Flood protection for major infrastructure such as roadways are designed to withstand storm events with a minimum 25-year return frequency (Ontario Ministry of Transportation, 1997).

The spatial distribution of urbanization adds to the complexity found in a built catchment. Not only is the amount of impervious area within the catchment important, but the spatial distribution of the area directly affects the magnitude of the change (Jacobson, 2011). Imperviousness varies with land use; commercial and industrial zones have higher imperviousness than residential or estate zones (United States Department of Agriculture, 1986). In addition, not all impervious areas within the watershed may be directly sewered, resulting in an Effective Impervious Area (EIA) which differs from the total Measurable Impervious Area (MIA) (Shuster *et al.*, 2005). Concomitantly, runoff characteristics also depend on soil type, depth, and vegetative cover; all parameters which vary spatially. Interrelated temporal and spatial variability is difficult to capture in any engineering exercise (Schumm, 1998) and characterizing change in the urban environment with bulk parameters may obfuscate the complexity of the system.

Low Impact Development (LID) strategies which aim to minimize the impacts of urbanization have been gaining recent acceptance (Dietz, 2007). LID approaches aim to mimic the natural, pre-development hydrologic regime, reducing the impacts of urbanization on water quality and habitat in addition to the hydraulic response. This is accomplished both with infrastructure; staggered stormwater management ponds, rain barrels, and interception galleries and through updated land use practices; clustered development, re-vegetation, and natural drainage systems. Multiple mitigation techniques at multiple scales; from the lot to the watershed scales, form a key precept of LID strategies. (United States Environmental Protection Agency, 2007). The net hydrologic modification is to increase both retention and infiltration in developed areas to reduce peak discharge and decrease lag times (Hood *et al.*, 2007).

2.2 Return Frequency

As a catchment urbanizes, a greater portion of rainfall from a given storm event will runoff as streamflow. Accordingly, the recurrence interval of a given streamflow event; the average time between floods of a specific peak magnitude, will decline. This can have a significant impact on stream geomorphology and ecology. Leopold (1968) presented some of the first methods attempting to relate urban development with changes in flood interval and magnitude. From a series of earlier studies, Leopold tabulated the change in mean annual flood discharge with urban development observed in several urbanized catchments. Combining this information with a regional flood frequency curve from data collected in the unurbanized Brandywine Creek basin, Pennsylvania, a series of curves predicting the change in flood magnitude with future urbanization was produced (Figure 2.5). While not accounting for stormwater management practices which may attempt to mitigate this hydrologic change, large increases in flood peaks are predicted.

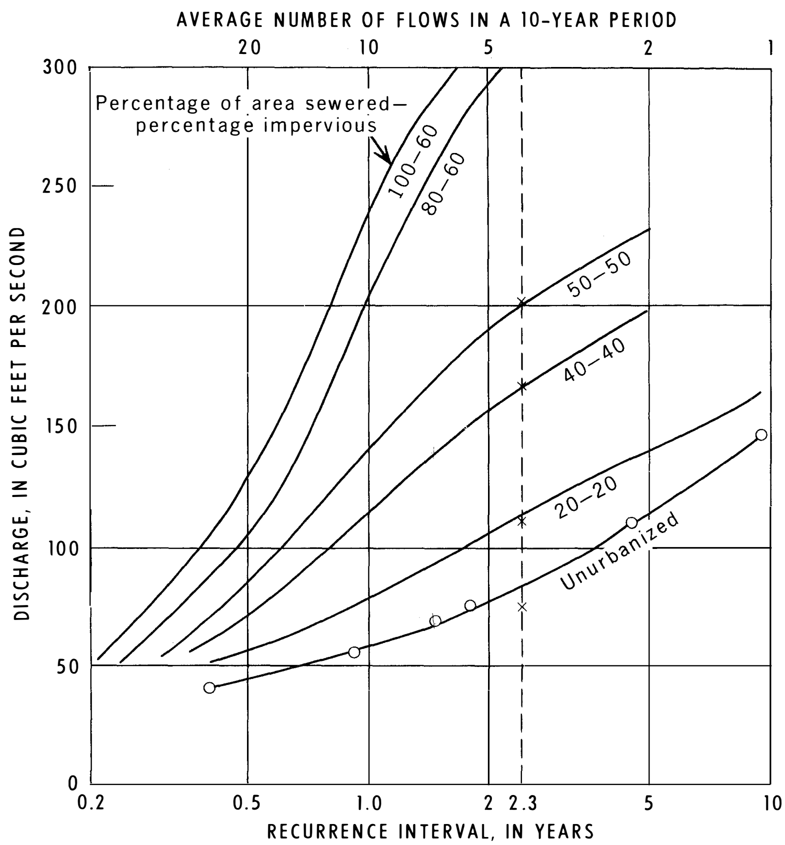

Figure 2.5: Flood-frequency curves for a 1-square-mile basin in various states of urbanization (from Leopold (1968))

In a comparative study of several catchments Hollis (1975) observed that urbanization disproportionately affects floods of different recurrence intervals. The magnitude of small floods (those occurring once a year or more) were found to increase by a factor of 10, whereas the peak magnitude of large floods (with return periods of 100 years or more) may only double. Hollis concluded that generally, as the recurrence interval increases the effect of urbanization on the storm response decreases. During severe and prolonged rainfall events in rural catchments, the soil zone becomes saturated to the point that the catchment in effect behaves as it were partially impervious. In addition, as the drainage systems are overwhelmed by runoff, the total conveyance of the network will reach an upper limit. Figure 2.6 illustrates the change in flood recurrence interval as a catchment is built out; the paved basin area can be considered analogous to measurable impervious area. Change in peak event discharge is manually fitted to data; some deviations are observed as the basins vary in size, morphology, climate, and geology.

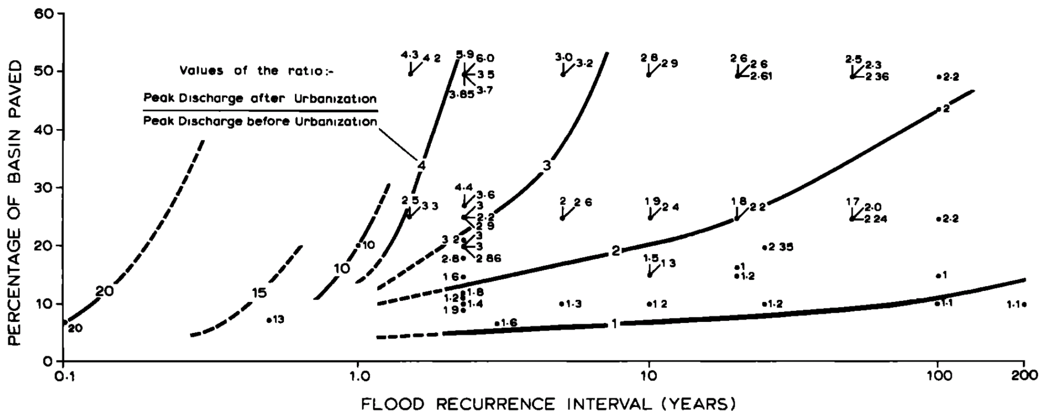

Figure 2.6: Effect of catchment imperviousness on flood recurrence interval (from Hollis (1975))

Changes in event frequency have implications for stream geomorphology; changes in the duration and timing of bankfull or channel forming events can alter the quasi-equilibrium state (Langbein & Leopold, 1964) of urban stream channels (Paul & Meyer, 2001; Shields Jr. *et al.*, 2003; Hawley *et al.*, 2012). Typical bankfull return periods in unaltered catchments range from 1 to 2 years (Leopold *et al.*, 1964). Hey (1978) observed for gravel-bed rivers in the U.K. that the bankfull flow recurrence interval was 1.5-years. Thorne & Soar (2001) compared bankfull width and discharge relationships to frequency distributions at 81 streams in the United States. Correlation was highest at a return frequency of 1.6 years, though it was noted that correlation values varied only slightly for discharges between the 1.5-year and 2-year recurrence. Annable (1996) found an average 1.6 year bankfull return period in a sample of rural southern Ontario catchments. The frequency of this event was observed to greatly increased where urban land use changes occurred; 2 to 18 bankfull events per year have been observed in urban southern Ontario catchments (Annable *et al.*, 2011). Aside from changes in flow duration patterns, increasing the paved area of a catchment decreases sediment loadings while at the same time artificial drainage increases the velocity of runoff. Combined, these flow partitioning and routing changes drive adjustment in channel form within urbanizing catchments (Hawley & Bledsoe, 2011).

2.3 Baseflow and Ecological Impacts

Urbanization can affect the groundwater system through a number complex and competing effects (Lerner, 2002). Substantial recharge can occur from the addition of leaking stormwater and drinking water distribution systems (Yang *et al.*, 1999). The retention of surface water by stormwater management systems or LID strategies (Ku *et al.*, 1992; Appleyard, 1995) may also increase recharge, as can the introduction of septic systems (Simmons & Reynolds, 1982) to rural watersheds. Alteration of the amount and type of vegetative cover can affect evapotranspiration both raising or lowering the water table (Tallaksen, 1995; White & Greer, 2006; Nie *et al.*, 2011). Changes to the groundwater recharge in urban areas undoubtedly affects baseflow conditions in adjacent streams (Paul & Meyer, 2001; White & Greer, 2006), however, the net effect on the watershed is highly variable.

Baseflow is an important ecological consideration; maintaining habitat, passage, and providing thermal refugia during summer months (Smakhtin, 2001; Annear *et al.*, 2004). Urbanization has been observed to reduce baseflow up to 75% (Simmons & Reynolds, 1982). In a comparative study of catchments in the Atlanta area (Georgia, USA) Rose & Peters (2001) noted baseflow recession constants were 35 to 40% lower in the urban watersheds. This was attributed to lower evapotranspiration losses which resulted in a smaller net change to groundwater storage during an event. Conversely, low flow discharge (as a fraction of the watershed area) was 25 to 35% less in the urban streams which was attributed to decreased infiltration as a result of more efficient routing of runoff and the paving of recharge areas. However, another comparative study found little difference in baseflow conditions when comparing an urbanized catchment against a forested rural catchment. This was attributed to increased recharge volumes from leaky storm pipes in the urban watershed balanced against increased transpiration from the vegetation in the forested watershed (Meierdiercks *et al.*, 2010b).

High flows also directly impact stream ecology (Konrad *et al.*, 2005); larger events control sediment transport and supporting aquatic life cycles. Patterns of high flows, both in peak and duration, are altered by urbanization, changing in magnitude and frequency. Variability in streamflow regime can be directly linked to the diversity and health of aquatic biotic communities (Poff & Ward, 1989; Konrad & Booth, 2005) and urbanization degrades both the quantity and quality of downstream aquatic systems (Booth & Jackson, 1997; Paul & Meyer, 2001).

Several authors have attempted to link hydrologic parameters relating the flow regime to stream habitat quality and biotic diversity. Konrad *et al.* (2005) identified the duration of flows that exceed the 0.5-year flood to be significant to channel stability with change observed in urbanizing basins. Variation in the fraction of the year daily mean discharge exceeds the annual mean discharge (T_{Qmean}) was found to be a reliable indicator of hydrologic differences resulting from urban development (Konrad & Booth, 2002; DeGasperi *et al.*, 2009). Baker *et al.* (2004) suggests that variability in peakedness or flashiness may represent the natural regime, and trends in this indicator may reflect detrimental change to aquatic life. In a study comparing hydrological indicators to stream health, DeGasperi *et al.* (2009) found High Pulse Count and High Pulse Range, the number of high flow pulses per year and the range in days between pulses per year respectively to correlate strongly with changes in benthic invertebrate community structure. May *et al.* (1997) notes that measures of total impervious area of approximately 10% have been identified as the level at which stream ecosystem impairment begins. Thus even minor urban development can affect large areas of seemingly natural downstream watercourse.

2.4 Summary

This chapter précised previous research in the field of urban hydrology. The impacts of urbanization affect multiple, completing hydrological processes with complex results. Generally, storm events of a consistent frequency produce larger runoff events as a catchment urbanizes. Storm events with a short return interval are affected more than larger magnitude events as the previous rural form of the watershed acted to retain storm flow. The event based analysis presented subsequently isolates every storm event from the hydrological time series, this should provide additional insight into the behaviour of these smaller, sub-annual storm events in urbanizing catchments.

Chapter 3

Methodology

The following chapter outlines the data and methods employed in this study and is organized as follows:

- **Section 3.1**: (*Site Selection*) discusses the selection of study catchments from Water Survey of Canada (WSC) gauging stations.
- **Section 3.2**: (*Hydrometric Streamflow Data*) presents the available hydrometric data for the selected study watersheds. Efforts made to process and verify archived instantaneous data are briefly summarized. Limitations of this dataset are discussed.
- **Section 3.3**: (*Event Parsing Algorithm*) outlines the automated computer code developed to identify and parse runoff events from the instantaneous record. Parameters governing this algorithm are presented and the limitations of this method discussed.
- **Section 3.4**: (*Hydrograph Variables*) discusses event based variables and parameters calculated for each identified storm event.
- **Section 3.5**: (*Aerial Photographic Analysis*) summarizes the air photo analysis undertaken to delineate the change in urban coverage with time. These methods are used to quantify temporal and spatial urbanizations patterns. By quantitatively estimating changes in land use, detected hydrologic trends can be correlated to urbanization.
- **Section 3.6**: (*Frequency Analysis*) outlines the procedures employed to estimate the recurrence intervals of detected event peaks.
- **Section 3.7**: (*Mann-Kendall Trend Test*) presents the method employed to statistically verify trends within the event dataset.
- **Section 3.8**: (*Flow Duration and Exceedance Probability Curves*) introduces duration and exceedance curves employed to qualitatively evaluate changes in the hydrologic regime with time and urbanization.

3.1 Site Selection

Primary station selection was limited to WSC gauging stations within urban, urbanizing and rural catchments (adjacent to urban or urbanizing catchments). The assessment of urban, urbanizing or rural land use was determined by temporal air photo interpretations and land use inventory mapping. All stations with a minimum 20 years of continuous, instantaneous hydrometric record were considered. Heavily regulated watersheds were eliminated (i.e., large reservoir systems); however, stormwater management and flood control systems are present in most urban systems and cannot be entirely avoided. Catchments with strong identifiable diurnal events associated with pollution control plants were also culled as this can make identification of small magnitude storm events difficult.

The screening process resulted in 17 catchments used in this study (Table 3.1). Twelve of the catchments are identified as urban watersheds; eleven of which are in the Greater Toronto Area (the exception being Laurel Creek at Waterloo (02GA024)) and should represent a similar hydro-climatic regime. These stations are classified as "urban" for the purposes of this study. Figure 3.1 illustrates a typical urban stream gauge, note the "dog house" style enclosure sitting atop the stilling well in panel (a) which contains the recording equipment. Panel (b) illustrates the construction of an artificial control, often required in urban streams to maintain a satisfactory stage-discharge relationship through all flow regimes (Rantz *et al.*, 1982).

Table 3.1: Selected WSC Study Catchments

StationID	**Station Name**	**Area (km^2)**	**Daily Record Start**	**Daily Record End**	**Type**
02HC019	Duffins Creek above Pickering	93.5	1960	2009	Agricultural
02HC009	East Humber River near Pine Grove	197	1953	2009	Agricultural
02HB004	East Oakville Creek near Omagh	199	1956	2009	Agricultural
02HB005	Oakville Creek at Milton	95.6	1957	2009	Urbanizing
02HB013	Credit River near Orangeville	62.2	1967	2009	Urbanizing
02GA024	Laurel Creek at Waterloo	57.5	1959	2009	Urban
02HA014	Redhill Creek at Hamilton	56.3	1977	2003	Urban
02HC027	Black Creek near Weston	58	1966	2009	Urban
02HC017	Etobicoke Creek at Brampton	63.2	1957	2009	Urban
02HC030	Etobicoke Creek below QEW	204	1966	2009	Urban
02HC033	Mimico Creek at Islington	70.6	1965	2009	Urban
02HC005	Don River at York Mills	88.1	1945	2009	Urban
02HC029	Little Don River at Don Mills	130	1965	1996	Urban
02HC024	Don River at Todmorden	316	1962	2009	Urban
02HC022	Rouge River near Markham	186	1961	2009	Urban
02HC013	Highland Creek near West Hill	88.1	1956	2009	Urban
02HD013	Harmony Creek at Oshawa	41.6	1980	2009	Urban

(a) Winter 1975

(b) Spring 1975 (control installation)

Figure 3.1: Typical urban gauge station (Laurel Creek at Waterloo, Ontario) (Photo credit: Water Survey of Canada)

Three study sites are located in agricultural/forested watersheds that have undergone nominal structural or land use change over the period of record (also referred to as domesticated watersheds). Only catchments adjacent or in close proximity to the selected 12 urban gauges were considered. A caveat for the selection of rural watersheds involved the compatibility of the event identification algorithm utilized in this study. As discussed in subsequent sections, event detection in rural catchments is problematic. The selected catchments represent well-drained agricultural basins with somewhat flashier storm event response. The presence of tile drains on agricultural fields may explain some of the flashiness in the event hydrographs. These stations serve as a control set, representing the typical pre-urbanized southern Ontario watershed while preventing changes in climatic patterns from being confounded with land use change in the urban watersheds.

Two relatively small but rapidly urbanizing watershed stations were also included in the analysis (identified as urbanizing). Of note, Sixteen Mile at Milton (02HB005) is heavily regulated by two large reservoirs 10km upstream from the gauge, immediately below the Niagara escarpment (Earthfx Incorporated, 2012) which provide flood protection for the Town of Milton. However, this gauge is located in the fastest growing community in Canada (The Toronto Star, 2012) and may provide anecdotal insights. The spatial distribution of the selected stations within southern Ontario is illustrated on Figure 3.2.

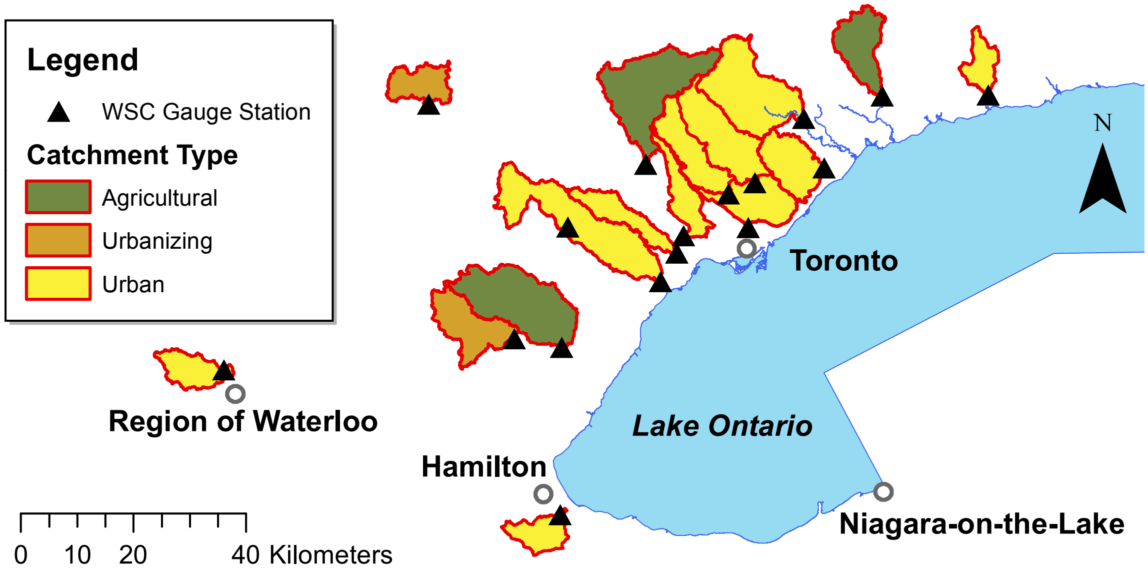

Figure 3.2: Selected WSC Study Catchments

3.2 Hydrometric Streamflow Data

Hydrometric data were obtained from WSC in several formats. Daily average streamflow is readily available through the WSC's hydrometric database, HYDAT (available online at www.ec.gc.ca/rhc-wsc). To better understand sub-daily processes, higher resolution data were requested from WSC. Hourly and sub-hourly data were available from 1996 and onwards by request from WSC's internal Ingres relational database called Compumod. The higher resolution "instantaneous" data are comprised of discrete points sampled from the hydrograph in regular time steps (typically 15 minute intervals) whereas the daily mean data represent a volumetric average. Figure 3.3 illustrates the relative difference in resolution between daily and instantaneous hydrograph data at an urban gauge.

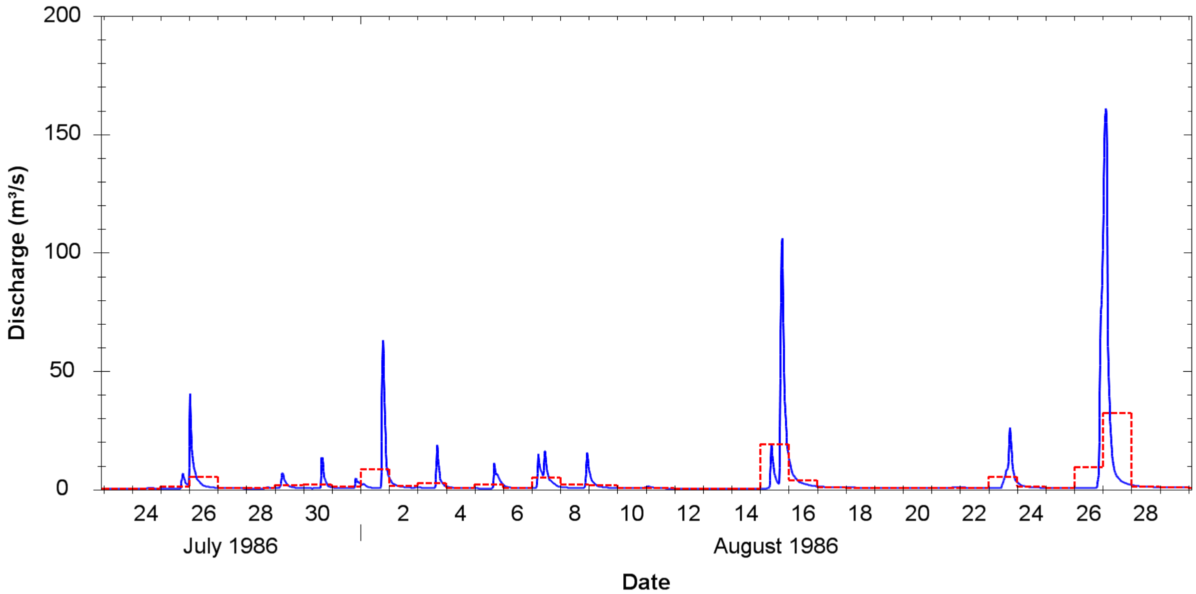

Figure 3.3: Comparison of Daily (red) versus 15 minute Instantaneous (blue) Hydrometric Data (Highland Creek near West Hill - 02HC013)

Given the substantial improvement in resolution offered by the instantaneous data, the possibility of using historical WSC gauge data in the urban watersheds was investigated. Data processing techniques making use of computer programs were first introduced by WSC in 1968 (Stewart & Comeau, 1974). Manual calculation techniques were time consuming, a technician was required to convert the recorded water level trace to a discharge hydrograph by hand. For a typical chart, this may have required thousands of interpolations from the stage-discharge relationship, and equally as many calculations to determine the daily mean discharge. The main goal of these initial programs was to automate the average and peak daily streamflow calculations to reduce the number of person hours spent processing data while increasing overall accuracy. Early computing processes utilized paper card decks as input files created from manually digitized hydrograph charts. The charts were digitized at sub-daily intervals, ideally at every break in slope on the recorded water level chart. Computations of daily figures were made from the high resolution (sub-hourly) hydrograph data, and published. The high resolution data were then archived for future use in electronic form. WSC maintains a electronic archive of these data in the original format. Reconstructing a complete streamflow hydrograph from paper records can be difficult and extremely time consuming (Topping *et al.*, 2003). Electronically archived WSC records offer both a digitized stream stage record and the various rating curves and corrections required to replicate the discharge hydrograph.

To access and exploit these archived data, a Visual Basic (.NET 2.0) computer program ArkWSC was written to extract and verify the hydrometric data. ArkWSC works in tandem with a legacy WSC DOS program, entitled HOURLY. HOURLY is an updated version of the program originally employed to process the card data. ArkWSC automates the input and output of files for the HOURLY program which extracts archived instantaneous data extracted from the HOURLY program. For each extracted instantaneous water level measurement, HOURLY determines the effective water level at that exact point in time and calculates the discharge. The data is not averaged or summed across a given time period (e.g., daily), and each point represents the observed hydrograph. The HOURLY program requires individual extraction runs not only for each year, but for each rating curve, chart type, and unit type. ArkWSC breaks each archived saveset (a file containing a station years worth of data) into a series of extraction blocks, runs the HOURLY program, and collates the generated 15 minute instantaneous output. Each day of data extracted is then tested against the published mean daily discharge values in the HYDAT database. In addition to the 15 minute instantaneous data, ArkWSC also processes the discrete water level points recorded in the saveset (a data set with irregular intervals primarily defined by the actions of the historical digitizer) and computes the effective gauge height and discharge for each chart point allowing the creation of an irregular instantaneous dataset. A detailed discussion of the development, extraction, and quality anaylsis of the instantaneous dataset is provided in Appendix A.

By combining the instantaneous data from WSC's CompuMOD database (1996-2008) with the extracted ArkWSC data (1969-1996), a continuous instantaneous (15 minute) hydrometric record spanning 1969 to 2009 was created for the study watersheds. Figure 3.4 illustrates the observed deviation between the daily and instantaneous hydrograph data at a typical urban gauge. Flows equalled or exceeded 1-3% of the time during the period of record are poorly represented by daily data at this urban gauge. Large discharges occur only for short durations in urban watersheds (minutes to hours); the reported mean daily data average these large discharges against the entire observed daily flow. Therefore the daily record poorly characterizes and these large flow events only observable in high resolution instantaneous data. Comparatively, there is less deviation between the observed instantaneous and mean daily discharge data observed in the less flashier agricultural catchments characterized by multi-day runoff events (Figure 3.5).

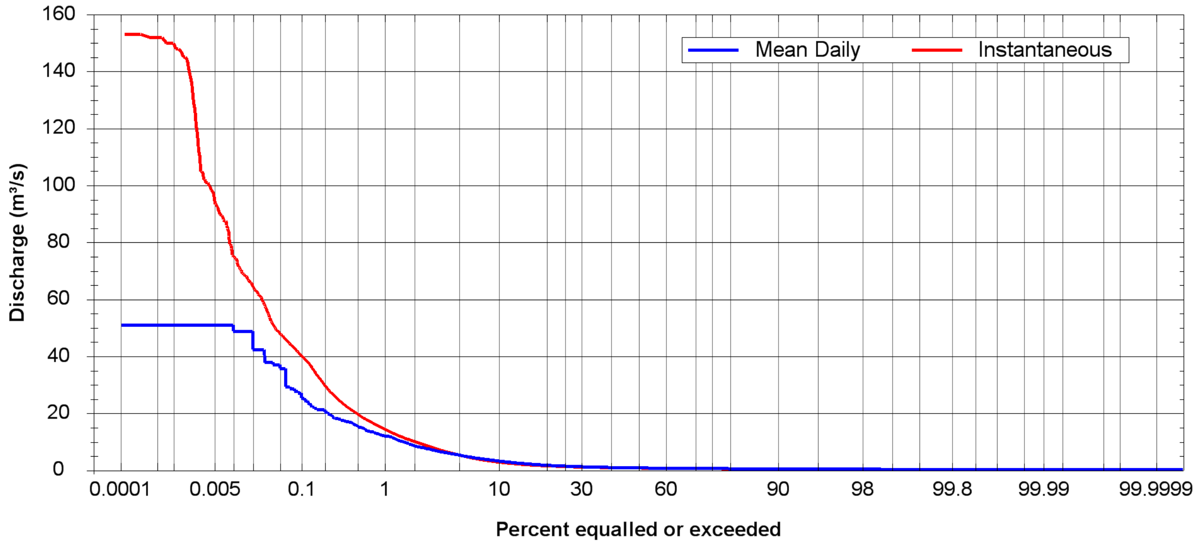

Figure 3.4: Observed occurrence of Instantaneous vs. Mean Daily Discharge (red) at an urban gauge (Black Creek near Weston - 02HC029)

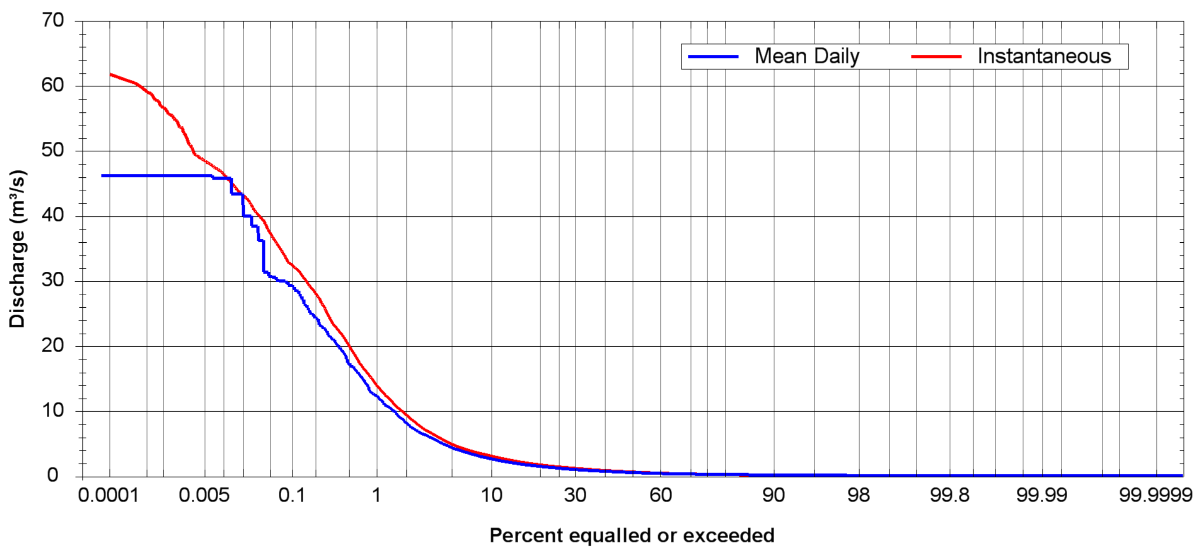

Figure 3.5: Observed occurrence of Instantaneous vs. Mean Daily Discharge at an agricultural gauge (East Humber River near Pine Grove - 02HC009)

It should be noted that wherever possible, 15 minute resolution data was used; however, there are some periods where hourly data represents the highest resolution available. These data largely occur at the transition period between paper recorders and digital data loggers (mid-1990s). Many early data loggers were programmed to record at hourly intervals as a result of storage and data transmission limitations. Changes to WSC procedures in the late-1990s resulted in most urban stations being sampled at a minimum 15 minute time interval. While not ideal, the hourly data was considered sufficient to apply the event detection methods introduced herein and no additional action has been taken with regard to these data.

While methods have been proposed to upscale mean daily streamflow data to sub-daily or peak daily temporal resolutions (Sangal, 1983; Fill & Steiner, 2003; Taguas *et al.*, 2008) these methods rely on shape factors and watershed coefficients to distribute mean daily data across triangular or power shape functions. These methods are prone to bias and under predict peaks in small catchments while over predicting peaks in large catchments (Sangal, 1983). While applicable to some catchments with multi-day events, these methods are wholly inappropriate for urban systems with events that may last only hours (Fill & Steiner, 2003). While briefly considered, no effort was made to upscale pre-1969 daily flow data.

3.2.1 Limitations and Uncertainty

There are gaps in the period of record at most urban stations. This may be a result of damage to the gauge due to flooding, relocation due to channel modification, or budgetary restrictions. Gaps in the period of record are a reality of field collected hydrometric data. Regardless, both the daily and instantaneous datasets were treated as continuous from 1969 to 2009 where possible.

In general, instantaneous streamflow data is not available for periods of ice or extreme backwater conditions. The stage-discharge relationship for a given hydrometric station is developed from many field measurements usually taken during periods of open or free flow, this relationship is therefore invalid during winter ice conditions. A number of techniques exist with which to estimate the under ice discharge, typically a daily mean discharge is estimated from the continuous water level and applicable field observations (Walker & Wang, 1997; Environment Canada, 1999b). Owing to the detailed and manually intensive nature of these computations, the instantaneous discharge hydrograph historically has not been corrected for ice conditions by WSC. As such, the instantaneous discharge data series is rarely continuous for most stations within the gauging network. Extreme backwater conditions due to vegetation or extreme flooding are also responsible for gaps in the instantaneous discharge hydrograph. The duration of the gaps vary from year to year and are affected by seasonal weather patterns and catchment land use. All mean daily values influenced by backwater are flagged within the HYDAT database. Daily discharge values calculated from estimated or assumed water levels are also flagged, there is rarely valid instantaneous data in these circumstances.

Table 3.2 summarizes the available mean daily and instantaneous hydrometric data for the period of instantaneous record (1969 to 2009). As daily mean data represents the official WSC product, daily mean data is available for every day of instantaneous record. The backwater ratio is a comparison of the missing gaps in instantaneous record to the total available daily record. The backwater ratio is not a measure of quality, rather it serves as a quick indicator of the length of record impacted by ice or vegetation events.

Table 3.2: Length of Hydrometric Record

StationID	**Station Name**	**Days of Average Daily Data**	**Days of Instantaneous Data**	**Backwater Ratio**
02HC019	Duffins Creek above Pickering	14643	10625	27%
02HC009	East Humber River near Pine Grove	14975	10211	32%
02HB004	East Oakville Creek near Omagh	14975	10638	29%
02HB005	Oakville Creek at Milton	14595	11421	22%
02HB013	Credit River near Orangeville	14975	13143	12%
02GA024	Laurel Creek at Waterloo	12382	10420	16%
02HA014	Redhill Creek at Hamilton	9373	7827	16%
02HC027	Black Creek near Weston	14975	12338	18%
02HC017	Etobicoke Creek at Brampton	11114	8175	26%
02HC030	Etobicoke Creek below QEW	14975	10956	27%
02HC033	Mimico Creek at Islington	14454	11566	20%
02HC005	Don River at York Mills	12067	10289	15%
02HC029	Little Don River at Don Mills	10109	8566	15%
02HC024	Don River at Todmorden	14975	14496	3.2%
02HC022	Rouge River near Markham	14463	11263	22%
02HC013	Highland Creek near West Hill	11609	8053	31%
02HD013	Harmony Creek at Oshawa	10490	7904	25%

The uncertainly within published daily streamflow data is difficult to precisely quantify. The relative quality of the data, or the uncertainty within the dataset, cannot be considered uniform through the full period of record. The attention to variations in rating curves, seasonal shifts due to ice or vegetation, equipment maintenance, and data verification will vary both spatially and temporally throughout the gauging network. It is difficult to estimate accuracy of a given stage-discharge curve, several authors report a discharge measurement uncertainly of 5% at the 95% confidence interval (Terzi, 1981; Herschy, 2002). Open water discharge measurements obtained by the WSC are typically fitted to within a 5% window, under ice measurements to within a 10% window (Hamilton & Moore, 2012). Hamilton (2008) observes that this uncertainty cannot be assumed to be uniform across the entire range of possible discharges. He further identified that the uncertainly in small discharges and velocity measurements may be high due to unavoidable limits on the scales and dimensions of available measurement equipment. Further uncertainty is associated with the estimated mean daily discharge values that are approximated without stage data. The actual uncertainty of flagged data is incalculable, and occurrence of estimated values in low flow statistics is about 50% more frequent than the national mean daily dataset (Hamilton, 2008).

No researchers have directly considered the uncertainty within the instantaneous dataset. Ideally, the error can be considered similar to that of the open water discharge measurements - 5%; the assumed error in the mean daily dataset. In urban streams however, hysteresis produced by unsteady flow conditions during flood events may introduce further uncertainty (Lindner & Miller, 2011). The constantly changing bed forms observed in some urban streams (Konrad & Booth, 2002; Annable *et al.*, 2012) can also affect the stage-discharge relationship, requiring many shift corrections by experienced technicians to ensure accuracy. Measurement resolution is also important; with events lasting only hours high resolution data are required to accurately characterize an event. Better understanding the uncertainty of the instantaneous dataset is an area requiring further research.

3.3 Event Parsing Algorithm

The instantaneous hydrometric data provided by WSC offers a significantly higher temporal resolution than mean daily dataset. This increased resolution allows individual storm events to be identified on the hydrograph. A computer code was developed to determine the start and end of each event in addition to determining pertinent hydraulic characteristics from basic assumptions about shape and form of a storm event hydrograph. Key assumptions include: that the hydrograph is positive at all times, all storm events within a catchment have a minimum duration and minimum detectable peak, and all events will gradually recede to a predictable minimum discharge in the absence of further precipitation. An identified event is considered to be over when the discharge drops below 25% of observed primary peak discharge; a subsequent increase in flow would signal the start of a new event. The resulting algorithm makes use of watershed specific constants to parse peaks and valleys observed on the time series hydrograph into storm events.

An event parsing algorithm was written in Visual Basic .NET (Appendix B) to identify pairs of valleys in the time series data. Peaks and valleys are identified as inflection points, or local minima, in the first derivative of the time series, the point at which the sign of the derivative changes from positive to negative or vice versa. The algorithm then recursively searches between the found valleys for peaks of significant magnitude. If the observed peak discharge between each pair of valleys exceeds a prescribed threshold the hydrograph bound by the valleys is taken as an event. By searching recursively between pairs of found valleys, all the individual events that exceed the threshold can be identified. Events are considered over when the event hydrograph drops below 25% of its observed peak relative to the discharge at the start of the event; this criteria establishes when the algorithm will consider the next detected peak as a separate event, and is required to parse separate events that occur close together. The primary (largest) peak discharge is also distinguished from any secondary peaks which may occur during an event. Figures 3.6 and 3.7 illustrate the algorithm as applied to a typical urban hydrograph.

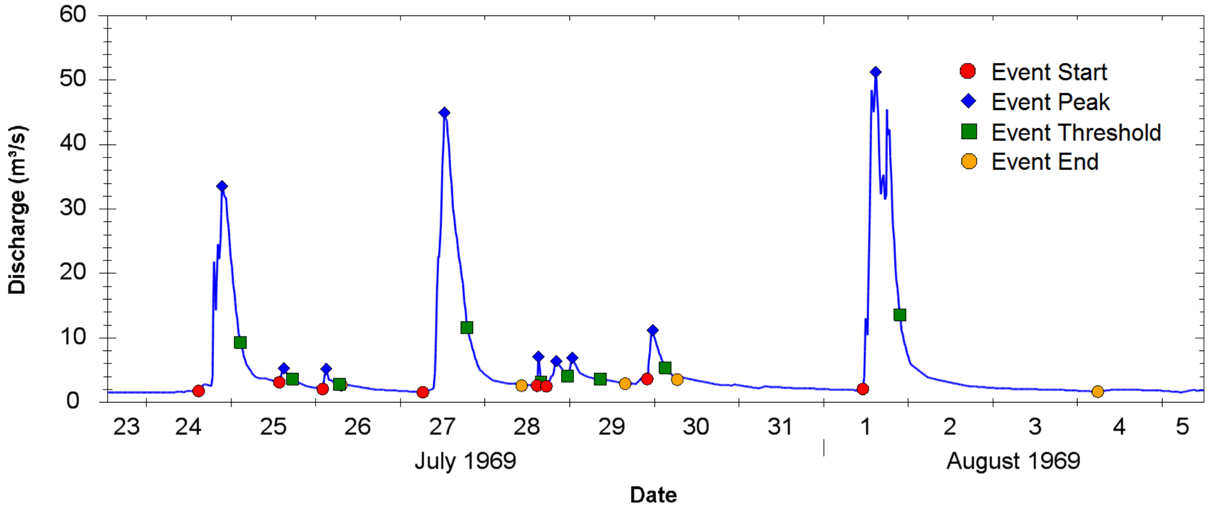

Figure 3.6: Typical Event Trace - Daily Scale (Don River at Todmorden - 02HC024)

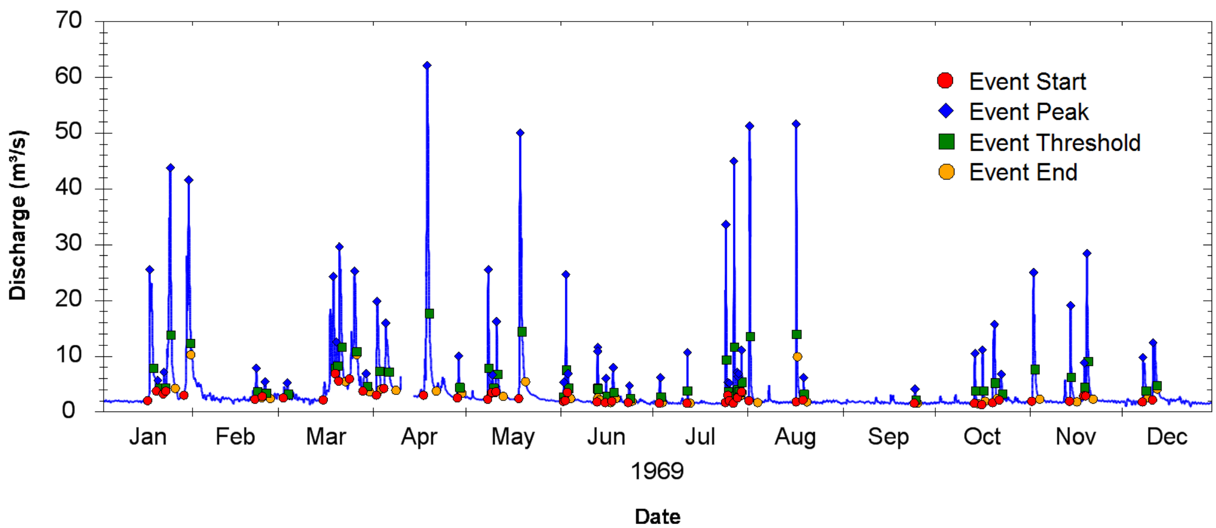

Figure 3.7: Typical Event Trace - Monthly (Don River at Todmorden - 02HC024)

Event definition is largely controlled by the selection of the minimum peak threshold. This absolute value determines the threshold at which the algorithm will either flag or ignore a found peak. If the threshold is set too high, the algorithm may ignore an actual event. Conversely, if the threshold is set too low noise, sensor resets, or minor inflections in the falling limb event would be incorrectly identified as an event. It should be noted that some events which are the result of precipitation in the upper portions of watersheds may not result in any discernible change in discharge at the gauging station. It also follows that some of these small events may cause a measurable but insignificant increase in discharge at a gauge station. Undoubtedly some events are missed when setting a minimum peak threshold, however, the total number is assumed to be minor. Future work may prevent the need to set a peak threshold by comparing the identified event with observed rainfall, however, this is beyond the scope of this study. Figure 3.8 illustrates identified event peaks at an urban station, note the incomplete record during the winter months and the exclusion of some small events.

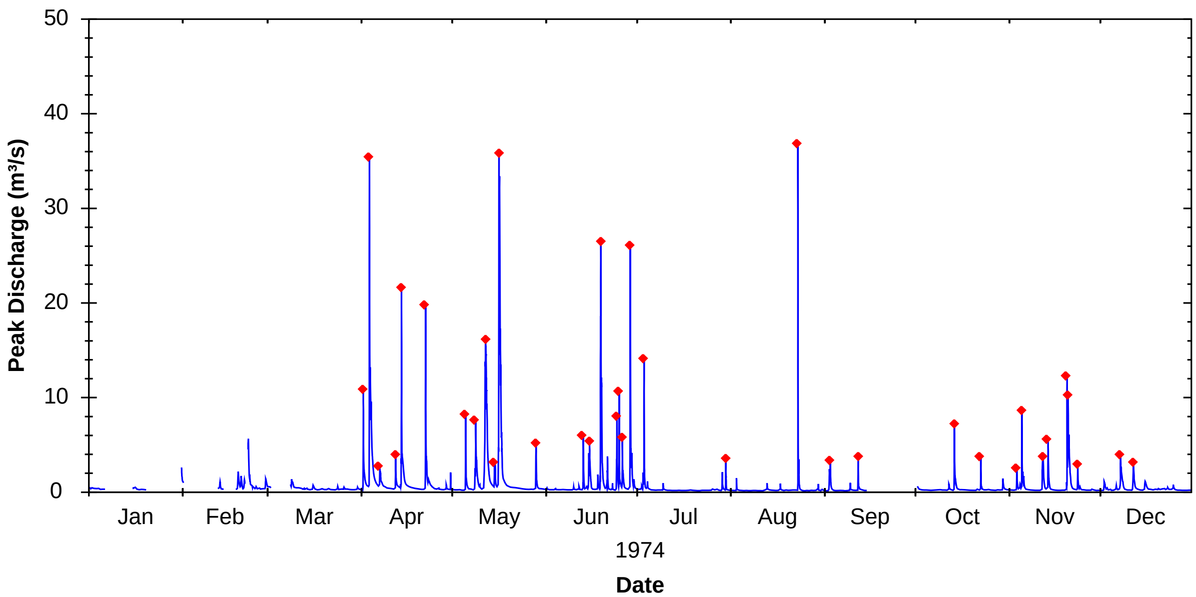

Figure 3.8: Identified Event Peaks (red) at Black Creek near Weston (02HC027)

The minimum peak thresholds employed by the algorithm at the study catchments are presented in Table 3.3. Several other, less critical thresholds are incorporated into the event parsing algorithm. Six points are required to define an event, from valley to valley, conceptually from the event start to the bottom of the falling limb. This requires an event duration of greater than 1.5 hours with 15 minute data. In signal processing terminology, this acts as a minimum amplitude threshold. If an identified event is missing more than 10 data points (effectively 2.5 hours of hydrograph) the event is discarded. In addition, the algorithm requires that a precision value be prescribed to identify noise. This threshold ensures minor variations in discharge at high flows are not misidentified as an event. A value of 0.00105 m^3/s was sufficient for the stations in this study, numerically slightly greater than smallest significant digit of the WSC dataset (Appendix A). The nature of the instantaneous streamflow dataset can present difficulties when applying automated methods. Several approaches to smooth the data were tested in the course of developing the event parsing algorithm. Experimental testing identified that some catchments may be noisy to the point where the parsing algorithm cannot reliably identify the event endpoints or isolate an appropriate peak. The use of a constant to define the minimum available precision of the data was ultimately employed as opposed to direct smoothing the data. While appropriate for the data employed in the study catchments, this may be insufficient when attempting to apply event parsing algorithms to larger, less flashy stream systems.

Table 3.3: Minimum event peak thresholds for parsing algorithm

StationID	**Station Name**	**Area (km^2)**	**Peak Threshold (m^3/s)**	**Type**
02HC019	Duffins Creek above Pickering	93.5	1	Agricultural
02HC009	East Humber River near Pine Grove	197	1	Agricultural
02HB004	East Oakville Creek near Omagh	199	1	Agricultural
02HB005	Oakville Creek at Milton	95.6	0.7	Urbanizing
02HB013	Credit River near Orangeville	62.2	0.5	Urbanizing
02GA024	Laurel Creek at Waterloo	57.5	1	Urban
02HA014	Red Hill Creek at Hamilton	56.3	2	Urban
02HC027	Black Creek near Weston	58	2	Urban
02HC017	Etobicoke Creek at Brampton	63.2	0.5	Urban
02HC030	Etobicoke Creek below QEW	204	1	Urban
02HC033	Mimico Creek at Islington	70.6	0.7	Urban
02HC005	Don River at York Mills	88.1	0.7	Urban
02HC029	Little Don River at Don Mills	130	0.7	Urban
02HC024	Don River at Todmorden	316	2	Urban
02HC022	Rouge River near Markham	186	2	Urban
02HC013	Highland Creek near West Hill	88.1	0.7	Urban
02HD013	Harmony Creek at Oshawa	41.6	0.5	Urban

Table 3.4 summarizes the number of detected events at each of the study catchments during the period of record (1969-2009). The normalized number of events is also presented; approximately 1.2 events per week of data were detected in the urban gauges versus 0.4 events per week in the agricultural. This is to be expected as paved, well-drained, impervious watersheds will route rainfall from the upper reaches of the catchment more quickly and efficiently than a rural or agricultural catchment resulting in an identifiable peak at the stem.

Table 3.4: Total number of detected events per station (1969-2009)

StationID	**Station Name**	**Number of Detected Events**	**Number of Detected Events per Week of Data**	**Type**
02HC019	Duffins Creek above Pickering	780	0.5	Agricultural
02HC009	East Humber River near Pine Grove	596	0.4	Agricultural
02HB004	East Oakville Creek near Omagh	659	0.4	Agricultural
02HB005	Oakville Creek at Milton	1433	0.9	Urbanizing
02HB013	Credit River near Orangeville	682	0.4	Urbanizing
02GA024	Laurel Creek at Waterloo	1100	0.7	Urban
02HA014	Redhill Creek at Hamilton	1040	0.9	Urban
02HC027	Black Creek near Weston	1846	1.0	Urban
02HC017	Etobicoke Creek at Brampton	1241	1.1	Urban
02HC030	Etobicoke Creek below QEW	2177	1.4	Urban
02HC033	Mimico Creek at Islington	1435	1.3	Urban
02HC005	Don River at York Mills	1789	1.2	Urban
02HC029	Little Don River at Don Mills	2049	1.7	Urban
02HC024	Don River at Todmorden	2816	1.4	Urban
02HC022	Rouge River near Markham	798	0.5	Urban
02HC013	Highland Creek near West Hill	1992	1.7	Urban
02HD013	Harmony Creek at Oshawa	1460	1.3	Urban

It should be noted that the thresholds employed in this study were selected by trial and error. Many custom visualization tools were created to plot hydrograph data with the results generated by the event parsing algorithm. Careful examination of the outputs of this algorithm are always required to ensure good fit to the observed data.

3.3.1 Limitations

In urban catchments with flashier peaky hydrographs, the above described algorithm performs well. Peaks are large, and falling limbs recede smoothly allowing the algorithm to precisely detect the starting end of an event. In more rural catchments, where events can take days or weeks for a runoff event to fully dissipate, the algorithm performs less ideally. The algorithm as presented, has difficulty parsing individual events from the spring melt events; these multi-day events have multiple staggered peaks and vary in structure significantly from year to year. Dickinson *et al.* (1992) notes in typical rural southern Ontario catchments, most annual streamflow peaks correspond with combined rainfall-snowmelt events. Meltwater and rain on snow freshet events can represent the majority of yearly flow at some stations but cannot be as succinctly characterized as runoff events in urban and domesticated watershed catchments. The above described algorithm was designed and tested for urban hydrographic data and care should be taken when apply the code to rural or more northern stations.

3.4 Hydrograph Variables

Figure 3.9 illustrates a typical event hydrograph and the main set of variables determined subsequent to the definition of each event. The presented variables are chosen to represent hydrologic function as well as define the hydrograph shape.

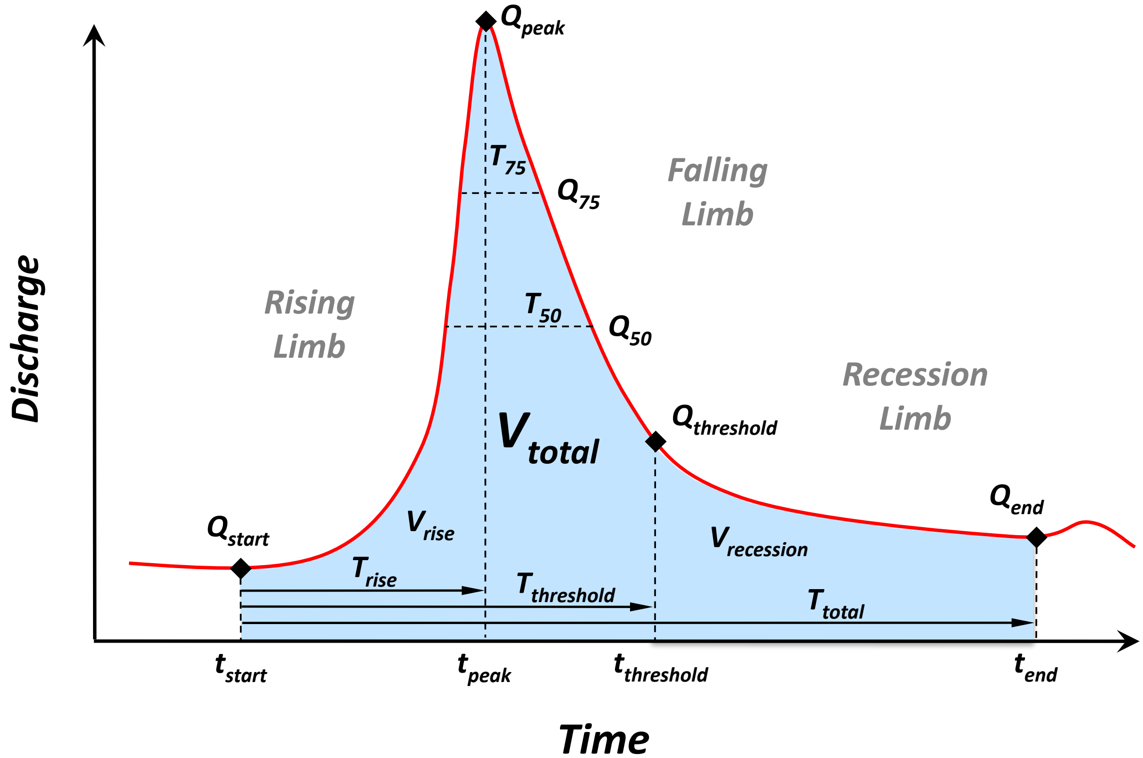

Figure 3.9: Conceptual Event Hydrograph

Where:

Q_{peak} = peak event discharge $[L^3/T]$

Q_{50} = discharge corresponding to 50% of the peak $[L^3/T]$

Q_{75} = discharge corresponding to 75% of the peak $[L^3/T]$

$Q_{threshold}$ = point on the falling limb of the hydrograph where the discharge falls below 25 % of the peak discharge. ($Q_{threshold} = 0.25 \times Q_{peak}$) $[L^3/T]$

Q_{pivot} = inflection point characterizing the end of direct runoff $[L^3/T]$

Q_{end} = the end of the recession phase of the hydrograph, taken as the last point in the falling limb where the discharge is decreasing $[L^3/T]$

V_{rise} = volume of discharge under the rising limb $[L^3]$

$V_{threshold}$ = volume of flow discharged between the event start and event threshold $[L^3]$

V_{total} = volume of flow discharged between the start of an event and the observed end of the recession limb $[L^3]$

T_{rise} = duration spanning the start and peak of an event (Time to Peak) $[T]$

$T_{threshold}$ = duration spanning the start and threshold of an event $[T]$

T_{total} = duration spanning the start of the event and the observed end of the recession limb $[T]$

T_{50} = duration spanning Q_{50} $[T]$

T_{75} = duration spanning Q_{75} $[T]$

$Flashiness$ = peak event discharge Q_{peak} divided by T_{rise} (Time to Peak) $[L^3/T^2]$

$Q_{average}$ = average event discharge (V_{total}/T_{total}) $[L^3/T]$

Time to peak is defined as the duration spanning the start of an identified event to the peak of that same event (Section 3.4). The definition of this parameter is different from the classical hydrological definition where time to peak is defined as the time from the centroid of the rainfall hyetograph to the peak of the stream hydrograph. The rise in stage at an urban gauge can be assumed to correlate closely with the onset of a rain event given the detailed resolution of the instantaneous data. Therefore, time to peak as defined here can be assumed be approximate to the timespan between the start of a rainfall event and the peak of its corresponding runoff event.

The threshold value, which as described above, corresponds to the point on the hydrograph at which the relative discharge recedes to below 25% that of the peak discharge. This parameter is used to aid the event parsing algorithm in separating overlapping events. The choice of 25% was chosen after experimentation with the data from the urban catchments; a higher threshold may be appropriate in rural or northern basins. Figure 3.10 provides an example of how this rule is employed. The two events on July 13 and 14 are separate, as the hydrograph drops below 25% of the relative peak (peak discharge less the initial discharge) of the July 13^{th} event. However, the July 15^{th} event is considered continuous as the discharge during the afternoon never drops below 25% of the relative peak. When comparing the various identified events on this trace it can be observed that variable T_{total}, or the duration of the each total observed event does not represent a consistent period. The duration between the threshold of an identified event to the start of the next is inherently random. This presents problems when comparing certain hydrograph variables. The partial event variables, which describe the hydrograph from its start to the 25% of peak threshold, may be used to compare multiple events, however, this confounds the "threshold" duration with the peak discharge of the found event. Neither set of variables are ideal; the "total" event variables are governed in part by the random duration between events while the "partial" or "threshold" variables are confounded with the peak discharge of the found event. Both will be considered during the subsequent discussion where possible.

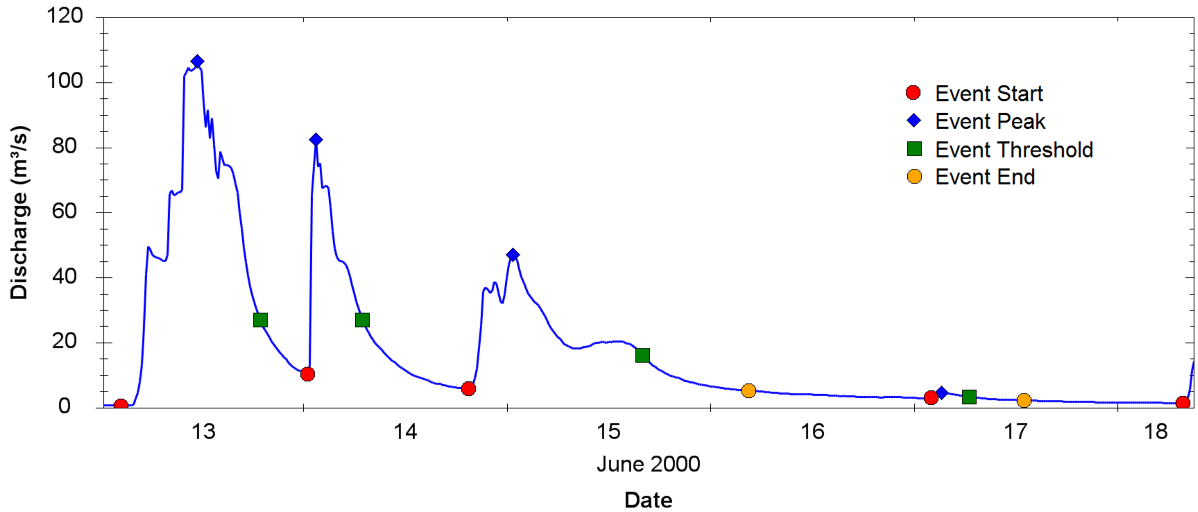

Figure 3.10: Example of overlapping events (Etobicoke Creek below QEW - 02HC030)

Care is required when analysing and comparing event variables, in particular the "partial" or "threshold" variables, as the duration of the event is confounded with the peak of the event. Kenney (1993) cautions that power laws relating two parameters with a common variable may introduce spurious self-correlation and specifically cites normalized peak-runoff volume relationships as possibly spurious. Meroney (1998) expresses further caution about the possible introduction of spurious or "virtual" correlation when conducting dimensionless analysis or when standardizing dimensionless parameters. When considering variables related by power or log-log relationships it is always necessary to consider the spurious case: that no correlation exists between the two original variables. In the spurious case, cross-multiplying by a common variable with the intent to normalize the data can result in a significant correlation. This false correlation, a result of the strong influence of the common variable, serves only to distort the results. Thus, while it may seem rational to attempt to normalize the identified hydrograph variables introduced above by the event peak or volume, extreme caution must be taken not to introduce spurious correlations between confounded variables.

3.5 Aerial Photographic Analysis

To capture the spatial and temporal change in land use due to urbanization an aerial photographic analysis of the urban watersheds was undertaken. This effort attempts to map temporal land use change in urban areas from historical aerial and satellite imagery. Photography spanning a 50 year period was digitized and the urban areas delineated. Detailed land use mapping was used to complement this analysis.

Topographic watershed delineations were obtained from WSC. Where possible, the effective catchment delineations were utilized for the analysis as this coverage more accurately captures the basin area draining to the gauge. Effective watershed delineations developed by Annable *et al.* (2012) for eight of the urban catchments were employed in place of topographic delineations.

The significant time and resources required to digitize, georeference and analyse available air photo records limited these efforts to catchments where significant urbanization had occurred during the period of record (those defined as “Urban” in Section 3.1). While the instantaneous hydrometric data utilized in this study dates to 1969, most of these gauging stations were constructed earlier. All but one of the stations in this study (Don River at York Mills, commissioned in 1945) were constructed after 1950. A comprehensive aerial survey was undertaken in southern Ontario during 1954 and 1955 at a uniform scale of 1 inch = 1 mile (1:63,360). Where possible this survey was obtained and formed a common temporal point of reference between studied watersheds. Air photos were then obtained in 8-10 year increments forward in time to form a detailed spatial and temporal coverage of the study watersheds. The origin, quality, and scale of the coverages varies, but are generally sufficient to map changes to land use over the study period as the study is bounded by the 1954 survey and a modern high resolution (30 cm true colour) orthographic survey undertaken in 2006 (Southwestern Ontario Orthophotography Project, 2006).

Scanned air photos were georeferenced and rubbersheeted (ESRI, 2011) to modern orthography and combined in a raster geodatabase. The urbanized area of each watershed was then delineated for each air photo period. An area was considered urbanized if there was evidence of servicing by catch basins, storm sewer, or other man made drainage. Parks were typically ignored, as were green belts and forest lands. Agricultural lands were not treated as urban and evidence of tile drainage was not considered. Major highways were treated as urban, however regional or county roads which do not have curbs and gutters were ignored. The main focus was to capture anthropomorphic land use change and to quantify well drained urban areas. The attempt was to capture the Effective Impervious Area (EIA) (Shuster *et al.*, 2005) rather than to strictly delineate the impervious catchment area. Figures 3.11 and 3.12 show typical airphoto coverages from 1954 and 2005 respectively with overlain delineated urban areas.

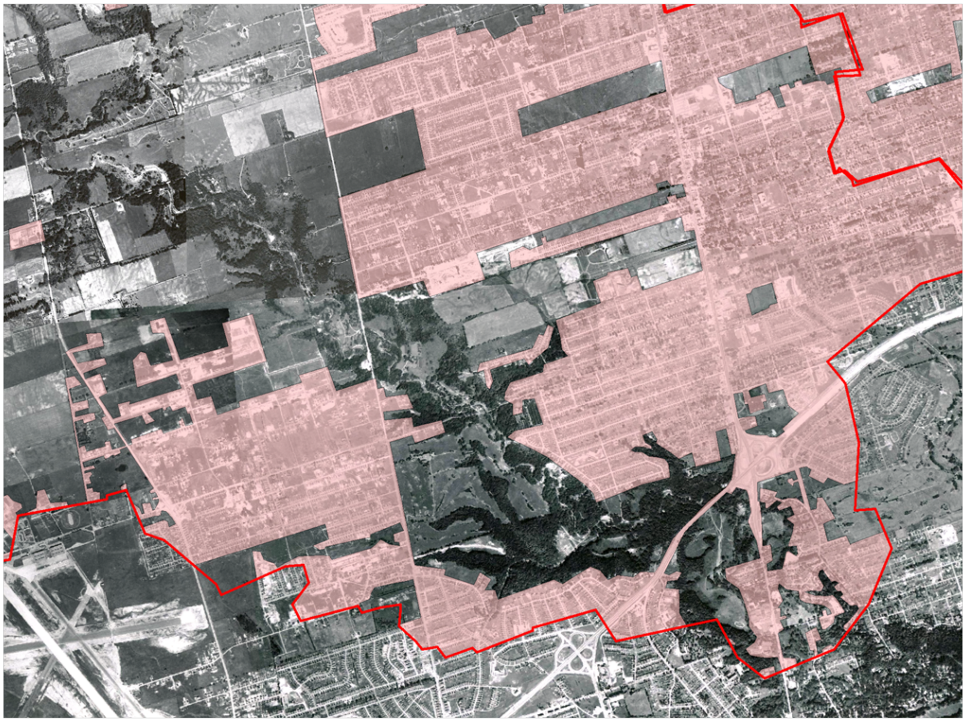

Figure 3.11: Delineated Urban Area (pink) - Upper Don Watershed - 1954

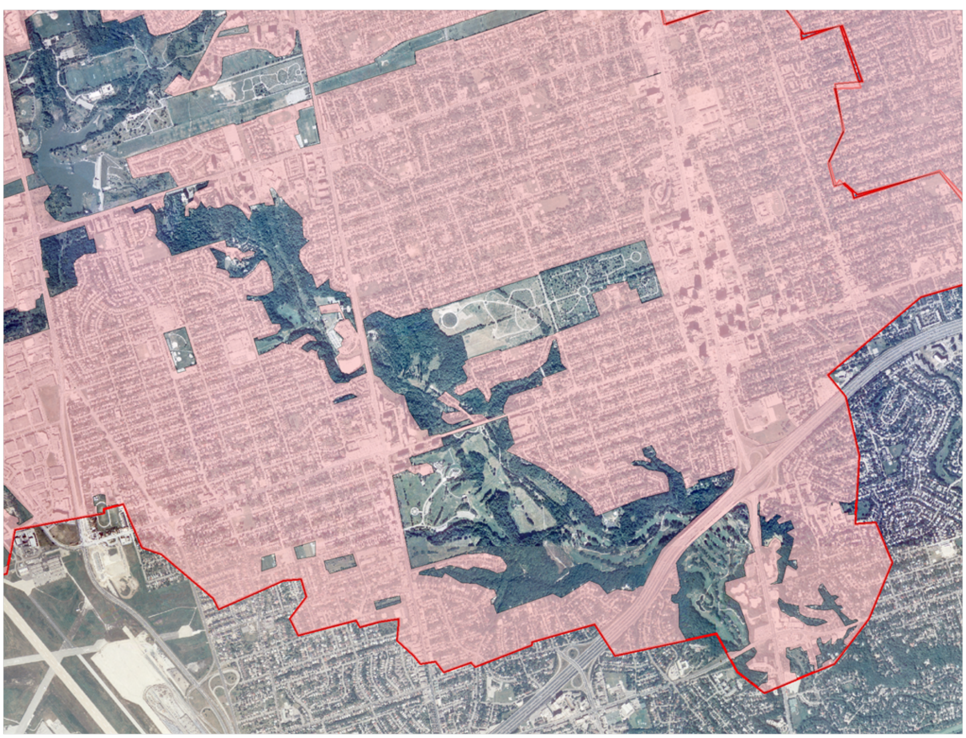

Figure 3.12: Delineated Urban Area (pink) - Upper Don Watershed - 2005

Figures 3.13 and 3.14 show the change in urban land cover and road network expansion respectively over the period of hydrometric record as derived from the air photo analysis. Urban land use and road network coverages are provided in Appendix C for each Urban watershed.

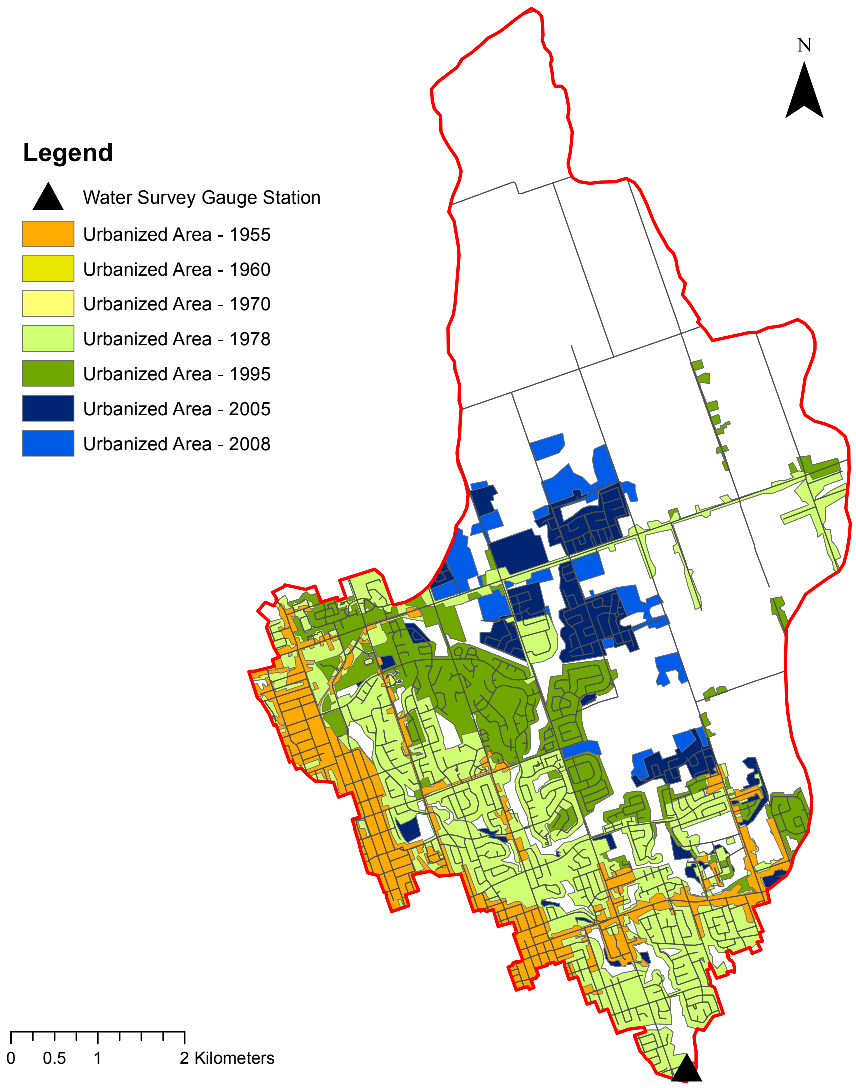

Figure 3.13: Observed urbanization - Harmony Creek at Oshawa (02HD013)

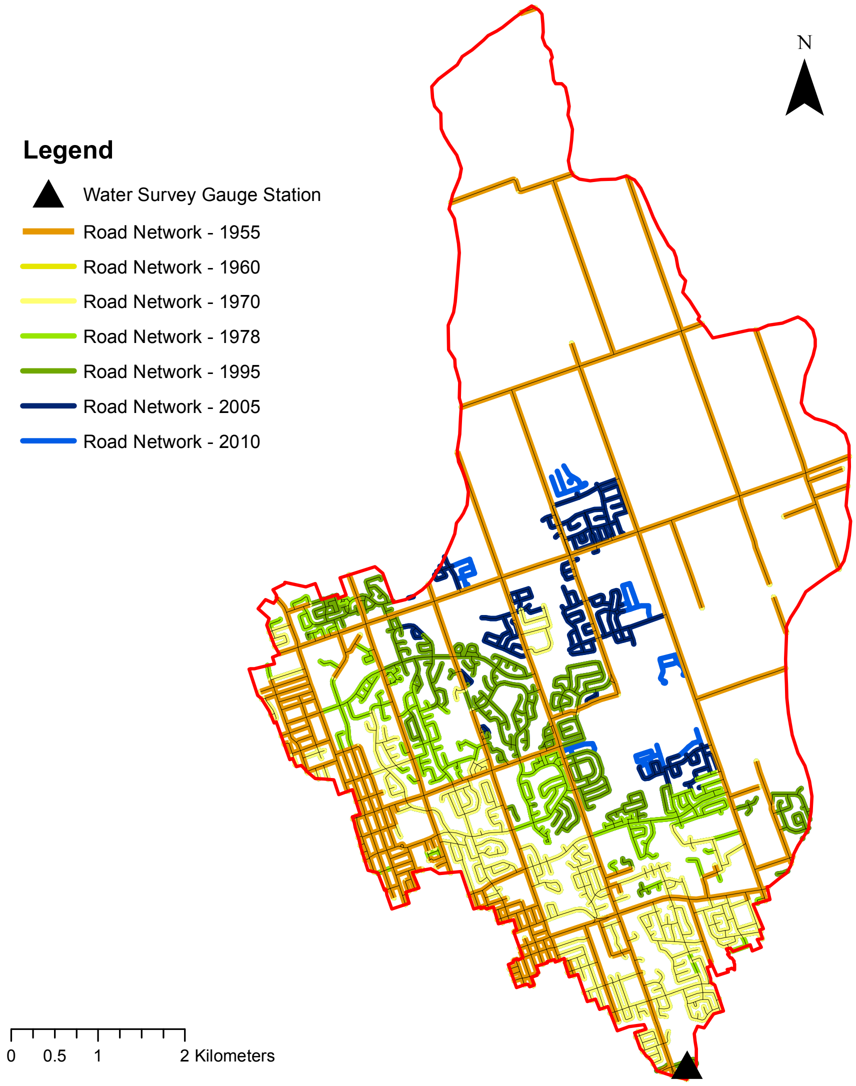

Figure 3.14: Observed road network expansion - Harmony Creek at Oshawa (02HD013)

Delineation of the urbanized area can be subjective, and experience has shown coverages can vary depending on the user. Four individuals were involved in the delineation of the urbanized areas over 3 years. To verify the method, the urban areas were compared to land use coverages obtained from the Southern Ontario Land Resource Information System (SOLRIS). Compiled between 2003 and 2005, SOLRIS is a land use inventory developed from geospatial databases of forests and wetlands, topographic maps, aerial photos, and satellite imagery (Ontario Ministry of Natural Resources, 2008). Figure 3.15 presents the SOLRIS land use coverage for Harmony Creek at Oshawa (some classifications have been merged for clarity). SOLRIS land use mapping is provided for each watershed in Appendix C.

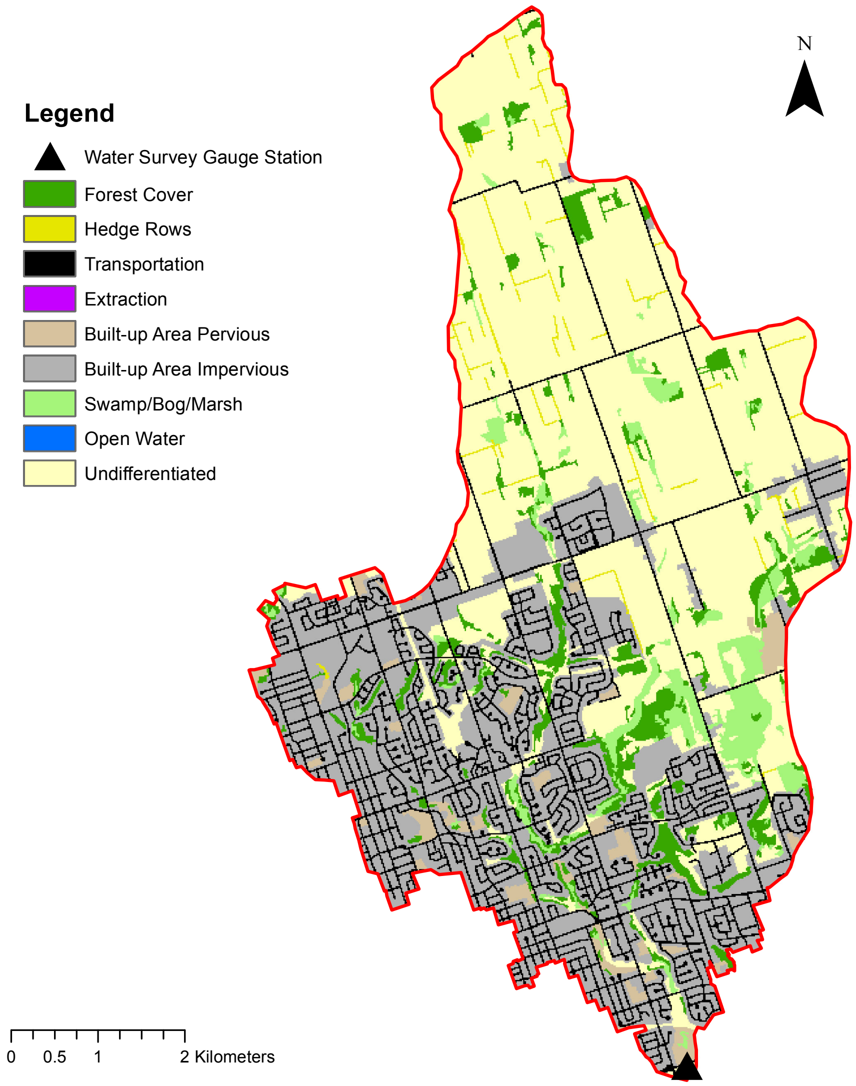

Figure 3.15: Mapped land use (SOLRIS) - Harmony Creek at Oshawa (02HD013)

Table 3.5 summarizes the urban areas delineated by the SOLRIS coverages and provides the interpolated 2005 urban areas as derived from the air photo analysis. Good agreement ($R^2 = 0.98$) is observed between urban areas derived from the two methods (Figure 3.16). As the SOLRIS dataset is derived from remote sensing data, the impervious area identified by this dataset is more closely related to the Total Impervious Area (TIA) rather than the EIA. The close correlation between the photographically derived EIA and the SOLRIS derived TIA suggests that the majority of impervious area within the study catchments is sewered.

Table 3.5: Urban area as delineated by SOLRIS versus aerial photography

StationID	Catchment Area (km^2)	From SOLRIS: Built-up Area Impervious (km^2)	Built-up Area Pervious (km^2)	Roads (km)	Total Urban Area (km^2)	Urban Area from Air Photos (2005) (km^2)
02GA024	58	11	3.2	5.1	20	21
02HA014	56	22	4.6	10	37	35
02HC027	58	38	5.5	13	56	51
02HC017	63	9.4	2.6	4.5	17	13
02HC030	204	105	13	33	151	118
02HC033	71	47	4.0	13	64	60
02HC005	88	48	6.1	14	69	66
02HC029	130	64	8.2	23	95	92
02HC024	316	166	20	56	242	234
02HC022	186	50	14	18	82	67
02HC013	88	57	5.8	18	81	76
02HD013	42	13	1.1	4.8	19	18

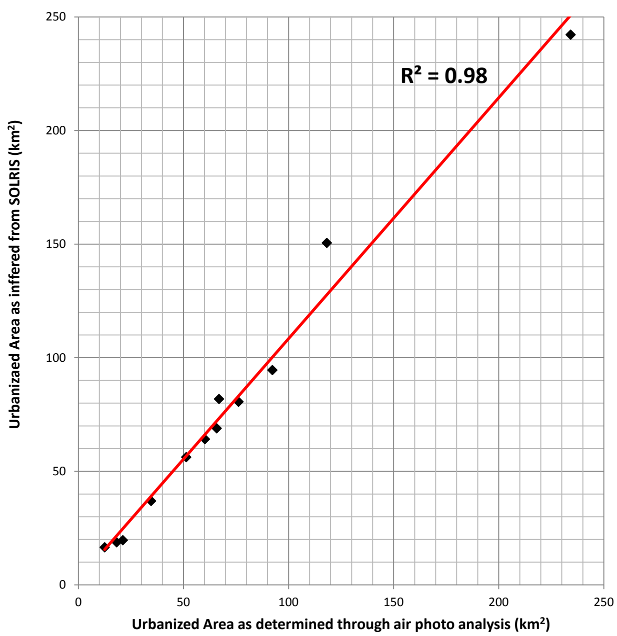

Figure 3.16: Urbanized area delineated by air photo analysis versus SOLRIS (2005)

Total road network length was calculated for each temporal coverage. Figure 3.17 illustrates the relationship between total roadway length and delineated urbanized area. Strong correlation is observed ($R^2 = 0.99$) suggesting a similar road density in the various study catchments, not unexpected due to the conformity observed in Canadian suburban development (McCann, 2006).

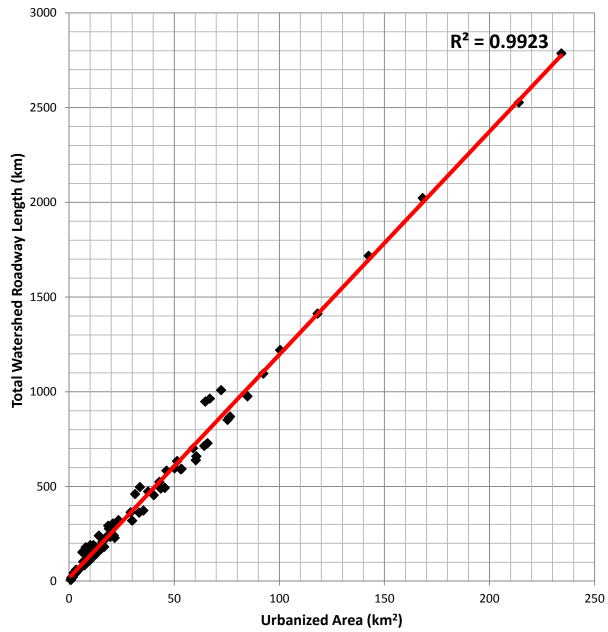

Figure 3.17: Total watershed roadway length compared to urbanized watershed area

3.6 Frequency Analysis

A key assumption in flood frequency analysis is that the parameters that describe the distribution of return probabilities are stationary. This requires parameters such as the mean or variance to be constant with time (Bras & Rodríguez-Iturbe, 1985). As urbanization introduces a systematic variation to the flood record, the assumption of stationarity within the hydrometric record must be discarded. Additionally, as urbanization occurs, serial correlation is introduced to the flood record (McCuen, 2003). Serial correlation (or autocorrelation) is a measure of the similarity between adjacent values of a time series. As a catchment urbanizes, successive floods increase in magnitude, resulting in a correlation between serial peaks. The assumption of independence is a requirement in most parametric statistical techniques (Walpole *et al.*, 2002), and makes fitting an urbanizing flood record to a probability distribution difficult. Cunderlik *et al.* (2007) proposed a method to incorporate event duration as a component within a flood-duration-frequency analysis. By analysing duration as a time dependant parameter, the observed trend can be incorporated into an updated frequency distribution. This approach, however, requires prior identification of, and sufficient data to, extrapolate the trend into the future.

As the event parsing algorithm described above has identified thousands of events within the hydrometric record at some urban stations, it may be possible to approximate the return period of each observed event peak empirically from the event dataset. Graphical plotting-position formulas lend themselves to this problem as the return interval can be estimated from the rank of the already isolated events. Weibull, Generalized extreme value

(GEV), and Cunnane (Cunnane, 1978) plotting positions were investigated. Little change in results were observed between the plotting functions where high frequency events are considered (where the event rank is greater than the length of record); none of the methods are ideally suited for predicting very large magnitude events (McCuen, 2005) as all plotting-positions functions give only crude estimates of the probabilities associated with the largest and smallest events (Maidment *et al.*, 1992). The Weibull plotting-position formula (Equation 3.1) was selected as it provides unbiased probabilities and has been shown to be applicable to describing low flow and partial series probabilities (Gordon *et al.*, 2004) and is often used to derive flow duration curves (Helsel & Hirsch, 2002). When employed, the length of record is considered to span the period between the first and last detected peaks of a given series. Gaps do exist within the instantaneous record, thus some events are not captured in the event dataset during the length of record. These gaps, however, largely occur during low water, and ice conditions when few large events occur. Disregarding the data gaps does bias the recurrence interval upward, however, the downward bias from reducing the length of record to include only days with valid instantaneous data would be more significant. This assumption was tested by experimentation, with the length of record taken both to include or disregard the data gaps. In practice, due to the large number of detected events, results vary little between the two approaches.

$$Recurrence\,Interval = \frac{1}{Exceedance\,Probability} = \frac{Length\,of\,Record + 1}{Event\,Rank} \tag{3.1}$$

The individual events plotted with the Weibull formula must still be independent to properly fit the parametric Weibull distribution. By only considering a small portion of the data series at time, it may be possible to minimize the degree of serial correlation between the event peaks. Additionally, by analysing the data with a moving-window approach, it may be possible to directly estimate the effect of urbanization on high frequency events. Figure 3.18 illustrates a moving window as applied to a series of detected event peaks. The return interval of each event within the window (shown in red) can be calculated with the Weibull plotting-position formula. Events of a specific return interval can then be compared across the entire period of record.

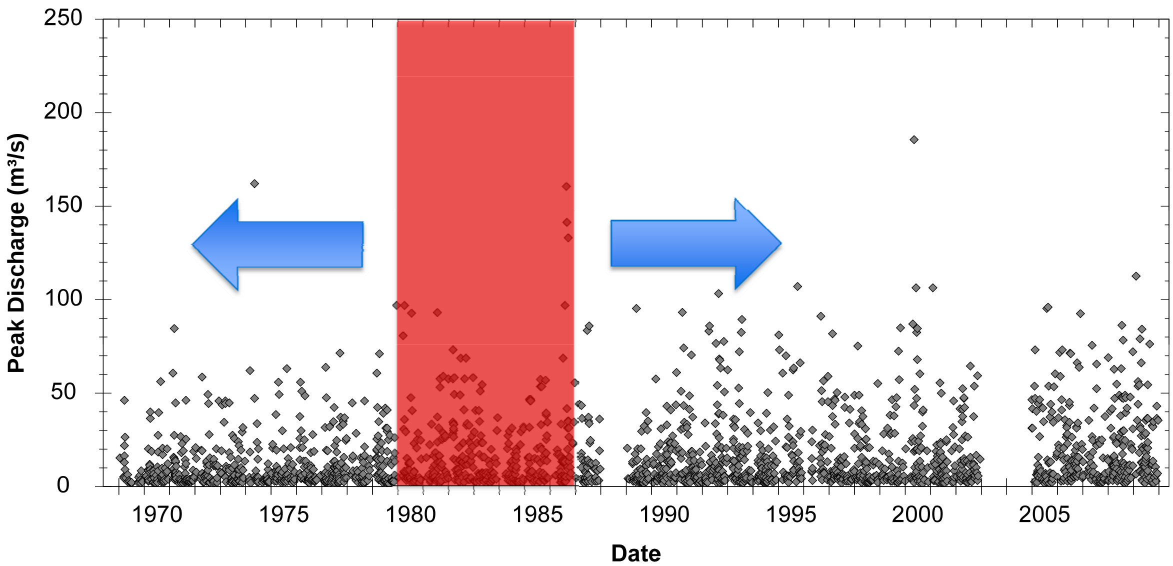

Figure 3.18: 7 Year Moving Window applied to peak event series (Etobicoke Creek below QEW (02HC030)

For each moving-window in the time series, the identified peaks are ranked and a return frequency is determined based upon the Weibull plotting position (Equation 3.1). For example, for a 7-year window, the Weibull function implies that the 8^{th} largest event in a 7 year period represents the 1 year return event. This approach is wholly unsuitable for estimating the return period of large flood events, however, given the number of events detected at the urban station (typically in excess of 250 events per 7 year period) it is assumed to adequately characterize the higher frequency events; a 4-month return interval would be represented by the 24^{th} ranked event. Ideally, the window would be kept as small as possible, however as the window length restricts the observed recurrence interval, a balance must be struck. Several window durations are subsequently presented in the discussion, typically 7- or 10-year. Most analyses were undertaken with several window durations to confirm the presence of trend unbiased by the selection of a specific duration. Changing the window duration will alter the magnitude of the observed trend and the implied uncertainty of the distribution; however, this method may produce insights into how urbanization has altered the frequency response of the study catchments.

Large frequency runoff events have been well characterised within southern Ontario (Sangal & Kallio, 1977; Glaves & Waylen, 1997). Glaves & Waylen (1997) compared a generalized extreme value (GEV) analysis with a partial series analysis conducted by Irvine & Drake (1987) and noted little difference between the predicted magnitude of floods with a return period greater than 4-years. As the GEV plotting function approaches the Weibull formula when considering small recurrence intervals, the exceedance probabilities of events with a return period of approximately 4-years should intersect probabilities calculated from the annual peak series. The Log Pearson III distribution was employed to derive flood return intervals from the annual peak series. The distribution was fitted with the method of moments as per Bulletin #17B standards (Water Resources Council (US), Hydrology Committee, 1981). Outlier removal via the Grubbs' Test and the estimation of regional skewness were implemented as per Bulletin #17B at each of the study catchments. Log Pearson III has been used to estimate flood return intervals in several of the study catchments previously (Annable *et al.*, 2011).

3.7 Mann-Kendall Trend Test

The investigation of the hydrological event variables requires a robust method capable of identifying and determining the statistical significance of trends. As stationarity cannot be assumed (Section 3.6), parametric trend detection methods such as linear regression are not statistically defensible. The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1948) is designed to detect gradual monotonically increasing or decreasing trends within a dataset. The Mann-Kendall has been employed in a number of hydrologic studies within Canada and along the Eastern seaboard of North America (Burn & Hag Elnur, 2002; Ehsanzadeh & Adamowski, 2007; Khaliq *et al.*, 2009; Armstrong *et al.*, 2011; Nalley *et al.*, 2012).

The null hypothesis (H_0) of Mann-Kendall test states that the data are a sample of n independent and identically distributed random values. The alternative hypothesis (H_1) of a two-sided test is that the distribution of x_k and x_j are not identical for all values of $k, j \leq n$ (Hirsch *et al.*, 1982). The Mann-Kendall test statistic S is calculated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sng}(x_j - x_k) \tag{3.2}$$

where the sign function is defined as:

$$\mathrm{sng}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \tag{3.3}$$

A positive value of S indicates an upward trend, while a negative value suggests a downward trend. For samples sizes larger than 10, the test statistic S can be assumed to be normally distributed (McCuen, 2003) with a mean value of 0 and a variance of:

$$Var[S] = \frac{n(n-1)(2n+5) - \sum t(t-1)(2t+5)}{18} \tag{3.4}$$

where t corrects the variance for ties within the dataset. The standardized test statistic Z is comparable to a Normal distribution as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var[S]}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var[S]}} & \text{if } S < 0 \end{cases} \tag{3.5}$$

where in a two-sided test for trend the alternative hypothesis (H_1) is rejected if the value $|Z| \leq Z_{\alpha/2}$. All trends are tested to a 95% significance level (p-value < 0.05) in this study.

Both serial correlation (see Section 3.6) and seasonality within a time series can affect the ability of the Mann-Kendall test to detect a significant monotonic trend (Yue *et al.*, 2003; Khaliq *et al.*, 2009). By parsing each event from the hydrograph, and calculating its constitutive properties such as peak magnitude or storm volume separately, the assumption is made that each event detected in the time series is independent of every other. Figure 3.19 illustrates identified event peaks plotted with the instantaneous hydrograph on a logarithmic scale for a typical urban study catchment. It can be observed that river discharge returns to low flow conditions quickly after a storm event. Reduction in storage and infiltration serve to move water quickly out of the basin, often resulting in a reduction of baseflow. Serial correlation might occur during winter melt events where sustained rain-on-snow produces a series of events with increasing magnitudes, however, warmer winter temperatures and efficient buried drainage networks largely result quick sustained melt events in urban catchments (Buttle, 1990). Serially correlated melt events, if present, will introduce seasonality into the event dataset, which can be addressed by considering only warm weather or convective runoff events. The long period of record (40 years) helps to average out any seasonal effects in the data (Helsel & Hirsch, 2002). Serially sequential storm events may perhaps be the result of a single weather system, but again, these effects are considered to be insignificant when taken over the long period of instantaneous record available.

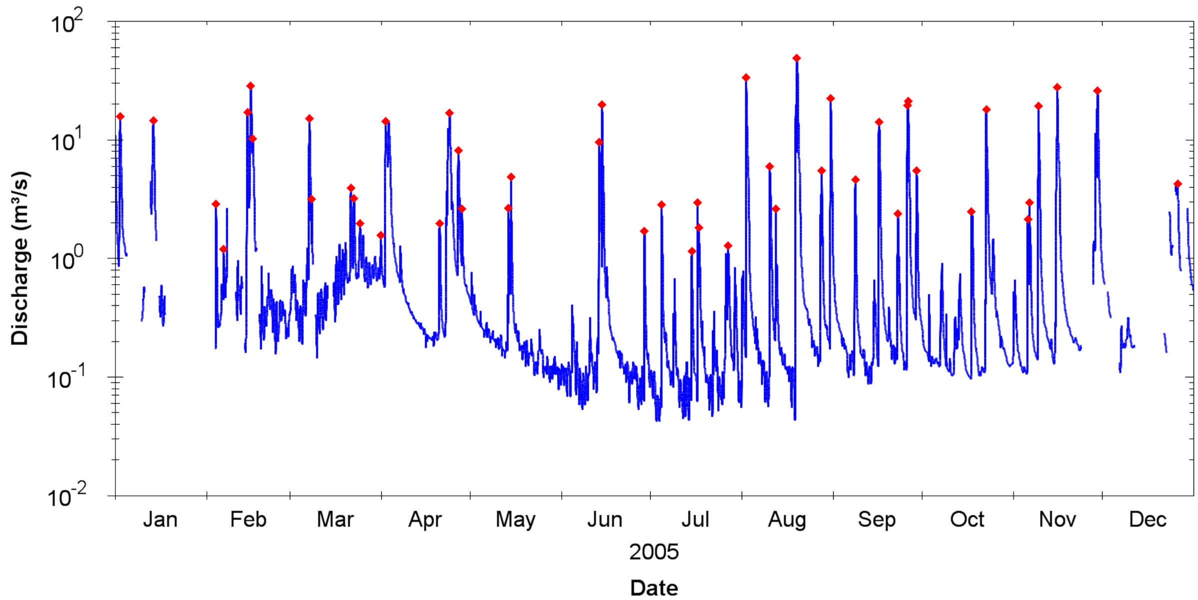

Figure 3.19: Identified Peaks (red) with 15 minute Instantaneous (blue) stream discharge, Mimico Creek at Islington (02HC033)

Serial correlation due to urbanization, however, is still present. Given the scale and magnitude of the impacts of urbanization, significant trends in the identified hydrograph variables are assumed to be the result of local anthropogenic land use changes. While global anthropogenic activities are introducing some change into the hydrologic regime (Cunderlik & Ouarda, 2009; Dickinson *et al.*, 2012), the focus of this approach is to identify impacts of local scale urbanization on runoff events.

3.8 Flow Duration and Exceedance Probability Curves

A Flow Duration Curve (FDC) is an analysis plot that characterizes the probabilistic relationship between magnitude and frequency at a gauge station (Searcy, 1959). Streamflow data (typically daily) is plotted against the fraction of time that the flow rate is equalled or exceeded (the exceedance percentile or probability). The flow duration curve represents an empirical cumulative distribution function of streamflow record at a gauging station (Maidment *et al.*, 1992). Figure 3.20 illustrates a flow duration curve for a typical urban station derived from 40 years of daily streamflow data.

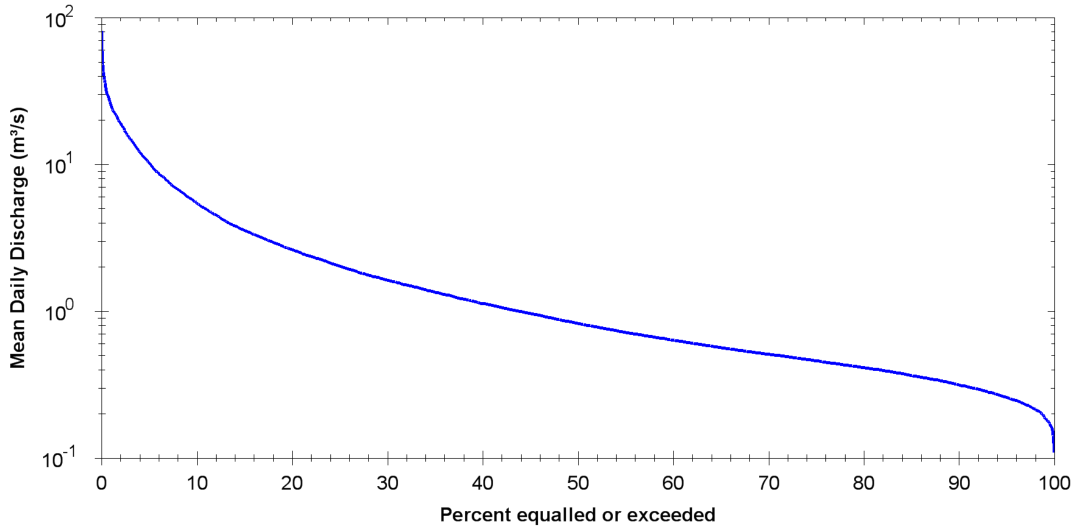

Figure 3.20: Flow Duration Curve, 1969-2009 (Etobicoke Creek below QEW - 02HC030)

Plotting the whole period of record as a flow duration curve effectively removes the influence of autocorrelation from the streamflow data (Vogel & Fennessey, 1994). As the build-out of impervious area with urbanization increases runoff magnitudes, changes to the hydrologic characteristics of the urban watersheds may, however, be evident by analyzing flow duration curves on an annual basis. Figure 3.21 provides a plot of annual flow duration curves at an urban station colourized by year; note the increasing trend in mean daily streamflow with time.

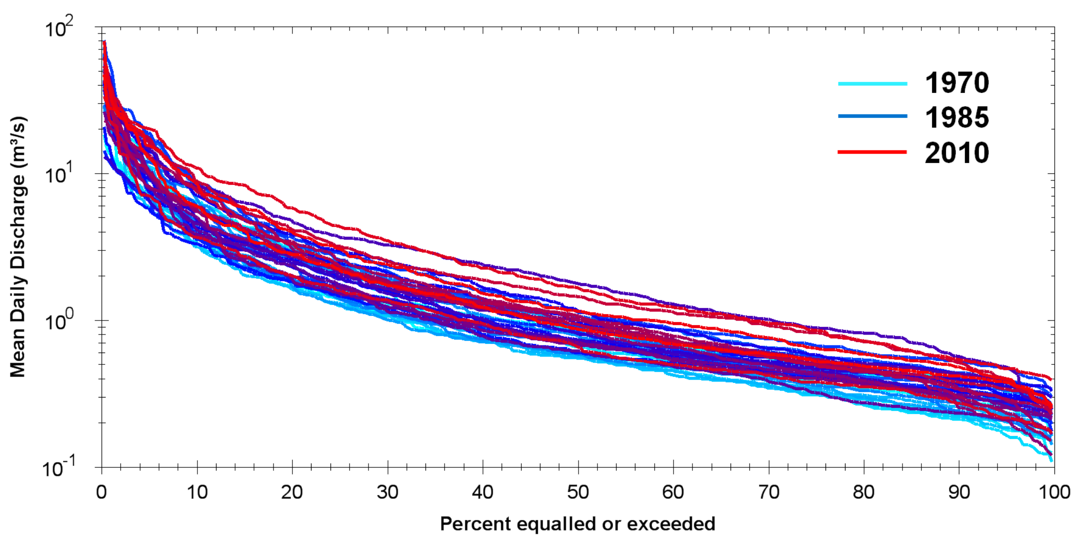

Figure 3.21: Annual Flow Duration Curve (Etobicoke Creek below QEW - 02HC030)

Considering larger periods of data, in consistent temporal intervals, comparable flow duration curves can be developed to isolate long term trends from the data set. By comparing the above presented streamflow data in flow duration curves of 4-year intervals, a clear increasing trend in discharge can be observed with less noise introduced by the natural variability in stream discharge (Figure 3.22). Annual and interval flow duration curves provide a simple graphical tool to examine changes in the hydrologic regime. Specific flow duration quantiles, for example the Q_{10} which describes the flow exceeded 10% of the time, have been suggested to represent thresholds for instream flow requirements (Acreman & Dunbar, 2004), water quality (Annear *et al.*, 2004), and geomorphic stability (Konrad *et al.*, 2005).

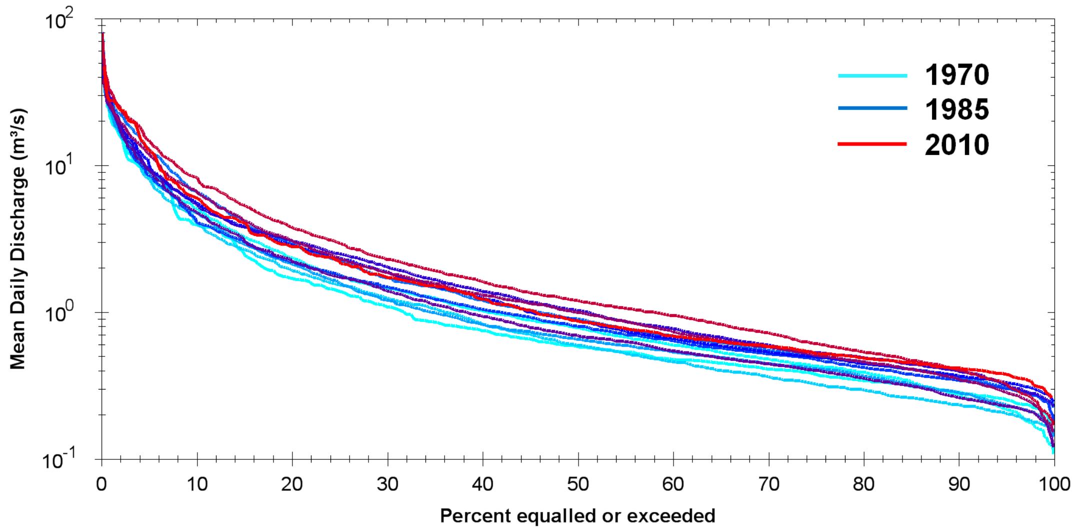

Figure 3.22: Flow Duration Curve - 4-year Moving Average (Etobicoke Creek below QEW - 02HC030)

The instantaneous hydrometric data is not continuous, or consistent in record length from year to year, this makes producing comparable annual flow duration curves with this difficult. However, the identified event peak discharge values can also be ranked and plotted against exceedance probability (Figure 3.23). This approach effectively produces plots of the cumulative Weibull distribution (Section 3.6) for the range of event peaks identified in each interval.

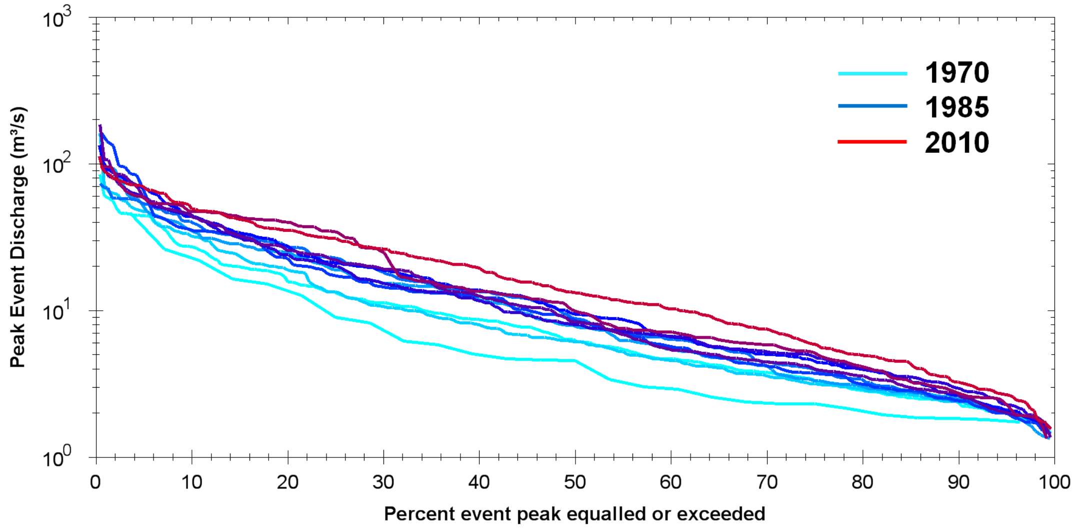

Figure 3.23: Peak Runoff Exceedance Curve - 4-year Moving Average (Etobicoke Creek below QEW - 02HC030)

The concept of the Exceedance Probability Curve (EPC) can be extended to other hydrographic variables as defined in Section 3.4. For example, Figure 3.24 presents total event volume exceedance probability curves computed on 4-year intervals at an urban station. These curves suggest that total event volumes for large storms have decreased with time while volumes for smaller events have increased; logical when considering large events will be intercepted by storm management systems while smaller events will generate more runoff due to an increase in impervious area. This approach allows the change in the estimated cumulative distribution function for each hydrograph variable to be analyzed as the study watersheds urbanize.

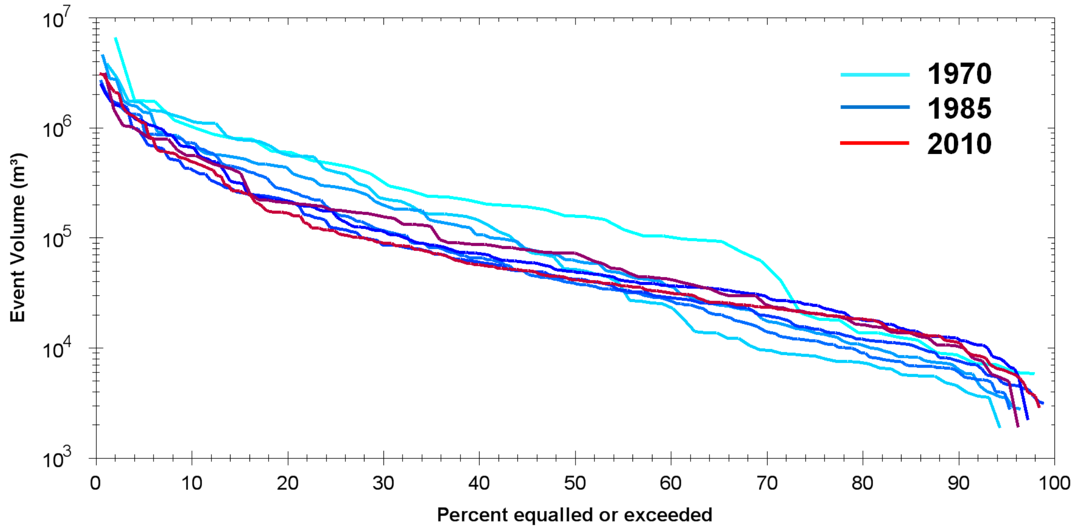

Figure 3.24: Event Volume Exceedance Curve - 4-year Moving Average (Etobicoke Creek at Brampton - 02HC017)

Chapter 4

Results

4.1 Event Identification

The event identification methodology presented in Section 3.3 was applied to the instantaneous hydrometric data set. Detected events have been analyzed as two groups. The first includes all events detected in the continuous period of instantaneous record; the second, a subset on the first, which only includes events between May 1^{st} and November 30^{th} of any given year. The need for a subgroup of "warm weather" events are three fold. First, significant gaps may exist in the winter and spring instantaneous record due to ice effects. Selecting a subset of the events helps to remove the effects of seasonality from the dataset. Second, spring snow melt events will induce a hydraulic response of a different nature than the convective storm events that dominate the summer months. Melt events may last days, and contribute substantially to groundwater infiltration (Gordon *et al.*, 2004) whereas summer storm events are characterized by short, intense bursts of streamflow. Thirdly, the event parsing algorithm employed in this analysis has difficulty appropriately parsing spring melt events due to the diurnal nature of melt events. Table 4.1 summarizes the number of events detected in the period of record for each gauge. A normalized number of events per week is produced by comparing the total number of detected events to the length of instantaneous record available (Table 3.2).

Table 4.1: Total number of detected events per station

StationID	Station Name	2008 Urban Area (%)	All Events	Warm Weather Events	Number of Detected Events per Week
02HC019	Duffins Creek above Pickering	>10	780	431	0.5
02HC009	East Humber River near Pine Grove	>10	596	371	0.4
02HB004	East Oakville Creek near Omagh	>10	659	263	0.4
02HB005	Oakville Creek at Milton	>20	1433	953	0.9
02HB013	Credit River near Orangeville	>25	682	302	0.4
02GA024	Laurel Creek at Waterloo	38	1100	827	0.7
02HA014	Redhill Creek at Hamilton	60	1040	721	0.9
02HC027	Black Creek near Weston	78	1846	1337	1.0
02HC017	Etobicoke Creek at Brampton	18	1241	829	1.1
02HC030	Etobicoke Creek below QEW	55	2177	1510	1.4
02HC033	Mimico Creek at Islington	82	1435	972	1.3
02HC005	Don River at York Mills	69	1789	1207	1.2
02HC029	Little Don River at Don Mills	68	2049	1392	1.7
02HC024	Don River at Todmorden	73	2816	1828	1.4
02HC022	Rouge River near Markham	40	798	541	0.5
02HC013	Highland Creek near West Hill	86	1992	1275	1.7
02HD013	Harmony Creek at Oshawa	45	1460	1116	1.3

A correlation between the normalized number of detected events in the study period and the state of watershed urbanization was observed (Figure 4.1). In heavily urbanized watersheds, precipitation from the upper portions of the watershed will reach the gauge more rapidly during a storm event. By contrast, in rural or forest catchments, infiltration and depression storage will retain water, reducing channel flows.

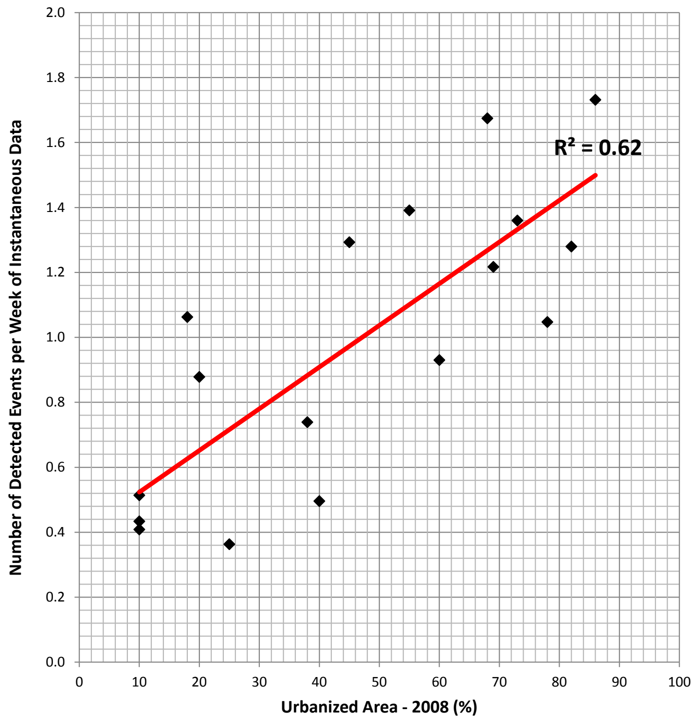

Figure 4.1: Normalized detected events versus 2008 urbanization extent

4.2 Land use, Coverage and Road Network Interpretation

Table 4.2 summarizes the change in urbanized area as determined from the aerial and GIS analysis (Section 3.5). Coverage values corresponding to the start of the instantaneous hydrometric period of record (1969) were interpolated from the temporal observed values. Observed urbanized area in the catchments varies from 1% to 89% for the period of photographic record (1954 onwards). Comparing the aerial analysis to the period of instantaneous stream discharge record (1969 onwards), the observed change in urban coverage varies from 17% to 39%.

Table 4.2: Observed change in urban land use

StationID	**Station Name**	**Catchment Area (km^2)**	**Percent Urban Area (1955)**	**Percent Urban Area (1969)**	**Percent Urban Area (2008)**	**Percent Change (1969-2008)**
02GA024	Laurel Creek at Waterloo	57.5	8	15	38	23
02HA014	Redhill Creek at Hamilton	56.3	12	27	60	33
02HC027	Black Creek near Weston	58	29	55	78	22
02HC017	Etobicoke Creek at Brampton	63.2	-	1	18	17
02HC030	Etobicoke Creek below QEW	204	-	20	55	34
02HC033	Mimico Creek at Islington	70.6	10	43	82	39
02HC005	Don River at York Mills	88.1	15	30	69	39
02HC029	Little Don River at Don Mills	130	9	30	68	38
02HC024	Don River at Todmorden	316	20	43	73	30
02HC022	Rouge River near Markham	186	5	7	40	33
02HC013	Highland Creek near West Hill	88.1	10	47	86	39
02HD013	Harmony Creek at Oshawa	41.6	8	20	45	25

Figure 4.2 shows the temporal change in urban areas (expressed as a percentage of watershed area) for a typical urban watershed, Little Don River at Don Mills (02HC029), derived from the urban coverages. Previous authors (Konrad *et al.*, 2005) have used roadway density (roadway length relative to the watershed area (km/km^2)) as an analogue for urbanization and change in impervious areas. It was observed that the increase in roadway density was directly proportional to the increase in urban area (Figure 4.3). These two parameters are analogues for urbanization, and effectively interchangeable in the study watersheds. A complete breakdown of the urban land use and road network change with time for each watershed is presented in Appendix C. As the two parameters appear exchangeable, change in urban area will be the preferred descriptive variables characterizing spatial urban change in the study catchments.

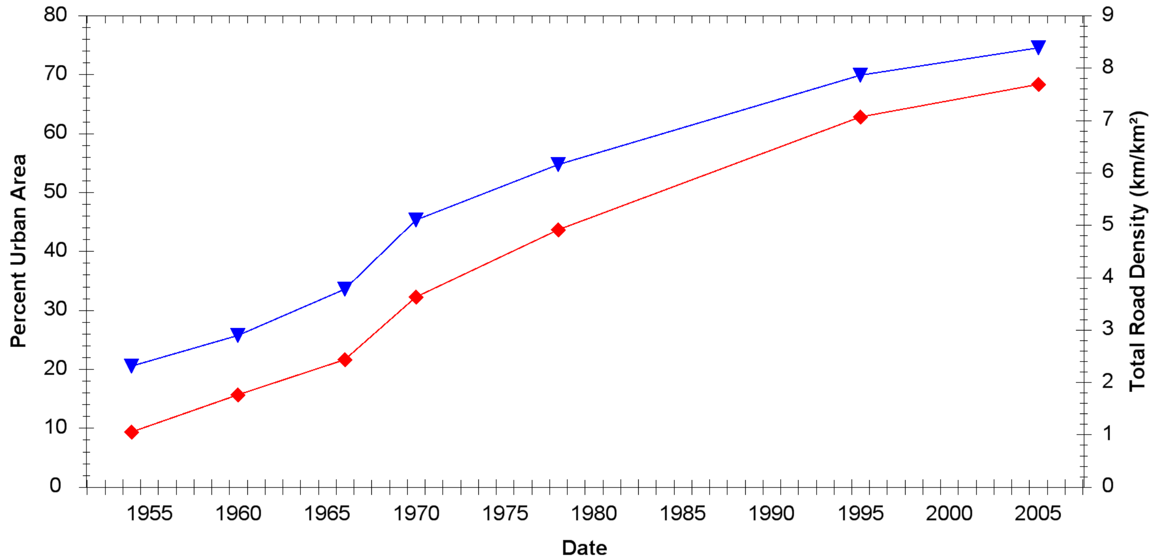

Figure 4.2: 02HC029 - Temporal Change in Urban Area (red) and Road Density (blue)

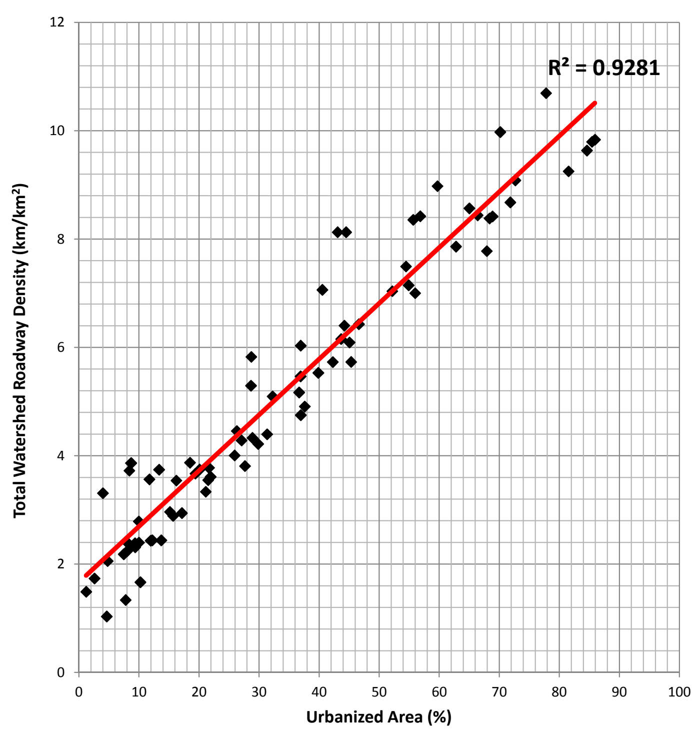

Figure 4.3: Total watershed roadway density compared to percent urban watershed coverage

By characterizing urbanization incrementally through the period of hydrometric record, the change in urbanized area can be substituted for time. Figure 4.4 shows each identified runoff event peak with time for a typical urban watershed (Highland Creek near West Hill; 02HC013). Figure 4.5 presents the same data plotted as a function of estimated urbanized fraction of the watershed. There is a 10 year gap in the instantaneous record at Highland Creek near West Hill (02HC013) as shown on Figure 4.4; however, this corresponds period with little change in land use (Figure 4.5).

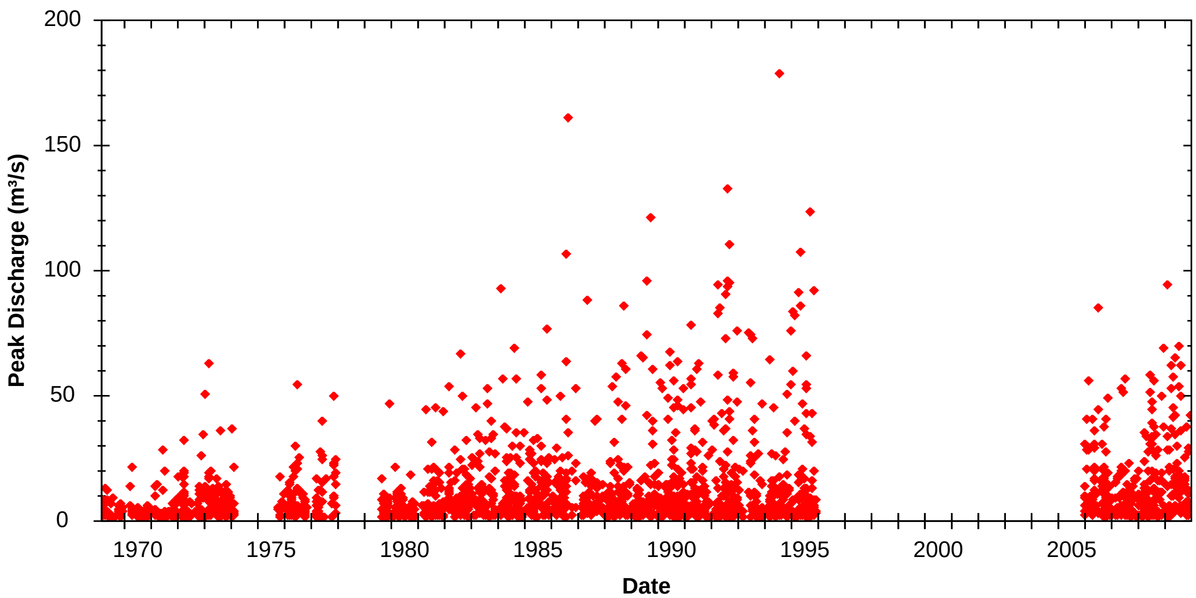

Figure 4.4: Identified Event Peaks at Highland Creek near West Hill (02HC013)

Figure 4.6 presents the above event data averaged in yearly intervals. Average event peaks at the Highland Gauge increased from approximately 4 m^3/s to 15 m^3/s during the period and the urban coverage of catchment increased from 47% to 86%; a clear increasing trend confirmed by the Mann-Kendall test.

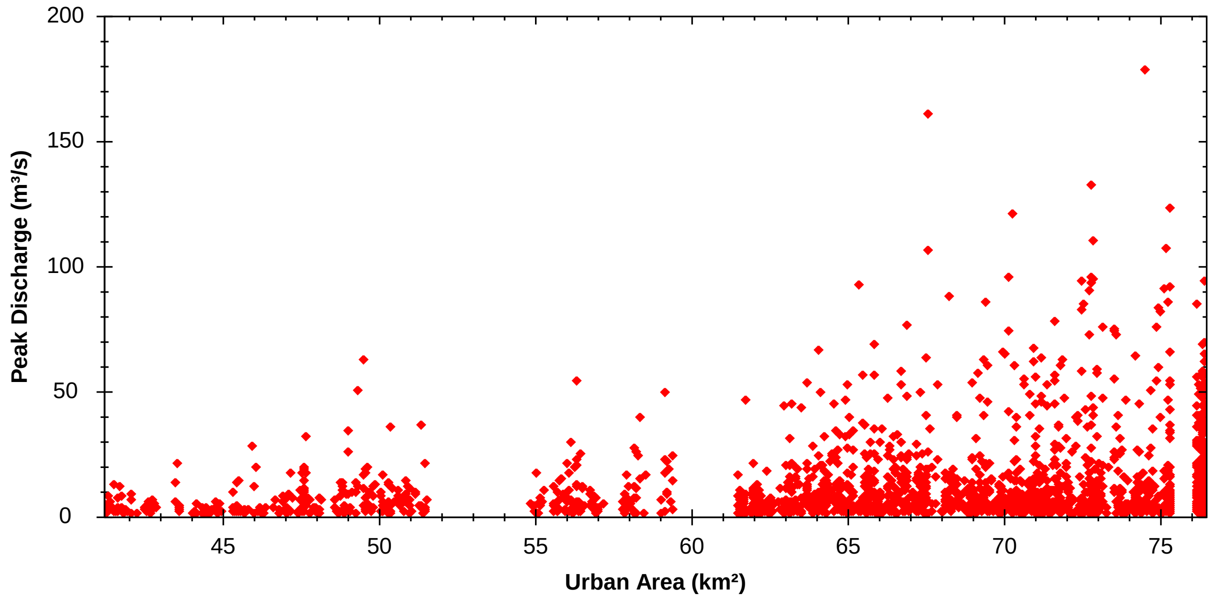

Figure 4.5: Identified Event Peaks at Highland Creek near West Hill (02HC013) with Urbanization

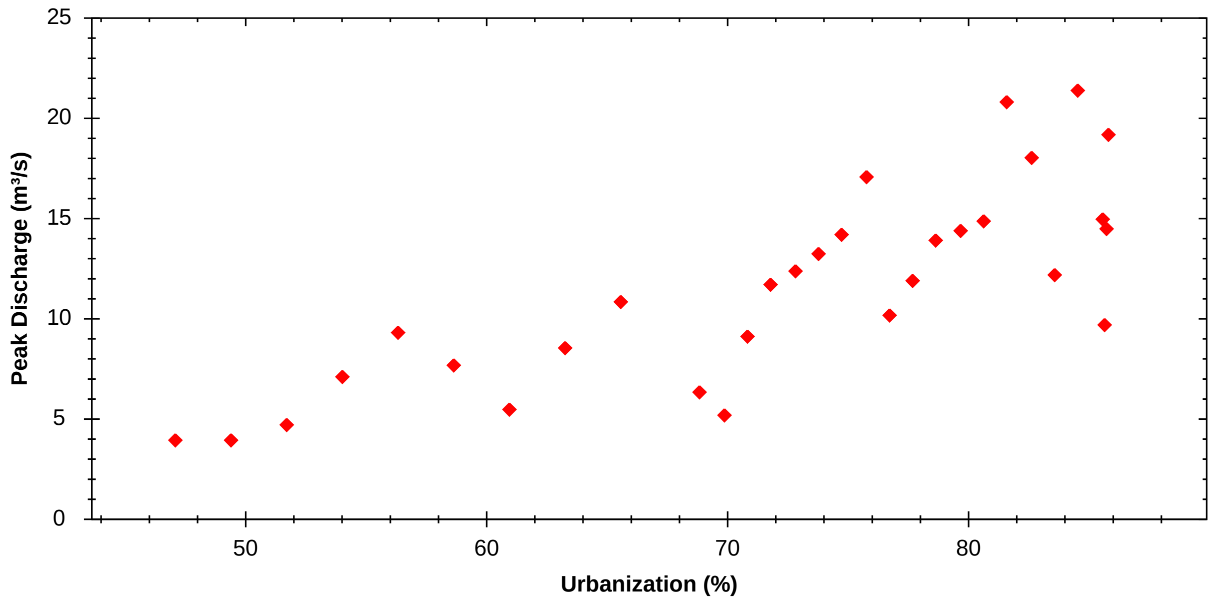

Figure 4.6: Yearly Averaged Event Peaks at Highland Creek near West Hill (02HC013) with Urbanization

4.3 Hydrograph Variable Trend Identification

To better understand the trends in the event dataset, various hydrograph variables described in Section 3.4 were each analyzed for temporal change primarily employing the non-parametric Mann-Kendall test for monotonic trends (Section 3.7). The Mann-Kendall test is applied to the hydrograph parameters as a time series, average yearly plots are provided for some variables for illustrative purposes only as year over year trends are strong enough that averaging all the events in a year produces observable trends. The time interval between data points is not a component of the Mann-Kendall test, the sign function only tests for a relative increasing or decreasing trend in a set of points. Statistically identified trends are valid whether the data are plotted as a time series or a function of urbanization.

4.3.1 Number of Events

As the total number of detected events per year serves as an indicator of the imperviousness of the catchment, it follows that an upward trend in the number of events per year should correspond with urban expansion. Figure 4.7 illustrates the increasing trend in number of detected events per year at Don River at York Mills (02HC005). The Mann-Kendall test confirms an increasing trend at this gauge and six other urban gauges. As years with partial records would skew the trends analysis, only years with more than 200 days of instantaneous record were considered. In addition, the number of events was normalized by the number of days with instantaneous record in each year so as not to bias years with partial records or extensive backwater periods. This increase is not seen at all stations which may be the result of the flashy nature of the previous agricultural land use observed in most of the catchments, geology, or the state of urbanization at the beginning of the period of instantaneous record (1969). Table 4.3 summarizes the observed trends in detected events.

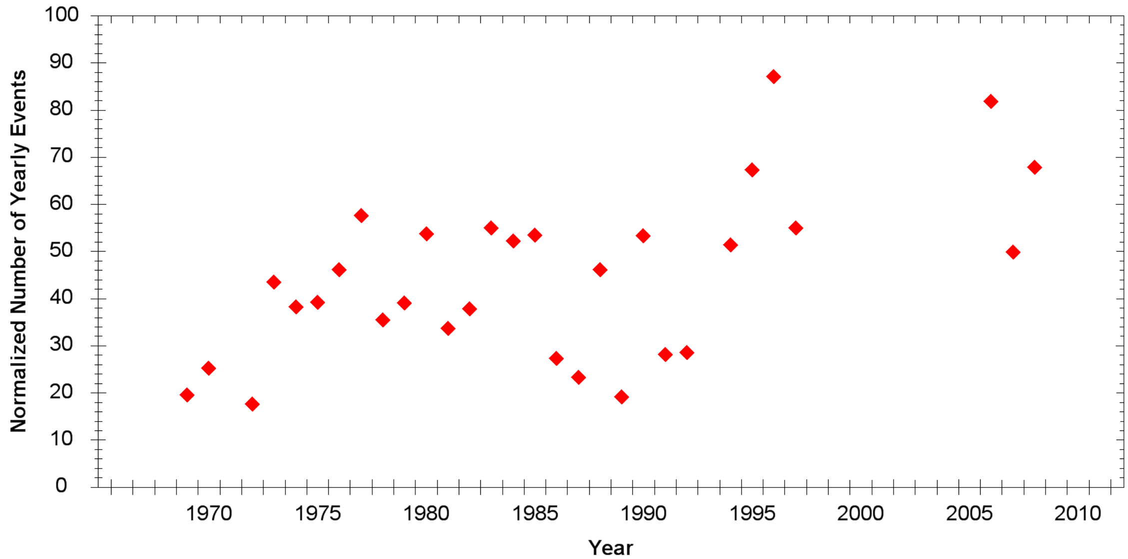

Figure 4.7: Number of Normalized Event Identified per Year at Don River at York Mills (02HC005)

Table 4.3: Detected Trends in Number of Yearly Identified Events

StationID	**Station Name**	**Urban Change (%)**	**Continuous Data Set**
02HC019	Duffins Creek above Pickering	<5	*None*
02HC009	East Humber River near Pine Grove	<10	*None*
02HB004	East Oakville Creek near Omagh	<10	*None*
02HB005	Oakville Creek at Milton	<10	*Increasing*
02HB013	Credit River near Orangeville	<15	*None*
02GA024	Laurel Creek at Waterloo	23	*None*
02HA014	Redhill Creek at Hamilton	33	*None*
02HC027	Black Creek near Weston	22	*None*
02HC017	Etobicoke Creek at Brampton	17	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*None*
02HC033	Mimico Creek at Islington	39	*None*
02HC005	Don River at York Mills	39	*Increasing*
02HC029	Little Don River at Don Mills	38	*Increasing*
02HC024	Don River at Todmorden	30	*None*
02HC022	Rouge River near Markham	33	*Increasing*
02HC013	Highland Creek near West Hill	39	*Increasing*
02HD013	Harmony Creek at Oshawa	25	*Increasing*

4.3.2 Peak

A classically observed trend in urban watersheds is an increase in peak event discharge with time increasing urbanization (Leopold, 1968; Seaburn, 1969; Hollis, 1975). Analysis of the observed peak values for the urban catchments in this study confirms this trend. Figure 4.8 presents yearly averaged event peaks as a function of the urbanized catchment area at Little Don River at Don Mills (02HC029) which increased from approximately 5 m^3/s to 11 m^3/s, a clear increasing trend which is confirmed by the Mann-Kendall test when applied to the total population of events.

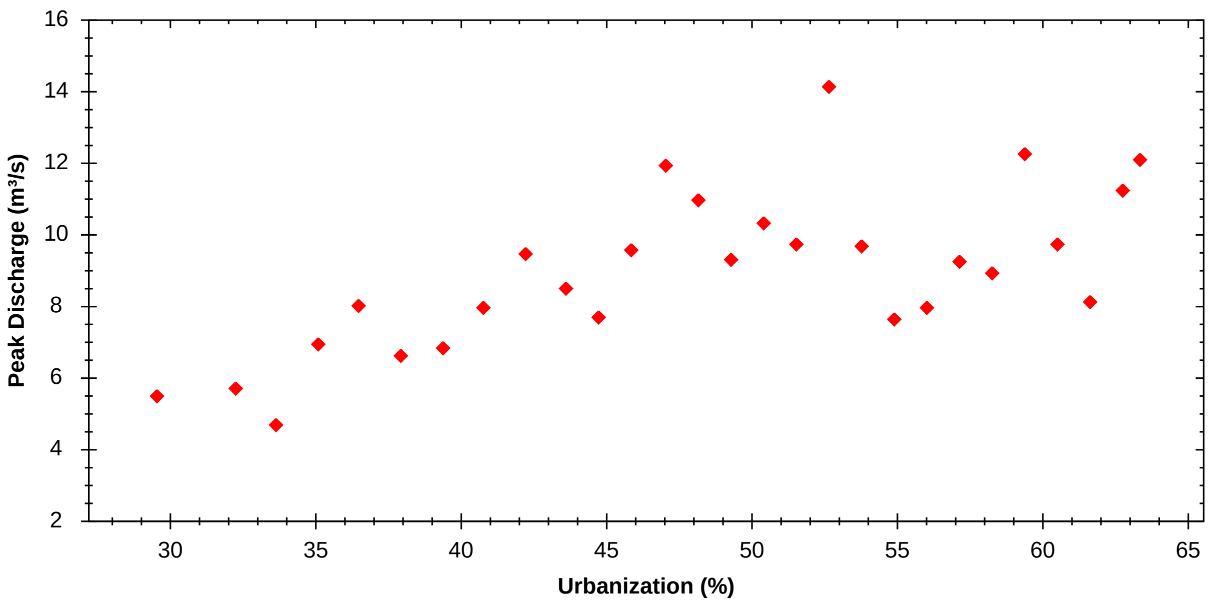

Figure 4.8: Yearly Averaged Event Peaks at Little Don River at Don Mills (02HC029) with Urbanization

Table 4.4 lists the Mann-Kendall trends in event peak at the study gauges. Increasing trends are observed at all but two urban catchments, with increasing trends in warm weather event peaks observed at all stations but Red Hill Creek at Hamilton (02HA014). The exception may be the result of the shorter period of instantaneous record at this gauge (1977-2003), a substantial portion of the upper catchment area being urbanized prior to the installation of the gauge (37% of the watershed was urbanized in 1977). Of note is the control set of rural catchments which show no trend in warm weather event peaks. Decreasing trends are observed at East Humber River near Pine Grove (02HC009) and East Oakville Creek near Omagh (02HB004) suggesting a decrease in observed spring peaks. This may be a spurious result however, as there are gaps in spring instantaneous data at these stations.

Table 4.4: Detected Trends in Peak Event Discharge

StationID	Station Name	Urban Change (%)	Continuous Data Set	Warm Weather Data Set
02HC019	Duffins Creek above Pickering	<5	*None*	*None*
02HC009	East Humber River near Pine Grove	<10	*Decreasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Decreasing*	*None*
02HB005	Oakville Creek at Milton	<10	*None*	*Increasing*
02HB013	Credit River near Orangeville	<15	*Increasing*	*None*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Increasing*	*Increasing*
02HC017	Etobicoke Creek at Brampton	17	*Increasing*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*Increasing*	*Increasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Increasing*	*Increasing*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Increasing*	*Increasing*
02HD013	Harmony Creek at Oshawa	25	*Increasing*	*Increasing*

4.3.3 Time to peak

Figure 4.9 shows the yearly averaged time to peak at Don River at Todmorden, a decreasing trend can be observed. A decreasing trend is expected with urbanization as increased drainage network density and efficiency results in faster runoff (Graf, 1977).

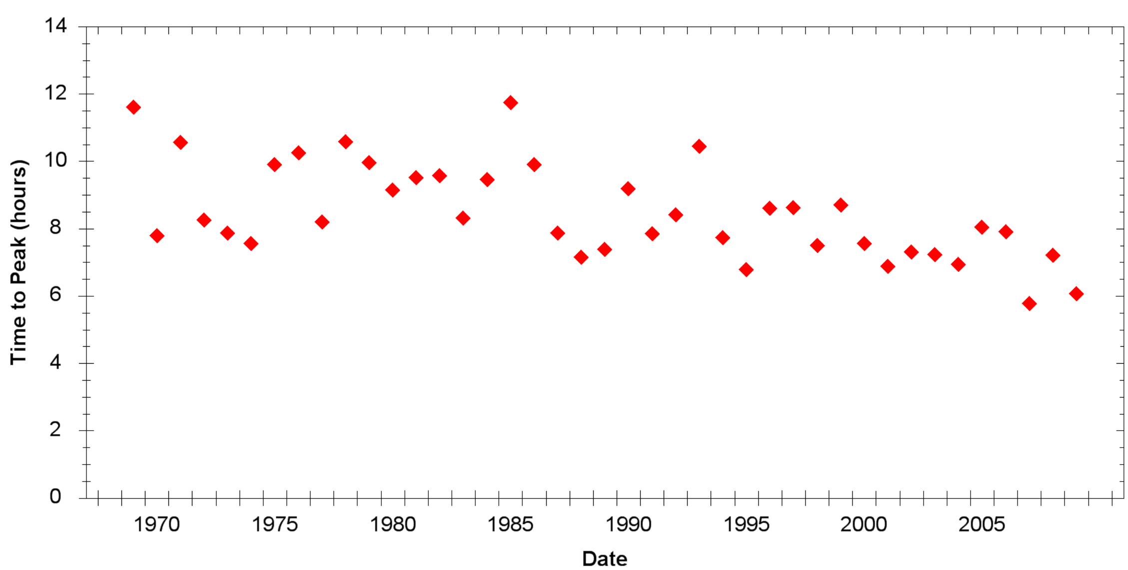

Figure 4.9: Yearly Averaged Time to Event Peak at Don River at Todmorden (02HC024)

It should be noted that with urbanization, the number of detected events increases. As suggested above, this may be the result of smaller events that may have previously been attenuated by depressional storage and groundwater infiltration not registering at the gauge. An increase in smaller events may skew the time to peak series downward, resulting in a false positive decreasing trend by Mann-Kendall test. This is also of concern when analysing trends in duration and volume parameters.

Table 4.5 presents the Mann-Kendall results, and as predicted a decrease trend is observed at approximately half of the study catchments. However, a number of urban stations show an increase in the time to peak when considering only warm weather events. This may be the result of stormwater management ponds attenuating event flow. Online stormwater ponds would affect the runoff behaviour of high frequency (lower magnitude) events by storing event flow during the rising limb whereas offline ponds would store peak flow during larger events. This increasing trend suggests that the storage provided by the stormwater management system in some catchments storage may increase the time to peak more than improved drainage and channel efficiency decrease it.

Table 4.5: Detected Trends in Time to Event Peak

StationID	**Station Name**	**Urban Change (%)**	**Continuous Data Set**	**Warm Weather Data Set**
02HC019	Duffins Creek above Pickering	<5	*None*	*None*
02HC009	East Humber River near Pine Grove	<10	*Decreasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*None*	*None*
02HB005	Oakville Creek at Milton	<10	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	<15	*Increasing*	*None*
02GA024	Laurel Creek at Waterloo	23	*None*	*None*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Decreasing*	*None*
02HC017	Etobicoke Creek at Brampton	17	*Decreasing*	*Decreasing*
02HC030	Etobicoke Creek below QEW	34	*None*	*Increasing*
02HC033	Mimico Creek at Islington	39	*None*	*None*
02HC005	Don River at York Mills	39	*Decreasing*	*Decreasing*
02HC029	Little Don River at Don Mills	38	*None*	*Increasing*
02HC024	Don River at Todmorden	30	*Decreasing*	*Decreasing*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Decreasing*	*Decreasing*
02HD013	Harmony Creek at Oshawa	25	*Decreasing*	*Decreasing*

4.3.4 Duration

The duration of an identified event can be described in two ways: the start of the event to the end of the observed recessional limb (total event duration) or from the start of the event to the point on the falling limb where discharge falls below 25% of the event peak (threshold duration: Section 3.4). While total duration describes the full hydrograph, this measure is not consistent between events as it is controlled by the length of time between events and the duration of the storm event and subsequent recession. With an increasing number of events observed at urban stations, it is expected this variable would also decrease over the period of record. The threshold duration variable is independent of other storm events, but is confounded with the event peak. Neither variable is an ideal measure, but as changes to event duration are of significance when considering urbanization, however the two variables when considered together may provide insight. The total event duration measured from each event hydrograph at Black Creek near Weston is presented on Figure 4.10. Figure 4.11 shows same data averaged on a yearly basis, a decreasing trend can be observed which is confirmed by the Mann-Kendall test.

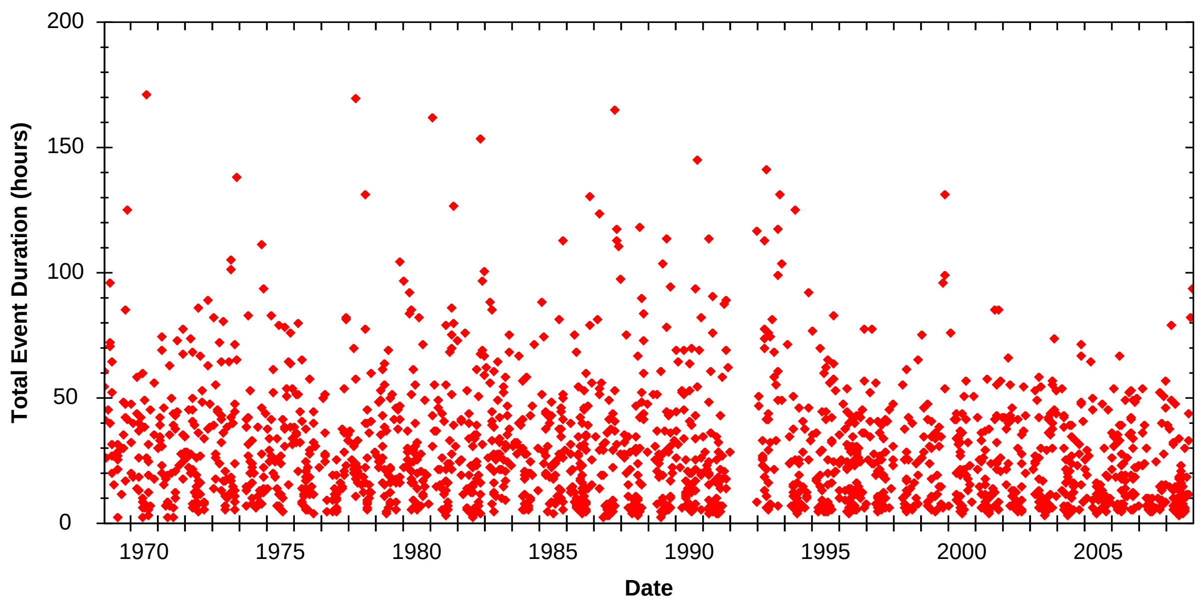

Figure 4.10: Total Event Duration at Black Creek near Weston (02HC027)

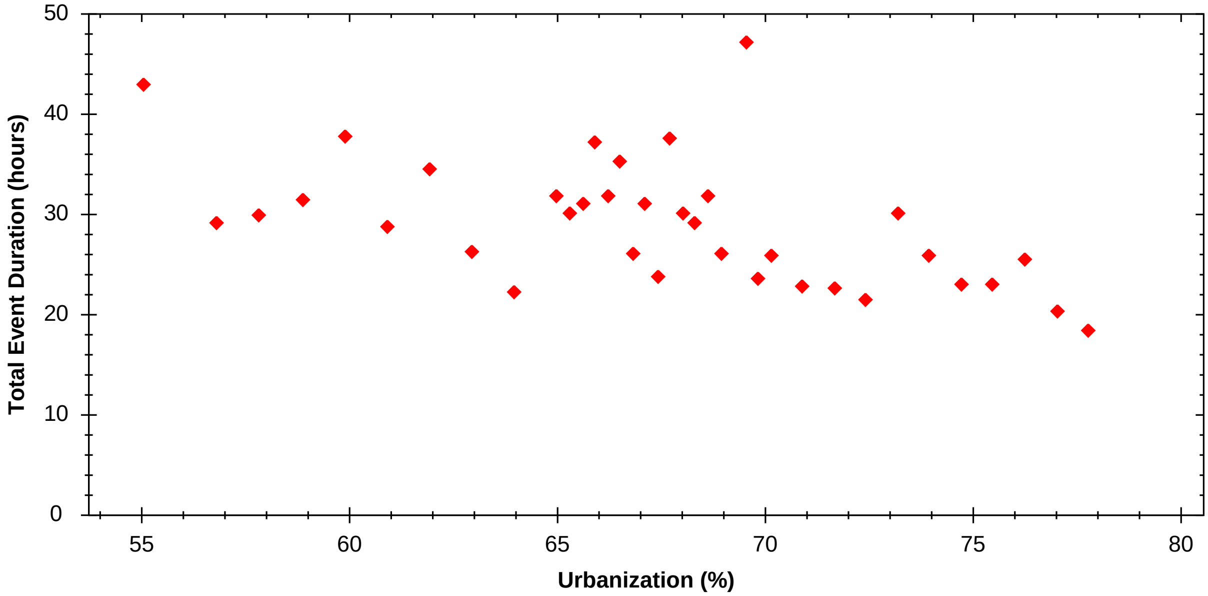

Figure 4.11: Yearly Averaged Total Event Duration at Black Creek near Weston (02HC027 with Urbanization)

The results of the Mann-Kendall trend test on the total event duration series are presented in Table 4.6. Increasing total event durations are observed in the same urban watersheds that demonstrate an increasing trend in time to peak Table 4.5. This suggests that while events reach peak discharge faster in these urban catchments, the entire storm event takes longer to dissipate; likely the impact of stormwater management systems. Conversely, decreasing trends are indicated at half the urban catchments suggesting events with shorter durations; the result of increasingly efficient drainage networks.

Table 4.6: Detected Trends in Total Event Duration

StationID	**Station Name**	**Urban Change (%)**	**Continuous Data Set**	**Warm Weather Data Set**
02HC019	Duffins Creek above Pickering	<5	*Increasing*	*None*
02HC009	East Humber River near Pine Grove	<10	*None*	*None*
02HB004	East Oakville Creek near Omagh	<10	*None*	*Decreasing*
02HB005	Oakville Creek at Milton	<10	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	<15	*None*	*None*
02GA024	Laurel Creek at Waterloo	23	*None*	*None*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Decreasing*	*Decreasing*
02HC017	Etobicoke Creek at Brampton	17	*Decreasing*	*Decreasing*
02HC030	Etobicoke Creek below QEW	34	*None*	*Increasing*
02HC033	Mimico Creek at Islington	39	*None*	*None*
02HC005	Don River at York Mills	39	*Decreasing*	*Decreasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Decreasing*	*Decreasing*
02HC022	Rouge River near Markham	33	*Increasing*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Decreasing*	*Decreasing*
02HD013	Harmony Creek at Oshawa	25	*Decreasing*	*Decreasing*

Table 4.7 considers trends in the threshold duration series. As with the total duration, inconsistent trends are observed in the warm weather dataset. Considering the complete event series, a decreasing trend is more prevalent and found in catchments with decreasing trends in total event duration. Of note, is the increasing trend observed in the full record in two of the agricultural basins which may suggest a shift in regional climatic patterns. The lack of a trend in the warm weather dataset suggests a possible change in runoff timing of winter, spring melt events at these stations, or spatially where precipitation events occur in the catchment and their routing characteristics.

Table 4.7: Detected Trends in Threshold Duration

StationID	Station Name	Urban Change (%)	Continuous Data Set	Warm Weather Data Set
02HC019	Duffins Creek above Pickering	<5	*Increasing*	*None*
02HC009	East Humber River near Pine Grove	<10	*None*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Increasing*	*None*
02HB005	Oakville Creek at Milton	<10	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	<15	*Increasing*	*None*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Decreasing*	*None*
02HC017	Etobicoke Creek at Brampton	17	*Decreasing*	*Decreasing*
02HC030	Etobicoke Creek below QEW	34	*None*	*None*
02HC033	Mimico Creek at Islington	39	*None*	*None*
02HC005	Don River at York Mills	39	*Decreasing*	*Decreasing*
02HC029	Little Don River at Don Mills	38	*None*	*Increasing*
02HC024	Don River at Todmorden	30	*Decreasing*	*None*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Decreasing*	*Decreasing*
02HD013	Harmony Creek at Oshawa	25	*Decreasing*	*Decreasing*

4.3.5 Volume

As the impervious nature of a catchment increases, factors such as decreasing infiltration, reduction of depression storage, and improved drainage network efficiency all contribute to directing water into the stream network. While storm management ponds may play a role in retarding flow, event volumes are expected to increase with urbanization regardless of timing. This prediction is confirmed by trend analysis, and the magnitude of the increase may be significant as suggested by Figure 4.12 which illustrates the increasing tendency in yearly averaged warm weather event volumes at Little Don River at Don Mills (02HC029). Yearly average event volumes increase by a factor of two over the period of record.

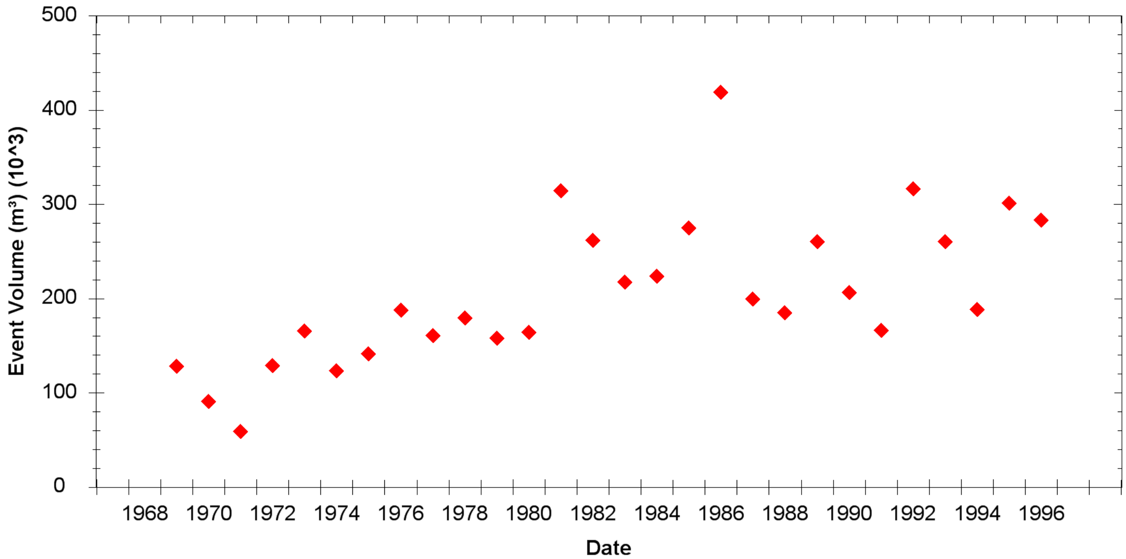

Figure 4.12: Yearly Averaged Warm Weather Total Event Volumes at Little Don River at Don Mills (02HC029)

In addition to considering the threshold and total event volumes, the rising limb volume (the cumulative discharge between the identified start of the event and the peak) can be derived for each event. Table 4.8 presents the Mann-Kendall results for this parameter. An increasing trend in rising limb volume is identified at six of the urban study catchments. In three of these basins an increasing trend in time to peak was detected, while in the others a decreasing trend was observed. This suggests that while the magnitude and timing of the event peak may be changing, the total volume of water routed off of the catchments in the early part of the events is increasing regardless.

Table 4.8: Detected Trends in Rising Limb Volume

StationID	Station Name	Urban Change (%)	Continuous Data Set	Warm Weather Data Set
02HC019	Duffins Creek above Pickering	<5	*None*	*None*
02HC009	East Humber River near Pine Grove	<10	*Decreasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Decreasing*	*None*
02HB005	Oakville Creek at Milton	<10	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	<15	*Increasing*	*Increasing*
02GA024	Laurel Creek at Waterloo	23	*None*	*None*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*None*	*None*
02HC017	Etobicoke Creek at Brampton	17	*None*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*None*	*None*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Decreasing*	*None*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*None*	*None*
02HD013	Harmony Creek at Oshawa	25	*Increasing*	*Increasing*

Table 4.9 and Table 4.10 present Mann-Kendall trends for the threshold volume and total event volume parameters. Increasing trends in storm event volumes are found at the majority of the urban stations. These trends are consistent despite the role small magnitude events may play in biasing the overall event volume trend downwards. Decreasing trends are observed at the "urbanizing" station, Oakville Creek at Milton (02HB005); however, this catchment is heavily regulated and this trend may be the result of changes in reservoir timing rather than urbanization. This trend is, however, not observed at every urban station. In the heavily urbanized Black Creek catchment for example, no trends in volume are observed in the period of record, despite detected trends in peak discharge and event duration. Storm water management systems are designed to mitigate the effects of urbanization in part by adding additional storage to the drainage system. It is expected that a well designed system would impact event runoff timing but act to detain the increased runoff volumes. However, change due to urbanization does not appear to impact storm runoff volumes or timing consistently in each watershed.

Table 4.9: Detected Trends in Threshold Volume

StationID	**Station Name**	**Urban Change (%)**	**Continuous Data Set**	**Warm Weather Data Set**
02HC019	Duffins Creek above Pickering	<5	*None*	*None*
02HC009	East Humber River near Pine Grove	<10	*Decreasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*None*	*None*
02HB005	Oakville Creek at Milton	<10	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	<15	*Increasing*	*Increasing*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*None*	*None*
02HC017	Etobicoke Creek at Brampton	17	*Decreasing*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*None*	*None*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Increasing*	*Increasing*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Increasing*	*Increasing*
02HD013	Harmony Creek at Oshawa	25	*None*	*None*

Table 4.10: Detected Trends in Total Event Volume

StationID	**Station Name**	**Urban Change (%)**	**Continuous Data Set**	**Warm Weather Data Set**
02HC019	Duffins Creek above Pickering	<5	*None*	*None*
02HC009	East Humber River near Pine Grove	<10	*Decreasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Decreasing*	*None*
02HB005	Oakville Creek at Milton	<10	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	<15	*Increasing*	*None*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*Increasing*
02HC027	Black Creek near Weston	22	*None*	*None*
02HC017	Etobicoke Creek at Brampton	17	*Decreasing*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*Decreasing*	*Decreasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*None*	*Increasing*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*None*	*None*
02HD013	Harmony Creek at Oshawa	25	*None*	*None*

4.3.6 Flashiness and Intensity Indicators

Event flashiness is considered here as the peak discharge of an identified event divided by the time to peak (Section 3.4). It should be cautioned that this is a contrived parameter with only a loose physical meaning. Here, flashiness is attempting to describe the peakiness, or sharpness of an observed hydrograph, and also characterize change in that peakiness with time. Applying the flashiness metric to the period of record at Don River at York Mills (02HC005) for example results in a slight observed upward trend (Figure 4.13). As with the previously discussed parameters, when averaged on a yearly basis, strong trends are observed, as illustrated at Oakville Creek at Milton (02HB005) on Figure 4.14.

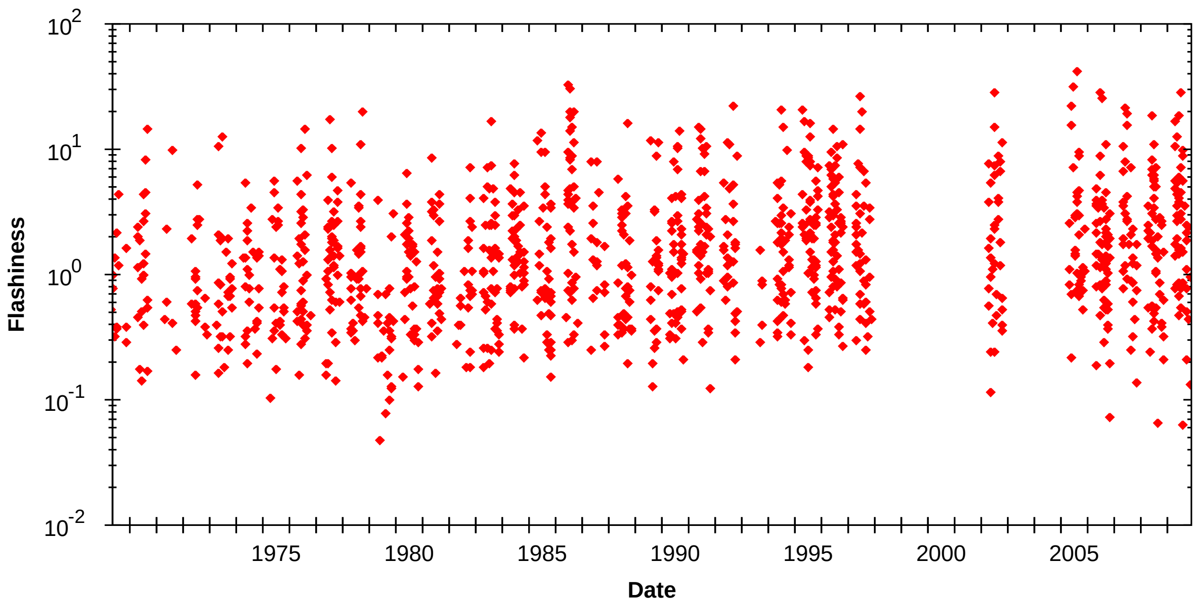

Figure 4.13: Event Flashiness at Don River at York Mills(02HC005)

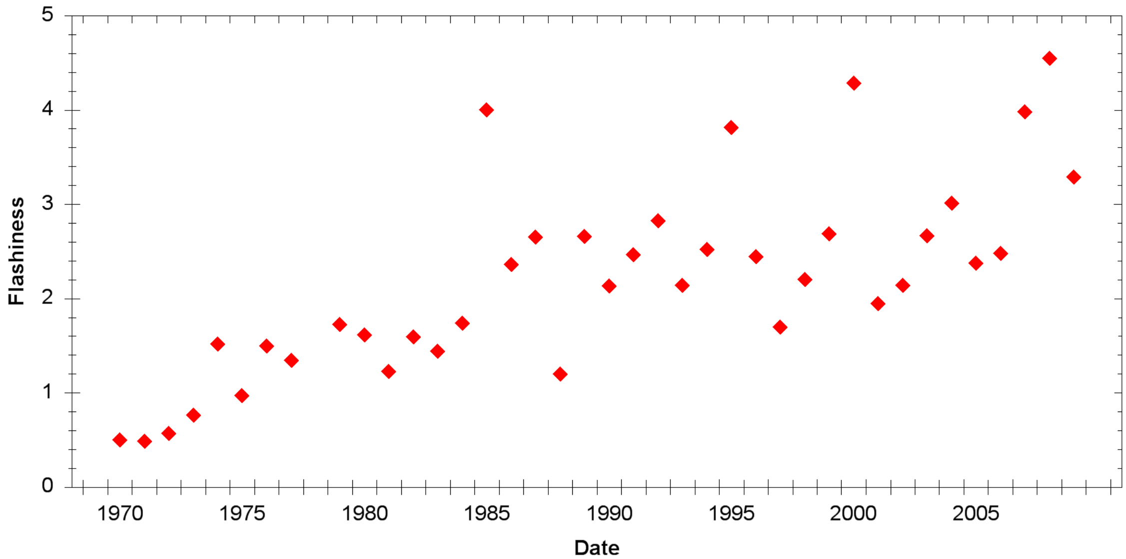

Figure 4.14: Yearly Averaged Event Flashiness at Oakville Creek at Milton (02HB005)

Results of the Mann-Kendall trend test when applied to each observed event in sequence are presented in Table 4.11. Increasing trends are identified at all the urban gauges when considering warm weather events, with the exception of Redhill Creek at Hamilton (02HA014) and Rouge River near Markham (02HC022). The upstream channel segment at Redhill Creek at Hamilton is quite steep (>3%), flood wave propagation down the creek may be channel controlled resulting in no change in flashiness as the catchment urbanized. The Rouge River near Markham has maintained an expansive belt width over the period of urbanization, and floodplain control combined with minor changes in peak and duration may explain the lack of an observed increasing trend in flashiness. No trends were observed in warm weather events in the agricultural basins during the period of record, suggesting the flashiness parameter may serve as a reasonable indicator or urbanizing influences. Flashiness further suggests a change in event timing with urbanization.

Table 4.11: Detected Trends in Event Flashiness

StationID	Station Name	Urban Change (%)	Continuous Data Set	Warm Weather Data Set
02HC019	Duffins Creek above Pickering	<5	*Decreasing*	*None*
02HC009	East Humber River near Pine Grove	<10	*None*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Decreasing*	*None*
02HB005	Oakville Creek at Milton	<10	*Increasing*	*Increasing*
02HB013	Credit River near Orangeville	<15	*Decreasing*	*None*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Increasing*	*Increasing*
02HC017	Etobicoke Creek at Brampton	17	*Increasing*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*Increasing*	*Increasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Increasing*	*Increasing*
02HC022	Rouge River near Markham	33	*Decreasing*	*None*
02HC013	Highland Creek near West Hill	39	*Increasing*	*Increasing*
02HD013	Harmony Creek at Oshawa	25	*Increasing*	*Increasing*

Other parameters extracted from the event hydrograph may also serve as good indicators of urbanizing influences. The maximum change in discharge between time steps (or 15 minute period) on the rising limb each observed event was calculated. Figure 4.15 plots flashiness against the maximum change in discharge for Highland Creek near West Hill (02HC013) demonstrating good correlation ($r^2 = 0.72$). The maximum rate of change parameter is a useful metric to describe flashiness as this parameter can be derived independently from the hydrograph shape parameters; however high resolution data is required. Trends observed in maximum rate of change per event (Table 4.12) are coincident with those observed for the event-based definition of flashiness (Table 4.11).

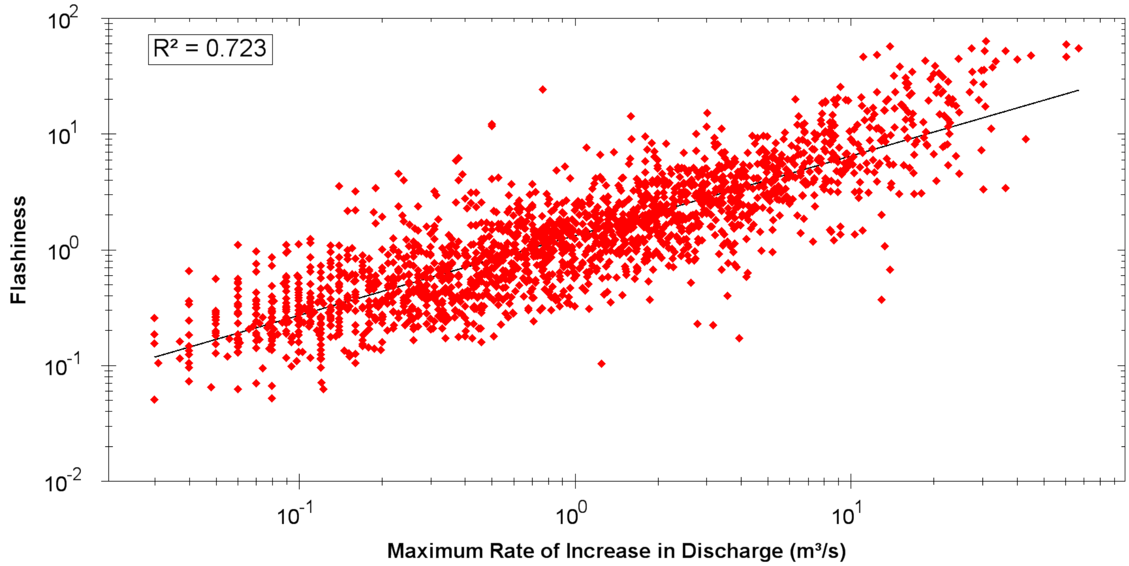

Figure 4.15: Flashiness versus Maximum Rate of Increase (Highland Creek near West Hill (02HC013))

Table 4.12: Detected Trends in Maximum 15 Minute Rising Limb Change in Discharge

StationID	**Station Name**	**Urban Change (%)**	**Continuous Data Set**	**Warm Weather Data Set**
02HC019	Duffins Creek above Pickering	<5	*None*	*None*
02HC009	East Humber River near Pine Grove	<10	*Increasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Decreasing*	*None*
02HB005	Oakville Creek at Milton	<10	*Increasing*	*Increasing*
02HB013	Credit River near Orangeville	<15	*Decreasing*	*Decreasing*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Increasing*	*Increasing*
02HC017	Etobicoke Creek at Brampton	17	*Increasing*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*Increasing*	*Increasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Increasing*	*Increasing*
02HC022	Rouge River near Markham	33	*None*	*None*
02HC013	Highland Creek near West Hill	39	*Increasing*	*Increasing*
02HD013	Harmony Creek at Oshawa	25	*Increasing*	*Increasing*

Also of possible interest as an indicator of urbanization is the average event discharge which may serve as an additional indicator of the event intensity. This represents a volume derived definition of flashiness as opposed to a peak based definition (event volume / event length). Both show similar results (Figure 4.15), which is expected, as both are based upon a similar set of hydrograph shape parameters (peak, duration, and volume). Trends observed in average event discharge are listed in Table 4.13.

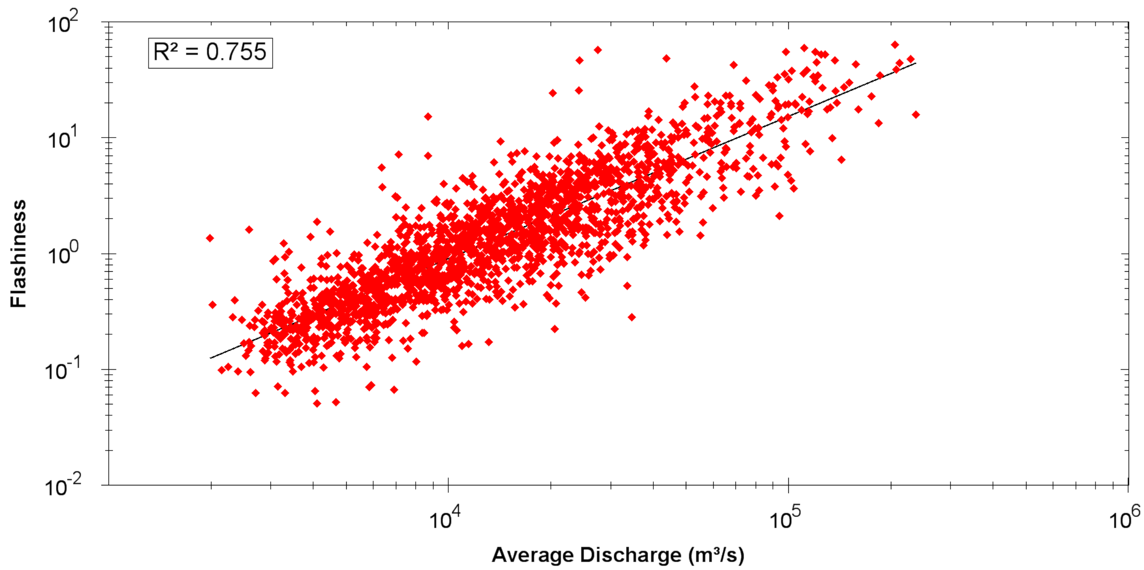

Figure 4.16: Flashiness versus Average Event Discharge (Highland Creek near West Hill (02HC013))

Table 4.13: Detected Trends in Event Intensity

StationID	Station Name	Urban Change (%)	Continuous Data Set	Warm Weather Data Set
02HC019	Duffins Creek above Pickering	<5	*Decreasing*	*None*
02HC009	East Humber River near Pine Grove	<10	*Decreasing*	*None*
02HB004	East Oakville Creek near Omagh	<10	*Decreasing*	*None*
02HB005	Oakville Creek at Milton	<10	*None*	*None*
02HB013	Credit River near Orangeville	<15	*Increasing*	*None*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*
02HA014	Redhill Creek at Hamilton	33	*None*	*None*
02HC027	Black Creek near Weston	22	*Increasing*	*Increasing*
02HC017	Etobicoke Creek at Brampton	17	*None*	*Increasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*
02HC005	Don River at York Mills	39	*Increasing*	*Increasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Increasing*	*Increasing*
02HC022	Rouge River near Markham	33	*None*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Increasing*	*Increasing*
02HD013	Harmony Creek at Oshawa	25	*Increasing*	*Increasing*

4.3.7 Summary

Table 4.14 summarizes the warm weather trends identified by the Mann-Kendall test at a 95% significance level (as per Section 3.7) in the study catchments for the parameters of peak discharge, recession volume, and recession duration. Trends in event parameters are present in all the urban study catchments. Increasing peak discharge is present in all but one study catchment and total event volume was found to increase in the majority of the watersheds studied. As identified by others (Leopold, 1968; Seaburn, 1969; Burns *et al.*, 2005; Chang, 2007), this represents the defining hydrologic characteristic of urbanization. Importantly, the agricultural catchments introduced to serve as a control group show no consistent trends, suggesting the trends observed in the urban watersheds are anthropogenic in nature. While increasing trends in peak magnitude and total event volume are observed consistently, changes to event duration show no clear trend. The lack of consistent trends in the timing and distribution of flow during runoff events suggests that build-out, drainage network design, and stormwater management systems play differing roles in the neighbouring urban catchments.

Table 4.14: Detected Hydrograph Trends (Warm Weather Dataset)

StationID	**Station Name**	**Urban Change (%)**	**Peak Discharge**	**Total Event Volume**	**Total Event Duration**
02HC019	Duffins Creek above Pickering	>5	*None*	*None*	*None*
02HC009	East Humber River near Pine Grove	>10	*None*	*None*	*None*
02HB004	East Oakville Creek near Omagh	>10	*None*	*None*	*Decreasing*
02HB005	Oakville Creek at Milton	>15	*Increasing*	*Decreasing*	*Decreasing*
02HB013	Credit River near Orangeville	>15	*None*	*None*	*None*
02GA024	Laurel Creek at Waterloo	23	*Increasing*	*Increasing*	*None*
02HA014	Redhill Creek at Hamilton	33	*None*	*Increasing*	*None*
02HC027	Black Creek near Weston	22	*Increasing*	*None*	*Decreasing*
02HC017	Etobicoke Creek at Brampton	24	*Increasing*	*Increasing*	*Decreasing*
02HC030	Etobicoke Creek below QEW	34	*Increasing*	*Increasing*	*Increasing*
02HC033	Mimico Creek at Islington	39	*Increasing*	*Increasing*	*None*
02HC005	Don River at York Mills	39	*Increasing*	*Decreasing*	*Decreasing*
02HC029	Little Don River at Don Mills	38	*Increasing*	*Increasing*	*Increasing*
02HC024	Don River at Todmorden	30	*Increasing*	*Increasing*	*Decreasing*
02HC022	Rouge River near Markham	33	*Increasing*	*Increasing*	*Increasing*
02HC013	Highland Creek near West Hill	39	*Increasing*	*None*	*Decreasing*
02HD013	Harmony Creek at Oshawa	25	*Increasing*	*None*	*Decreasing*

It should be noted that each of the studied urban catchments have different degrees of urbanization at the start and end of the study period (Section 4.2). Trends may be more significant in watersheds moving from agricultural to urbanized rather than in partially urbanized catchments. Also, the relative change in urban area over the study period is not uniform. This may explain some of the variability in event volume and event duration trends. However, even watersheds with similar increases in urban area over the study period show differing trends, for example Don River at York Mills (02HC005) and Little

Don River at Don Mills (02HC029). This further suggests spatial build-out patterns and other catchment specific impacts control the change in event characteristics.

4.4 Flow Duration Curves

To better understand the change in frequency distribution of storm flow, a qualitative analysis of flow duration curves was undertaken. First by considering changes in the annual mean daily discharge dataset. The relative annual change in the distribution of daily mean streamflow at Highland Creek near West Hill (02HC013), for example is shown in Figure 4.17. While some variation is observed, no strong trend with time is observed.

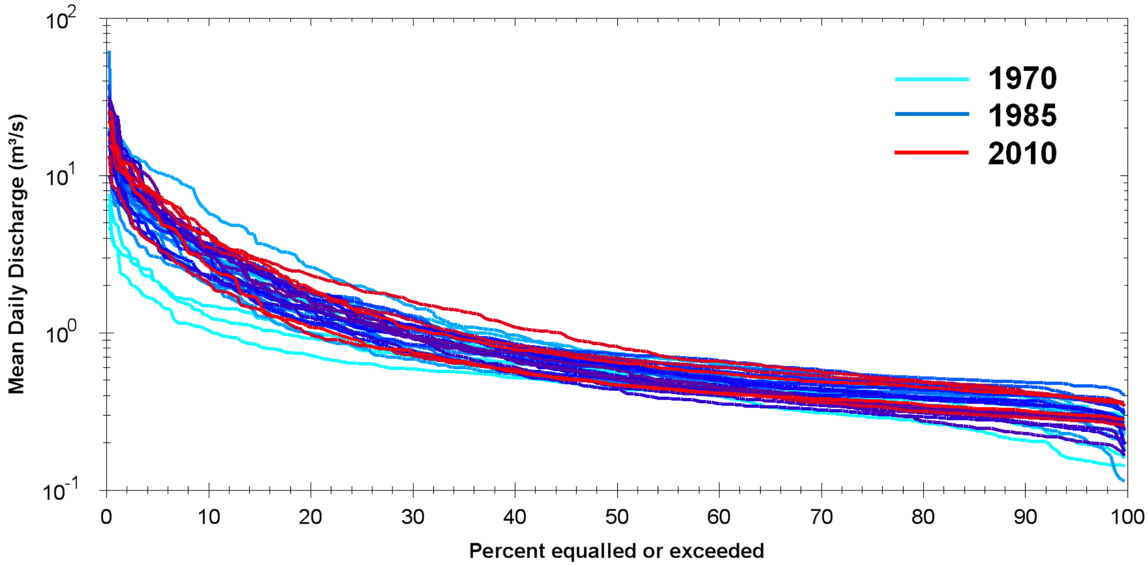

Figure 4.17: Yearly Flow Duration Curve (Highland Creek near West Hill(02HC013))

The annual peak event exceedance curves for Highland Creek near West Hill are presented on Figure 4.18. A distinct trend toward higher event peak magnitudes can be observed with time, as was suggested by the Mann-Kendall tests for trend applied to the event series. Interestingly, while observed peak event discharges are increasing with urbanization, no temporal patterns in the flow duration curves generated from daily mean streamflow were identified (Figure 4.17).

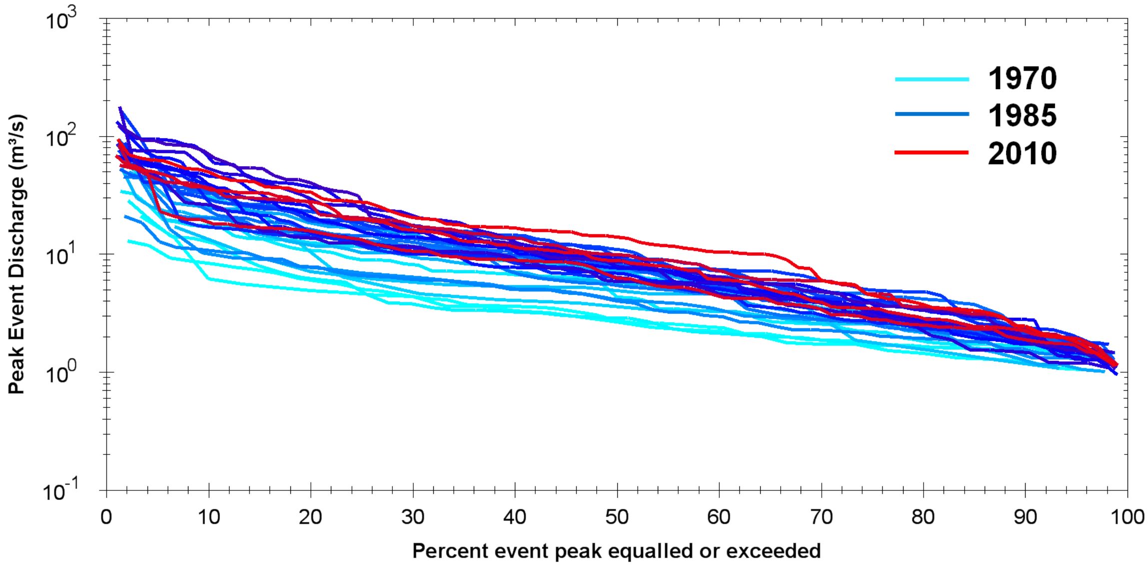

Figure 4.18: Yearly Peak Flow Duration Curve (Highland Creek near West Hill(02HC013))

For visual clarity, the peak event exceedance curves were also plotted on 4-year intervals which serves to smooth the natural variability present in the peak event series. Figure 4.19 illustrates the peak event exceedance curves at Etobicoke Creek below QEW (02HC030) grouped in 4-year increments between 1969 and 2009. The observed increase with time confirms the rising trend in peak event discharge as suggested by the Mann-Kendall test.

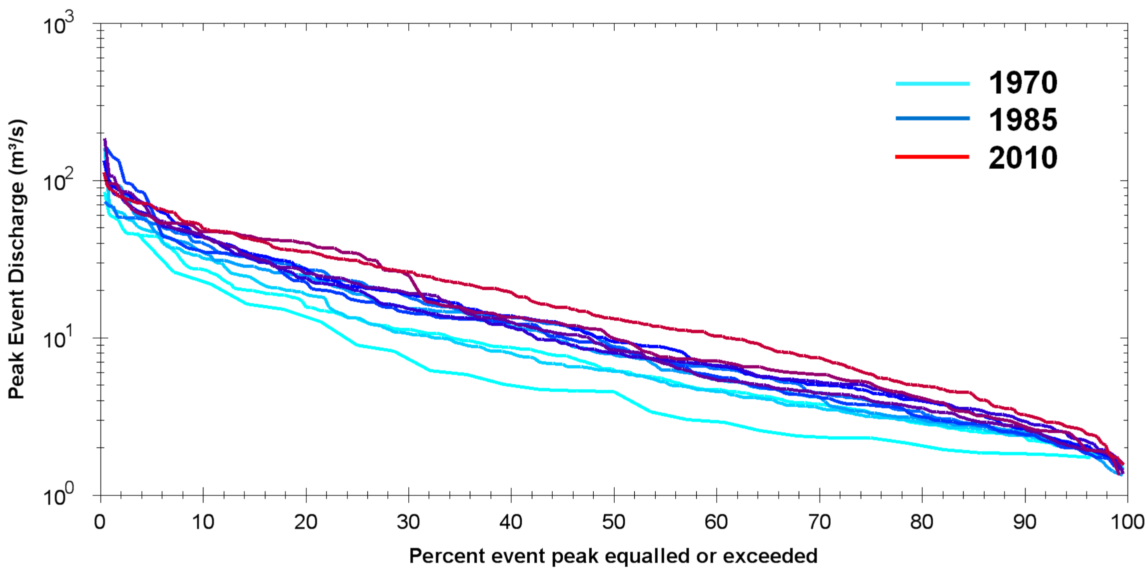

Figure 4.19: Peak Flow Duration Curve - 4-year Moving Average (Etobicoke Creek below QEW (02HC030))

Flow and peak duration plots for each of the study catchments are provided in Appendix D. As shown on Figures 4.18 and 4.19, the magnitude of the increase in peak event discharge is larger for higher frequency events (those peak events equalled or exceeded 50% of the time) in low frequency events (those with interannual or greater return periods). Some plots suggest the increasing trend as indicated by the Mann-Kendall tests may not hold true for every event frequency. At the upper gauge within the Etobicoke Creek watershed (Figure 4.20), the peak exceedance curves suggest peak magnitude is decreasing in low frequency events while increasing in high frequency events. A more rigorous analysis of event return frequency is required.

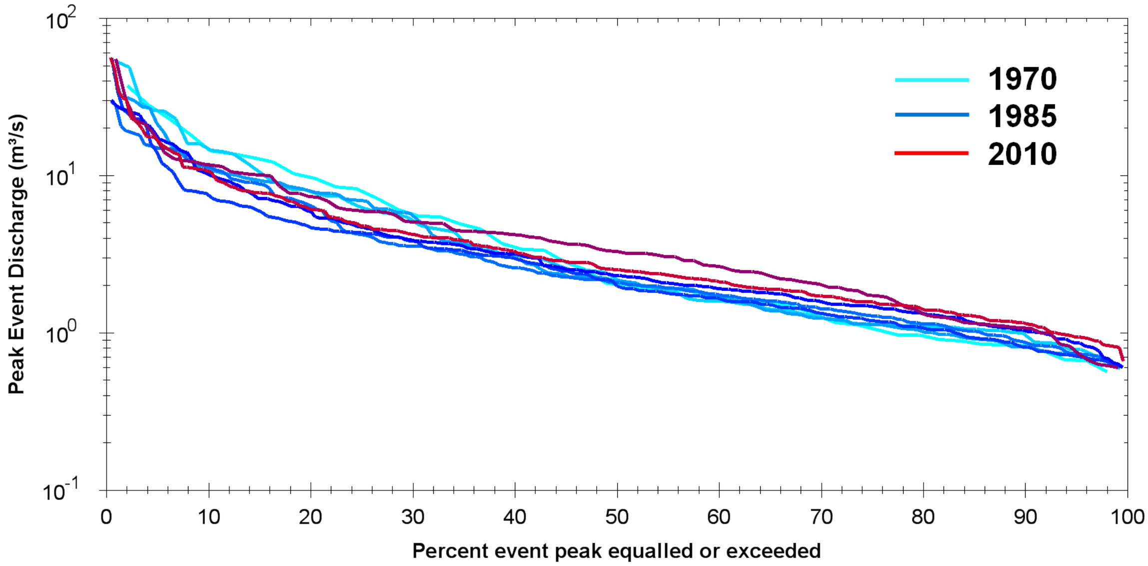

Figure 4.20: Peak Flow Duration Curve - 4-year Moving Average (Etobicoke Creek at Brampton (02HC017))

4.5 Frequency Analysis

When considering every event in the time series together, significant trends emerge in event peak, duration, and volume. However, this analysis lumps all storm events, large and small together which may obfuscate change that is occurring only to a subset of those events. Results above suggest change in the pattern and distribution of high frequency storm (low to moderate magnitude events) is different to that of low frequency (flood) events. It is difficult to class or group events by frequency in the urban systems, as the magnitude of an event with a specific recurrence interval is changing with urbanization (Section 3.6). For example, a 1-year return event in 2009 may be characterized by a larger peak discharge than that of a 1-year event that occurred in 1969. Therefore if a particular magnitude of event is occurring more frequently with no significant change in climate, events of a similar magnitude from across the period of record cannot be directly compared. Non-stationarity in peak discharge has been established, and the peak exceedance curve analysis demonstrates that the distribution and frequency of events is changing with time.

The lack of consistent trends in the hydrograph events observed in agricultural basins leads to the assumption that changes in climate have played no significant role over the past 40 years in the hydrographic change observed in the urban catchments. If climate is unchanged, then the inference that discharge events of a similar frequency are representative of precipitation events of a similar frequency can be made. The analysis presented below attempts to determine the frequency of each detected event accounting for change due to urban development with time.

4.5.1 Low Frequency Events

To first investigate the applicability of the Weibull plotting position to the peak event series, the exceedance probability of all events in the time series were determined and compared against the probabilities determined with the Log Pearson III distribution calculated from the annual peak series. Figure 4.21 presents this analysis for the Don River at Todmorden watershed (the largest catchment in the study). Good agreement is found at the upper end of the frequency plot between the Weibull and Log Pearson III analysis. As the recurrence interval falls below 8-10 years, the probabilities deviate as Log Pearson III is only appropriate for large magnitude flood events (Water Resources Council (US), Hydrology Committee, 1981; Glaves & Waylen, 1997). While some catchments correlate well, others deviate from the expected linear relationship as a result of shifting frequency distributions due to land use change (Figure 4.22).

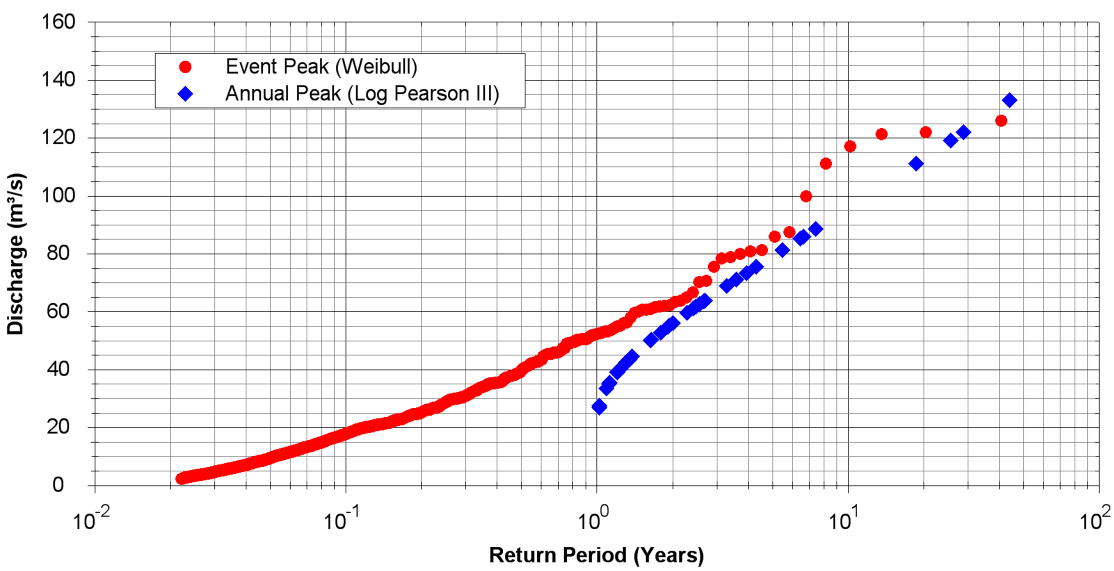

Figure 4.21: Event Recurrence Interval - Don River at Todmorden (02HC024)

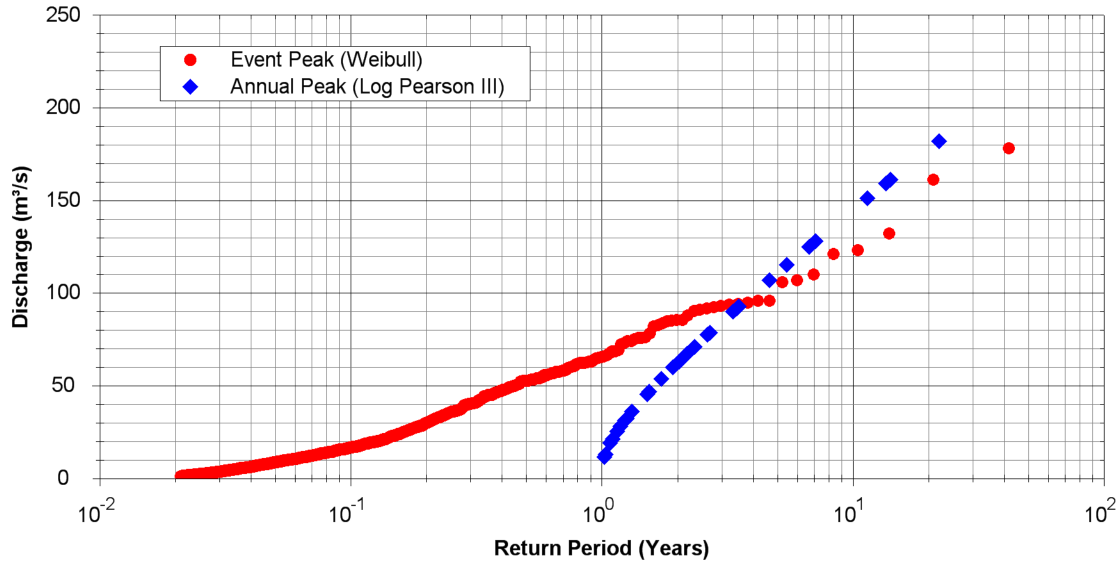

Figure 4.22: Event Recurrence Interval - Highland Creek near West Hill (02HC013)

The Log Pearson III plots are provided with the event peak Weibull plots for all study catchments in Appendix E. While outliers in the peak annual series were removed via the Grubbs test, outliers have not been removed for any of the presented Weibull analyses. The Weibull distribution appears to be appropriate for use with the event peak series, however, the effects of urbanizations skew the results when considering the entire period of record in some watersheds. It should be noted that the Log Pearson III distribution may also be affected by changing land use, however, as the method only considers the annual peak, shifting probabilities in events occurring more often than once per year would not affect the results.

4.5.2 High Frequency Events

Applying a 10-year moving window to the peak series data allows events of a specific frequency to be characterized over the complete period of instantaneous record (Figure 4.23). Figure 4.24 presents the results of this analysis at Etobicoke Creek below QEW for a representative high frequency return discharge. Results suggest that in this catchment the magnitude of the 9-month return increases from 45 m^3/s to 80 m^3/s from the early 1970s to the early 2000s then plateaus. Due to the gaps in instantaneous data at this gauge (2003 to 2004 data do not exist), the analysis is unable to produce a continuous estimate of return discharge.

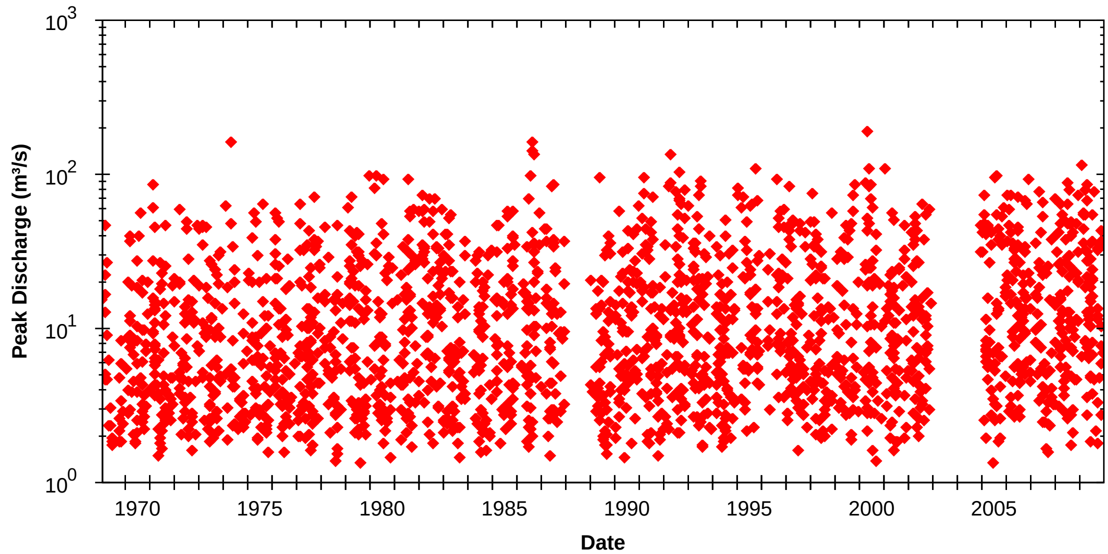

Figure 4.23: Peak Event at Etobicoke Creek below QEW (02HC030)

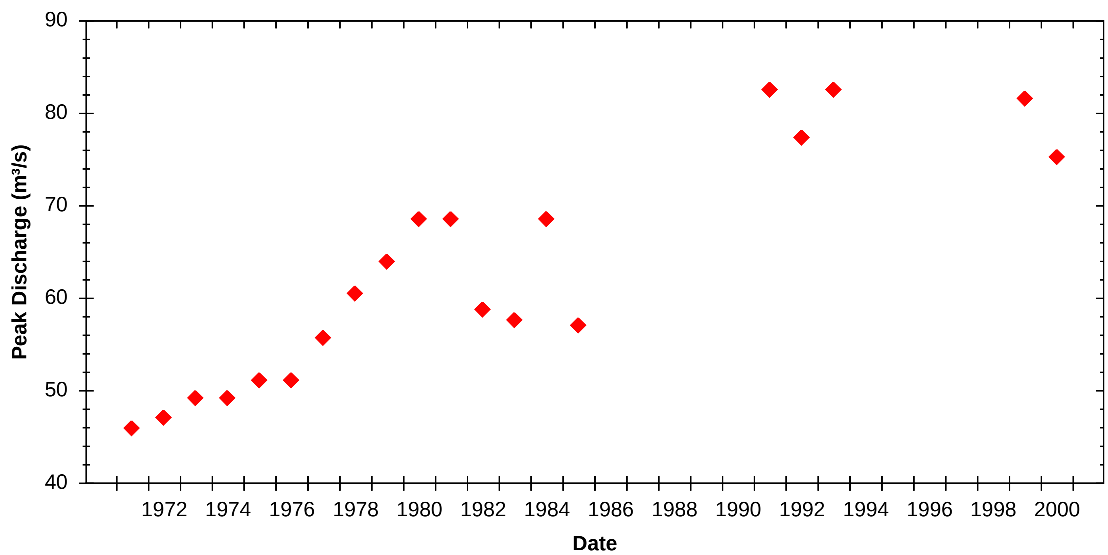

Figure 4.24: Change in 9 Month Return Discharge at Etobicoke Creek below QEW (02HC030) (10 year Moving Weibull)

When applying this method at stations of larger catchment areas, cyclical patterns are present in the high frequency return discharge plots at some stations. Figure 4.25 illustrates the 10 month return discharge at Don River at Todmorden (02HC024), note the 16 year oscillation that corresponds with a nearly 100% change in peak magnitude, possibly suggesting the influence of low frequency climatic fluctuations (Redmond & Koch, 1991; Mann *et al.*, 1998). Variability in streamflow in Canadian watersheds have been found to be controlled by the North Atlantic Oscillation, the Pacific North America atmospheric teleconnection, and the El Nio Southern Oscillation (Coulibaly & Burn, 2004). An identified interdecadal mode in the 15-to-18 years period range appears to represent long-term variability in climate patterns due to the El Nio Southern Oscillation (Mann & Park, 1994). Prokoph *et al.* (2012) detected 11 year cycles corresponding to solar sunspot activity in the maximum annual streamflow series at several WSC gauges with the trend superimposed by the stronger North Atlantic Oscillation and El Nio Southern Oscillation. While the observed oscillation in Figure 4.25 may be a result of these influences, it is difficult to isolate interannual oscillations or trends from the event peak series as non-stationarity introduced by shifting climate patterns may be obfuscated by urbanization. Also, trends are inconsistent between watersheds, and oscillations are not observed in the agriculturally dominated control catchments (Figure 4.26). This may be due to the smaller number and magnitude of events detected in the domesticated catchments obscuring this trend. Don River at Todmorden (02HC024) also represents the largest catchment in the study area and may amplify the low frequency signal by increasing peak magnitudes and decreasing peak runoff times over a large area. Investigations of climatic trends within the event dataset is beyond the scope of this study; however, the possible presence of climatic fluctuations within the data warrants further research.

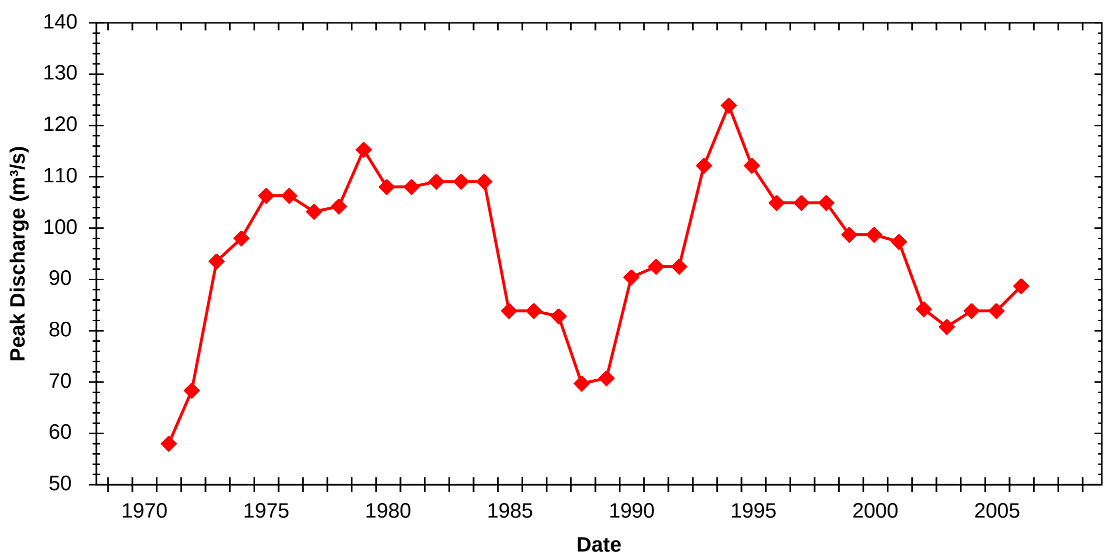

Figure 4.25: 10 Month Return Discharge at Don River at Todmorden (02HC024) (10 year Moving Weibull)

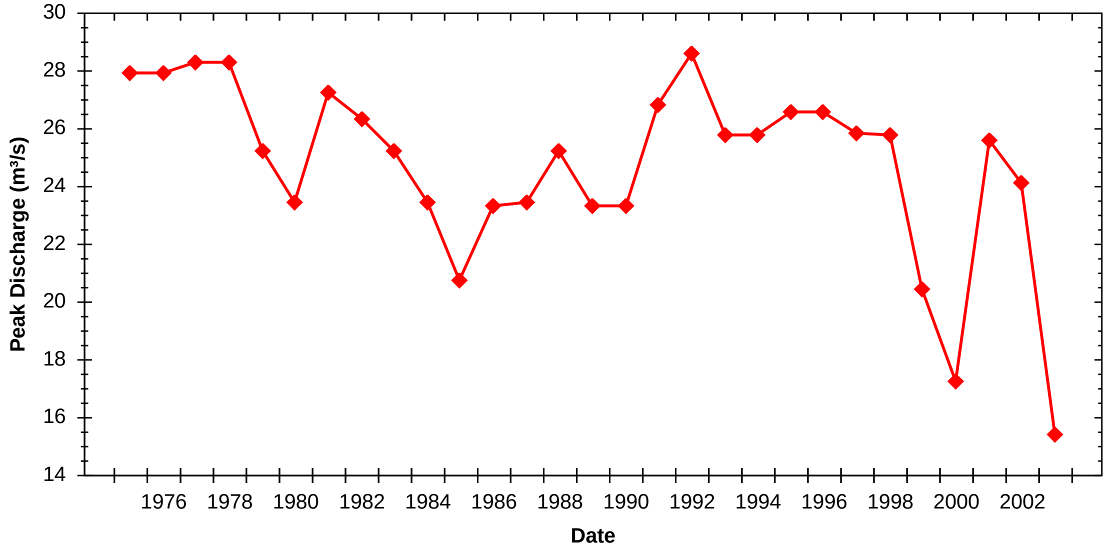

Figure 4.26: 10 Month Return Discharge at Duffins Creek above Pickering (02HC019) (10 year Moving Weibull)

When this approach is applied to multiple recurrence intervals, the overall change to the high frequency events at a gauge can be captured (Figure 4.27). At Etobicoke Creek below QEW (02HC030), a consistent increase in return discharge is observed, with the greatest change observed in the highest frequency events. This is coincident with the findings of previous authors who observed urbanization preferentially affects mid to high frequency events (Hollis, 1975).

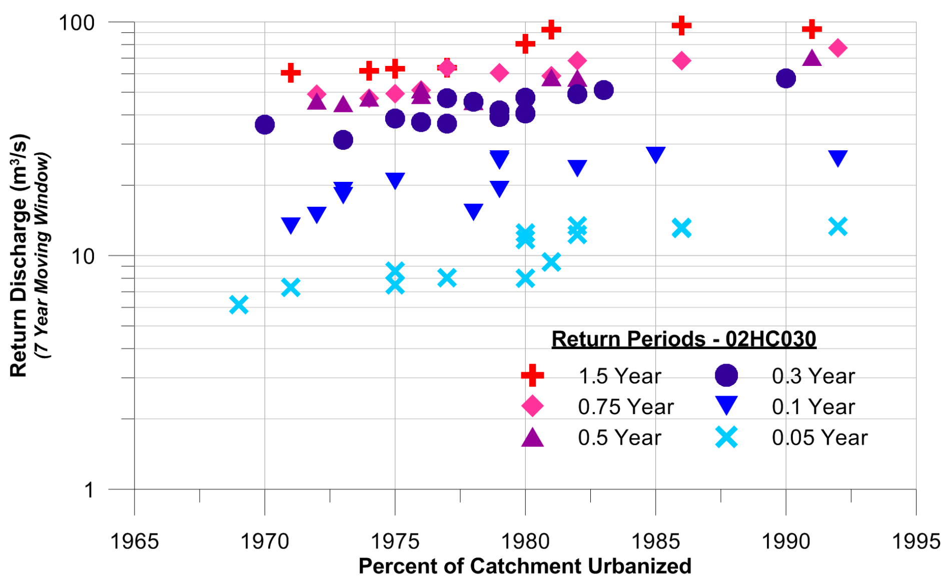

Figure 4.27: Change in Various High Frequency Return Discharges at Etobicoke Creek below QEW (02HC030)

Utilizing the urban area delineations outlined in Section 4.2, we can transform the frequency results from the temporal domain to a spatial domain. For each Weibull derived return discharge, the year is substituted for the percent urban land cover in that year. Figure 4.28 presents the change in return discharge frequency as a function of watershed urbanization for the Etobicoke Creek below QEW (02HC030) catchment. While not necessarily of specific interest on its own, by transforming the return discharges to the spatial domain, the various urban catchments in the study may be compared against each other.

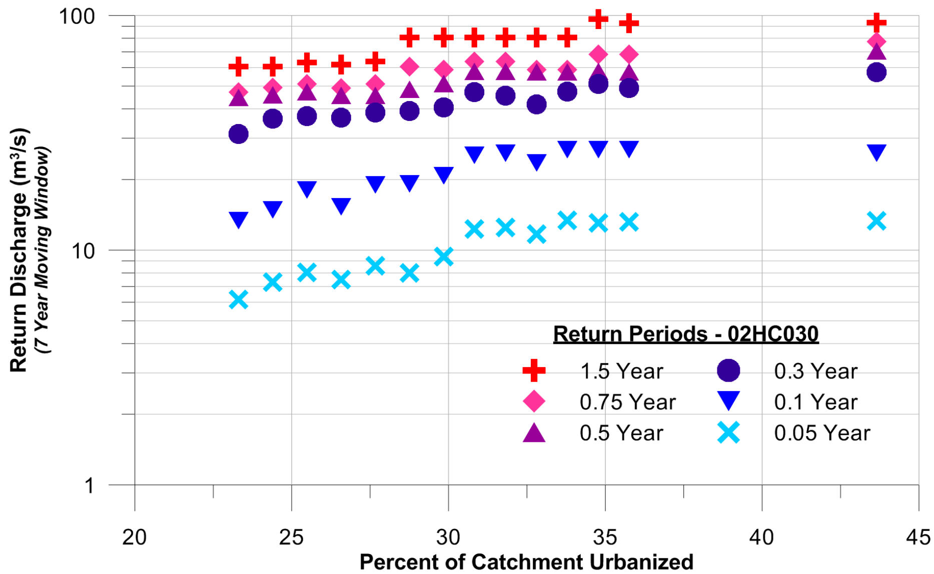

Figure 4.28: Change in Various High Frequency Return Discharges at Etobicoke Creek below QEW comparing with Urbanization (02HC030)

Plotting the peak event discharge against the estimated return period better represents the change in estimated return frequency distribution as illustrated on Figure 4.29, curves are colour by the urbanized percent area of the watershed. Events with a return period of between 1-month and 1-year show a consistent increase of approximately 30 m^3/s in peak magnitude. No clear trend is observable in the annual or greater return period; however, the error in the estimated recurrence interval increases with larger events.

Not all urban stations demonstrate an increasing trend in event discharge for all return periods. At Rouge River near Markham (02HC022) where no trend in event peak was found when employing the Mann-Kendall trend test, a decreasing pattern can be observed in the return discharge (Figure 4.30). Events with an approximately annual return period have been reduced during urbanization, likely due to the construction of stormwater management systems. Some degree of reduction is observable in events with a recurrence interval greater than 4 months.

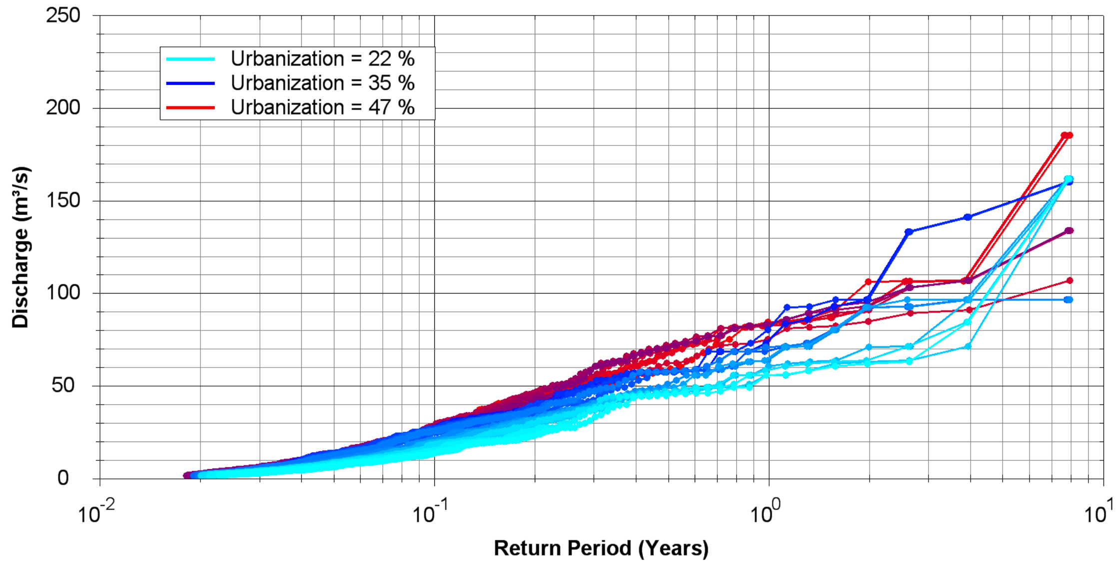

Figure 4.29: Change in Event Return Period with Urbanization at Etobicoke Creek below QEW (02HC030) (7-Year Moving Window)

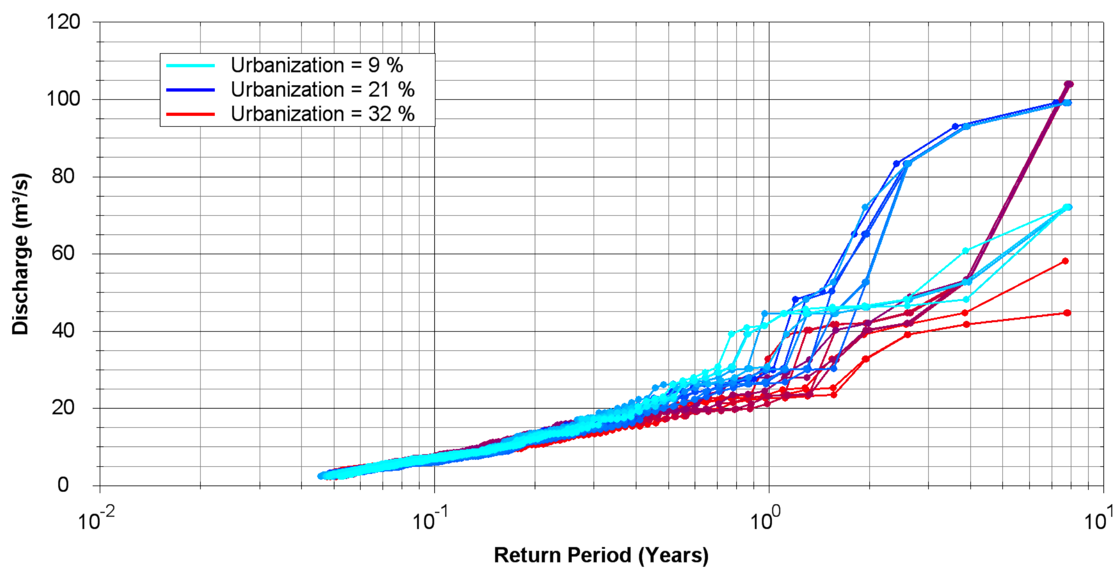

Figure 4.30: Change in Event Return Period with Urbanization at Rouge River near Markham (02HC022) (7-Year Moving Window)

The effect of urbanization is also not consistent when comparing return intervals at a single gauging station. Figure 4.31 presents the estimated frequency change at Don River at Todmorden (02HC024). Increasing patterns appear for short return periods (less than 5 months); however, no clear trend is present in the distribution of larger events. The majority of urban development in this catchment occurred in the headwaters during the period of record, the increase in magnitude of high frequency events may be the result of smaller events running off rather than being retained. At Harmony Creek at Oshawa (Figure 4.32), return discharge increases consistently for all recurrence intervals during the period of record. Development in this catchment spread from its stem, working upward into its headwaters. The spatial location of development within an urban watershed may have an effect on the degree of change observed in runoff frequency.

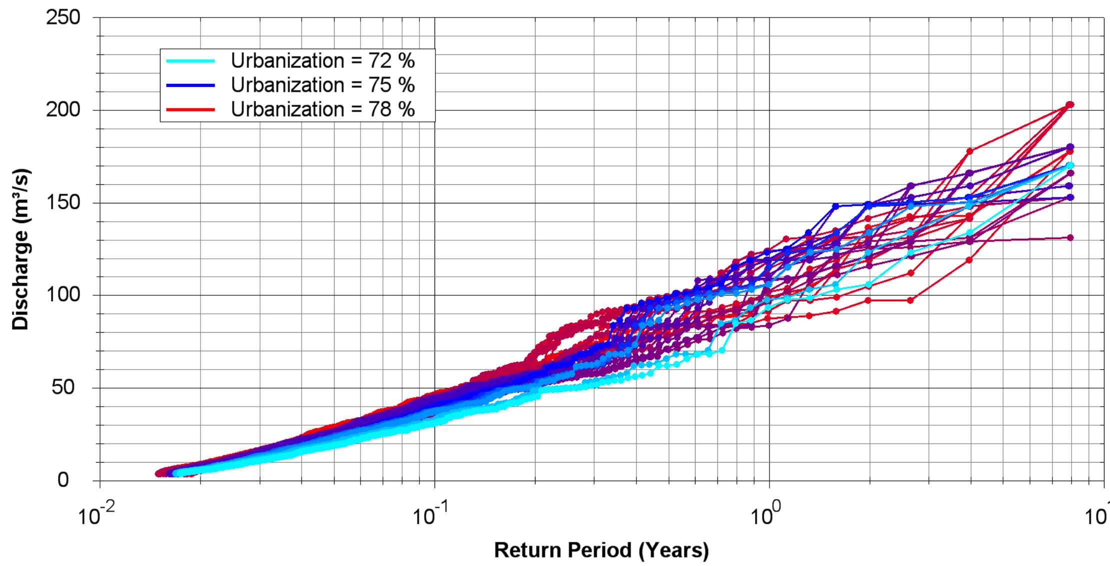

Figure 4.31: Change in Event Return Period with Urbanization at Don River at Todmorden (02HC024) (7-Year Moving Window)

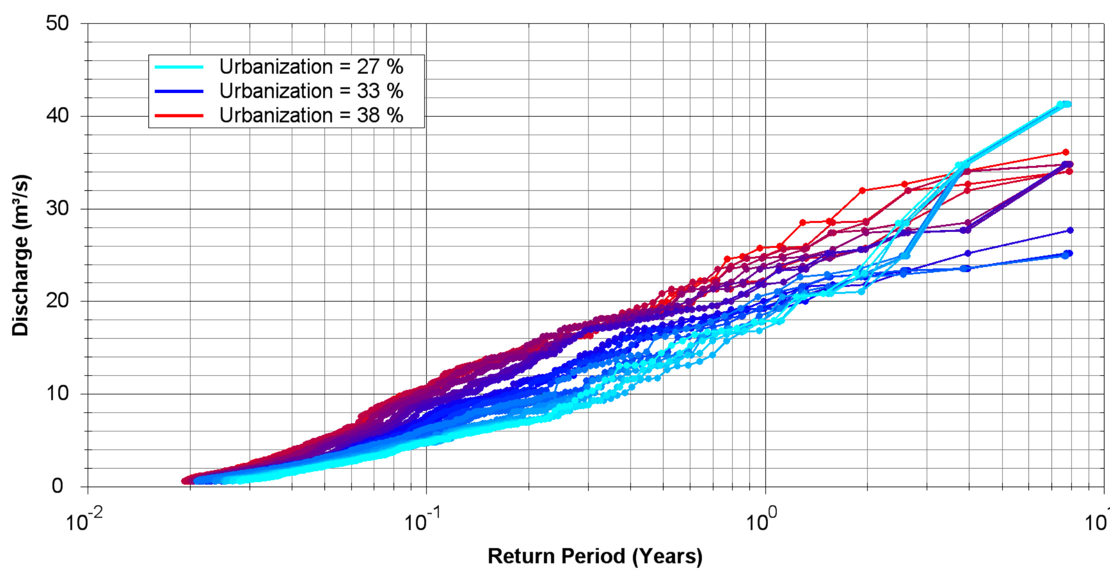

Figure 4.32: Change in Event Return Period with Urbanization at Harmony Creek at Oshawa (02HD013) (7-Year Moving Window)

Some urban watersheds where the Mann-Kendall trend test suggested an increasing trend in peak event discharge show no clear change in the estimated recurrence interval with urbanization. Laurel Creek at Waterloo (Figure 4.33) shows a great deal of variability, however, no strong patterns in change to any specific return period. Etobicoke Creek at Brampton also demonstrates no clear trend (Figure 4.34). The degree of urbanization within these catchments is less than in other study catchments, and the change over the observed period of record is small (10%). There may be a minimum change in urban area required to induce an identifiable trend in the return interval of high frequency events.

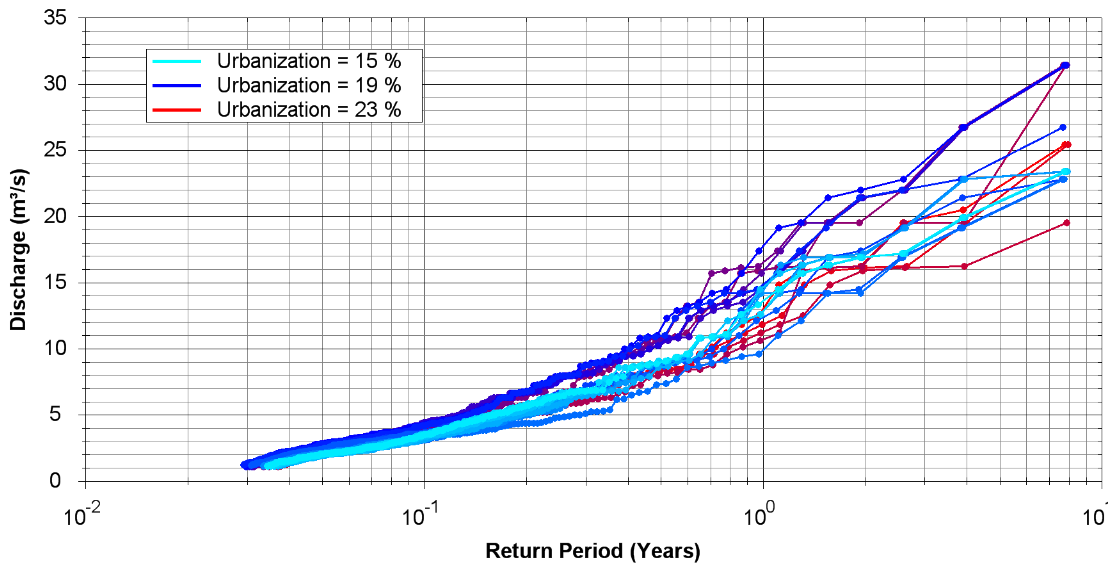

Figure 4.33: Change in Event Return Period with Urbanization at Laurel Creek at Waterloo (02GA024) (7-Year Moving Window)

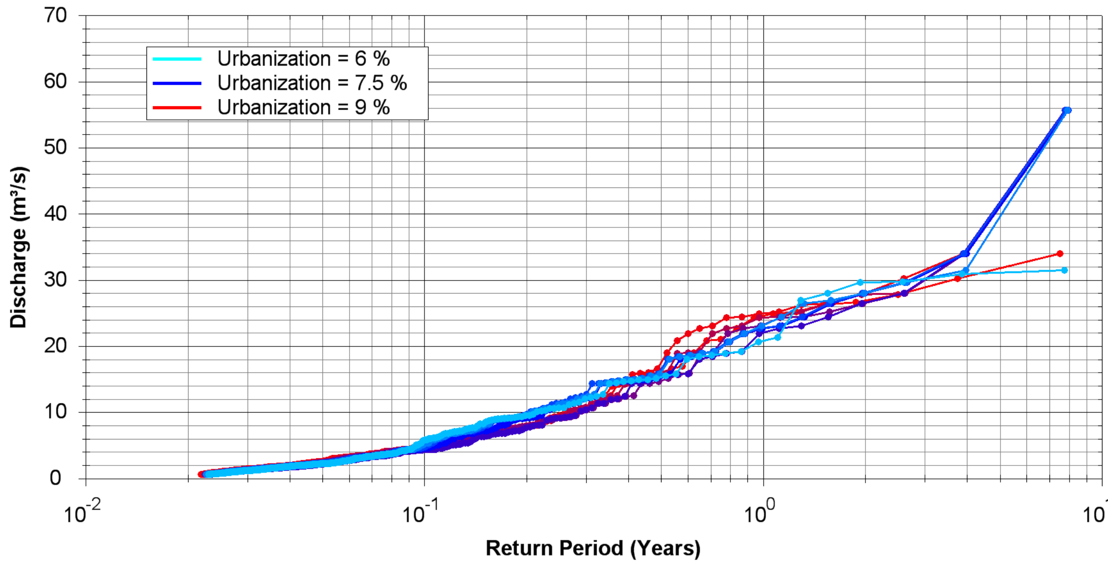

Figure 4.34: Change in Event Return Period with Urbanization at Etobicoke Creek at Brampton (02HC017) (7-Year Moving Window)

Moving window plots describing the peak event discharge as a function of estimated return period with urbanization are provided for all study catchments in Appendix F. Figures are provided with moving windows intervals of 5- and 9- year to illustrate consistent trends unbiased by the selected of a specific moving window interval.

4.5.3 Change in Bankfull Return Period

As the 1.5-year return discharge corresponds approximately with the bankfull or channel forming flow in rural southern Ontario watersheds (Section 2.2), this return interval is of specific interest when considering the geomorphic stability of a stream reach. Figure 4.35 presents the derived return discharges at the 1.5-year return period for the above urban catchments. Catchment urbanization may alter the return frequency of this specific event; however, some watersheds show no change to this return discharge with time (Harmony Creek at Oshawa; 02HD013), while others demonstrate extreme change (Highland Creek near West Hill; 02HC013).

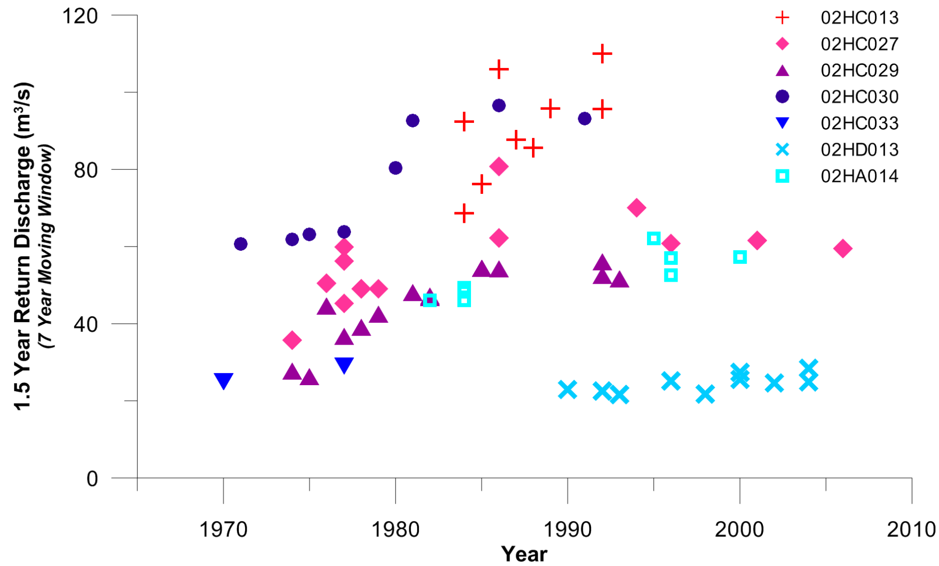

Figure 4.35: Change in 1.5-year Return Discharge for Various Urban Catchments

Figure 4.36 presents the derived 1.5-year return discharge at several of the urban gauges as function of urbanized area. A loose, linear trend upward with increasing urban land use is observed. This can also be expressed in terms of percent urban cover, which serves to normalize the return discharge by the total watershed area (Figure 4.37). A consistent trend between the various catchments is observed, whether this is a linear or power trend is not clear from the data, however it can be assumed that the trend is weaker in less urbanized catchments (the 1.5-year return discharge is not zero for any conceptual watershed).

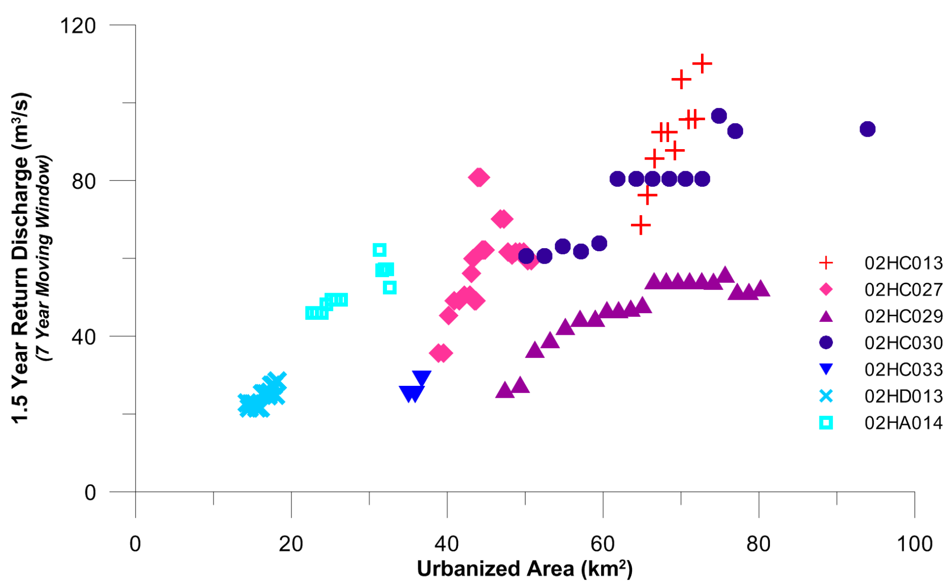

Figure 4.36: Change in 1.5-year Return Discharge with Urbanized Area

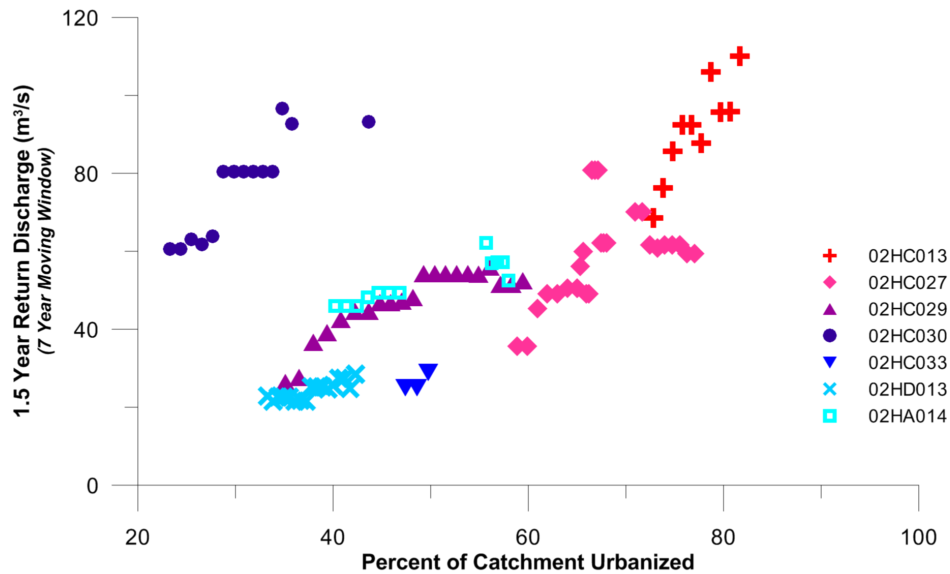

Figure 4.37: Change in 1.5-year Return Discharge with Percent Urbanized Area

Etobicoke Creek below QEW (02HC030) plots well away from the main group of urban stations, this may be a result of the urban delineation method employed. Centered within this watershed, Pearson International Airport has a foot print in excess of 20 km^2 (10%), a large portion of which is characterized by grass fields. Most of this was considered unurbanized land as clear indications of drainage could not be identified from the aerial photography. It is suspected that some drainage occurs via grasslined channels or swales on top of compacted till, and that the area may be well drained. Considering the airport as entirely impervious does not correct the deviation away from the other urban catchments, change in peak discharge magnitude appears larger in this catchment. This suggests that hydrologic impact of the airport lands is different from that of the urban development characterized in the other catchments. A more detailed investigation of this area would be required to characterize the drainage from this large, paved area.

A subset of the urban stations demonstrating strong trends in the 1.5-year return interval gauged over a significant period of urban development (+15% land use change) were selected for further study. The change in frequency of a specific peak discharge overtime can be calculated with Weibull plotting-positions just as discharge for a given frequency was calculated above. The change in field observed bankfull discharge estimates collected by Annable *et al.* (2011) (Table 4.15) can be compared to catchment urbanization (Figure 4.38). A bankfull discharge is specific to a given reach and would change over time as that channel equilibrates to new watershed conditions, therefore the bankfull return intervals are less accurate when moving backward through the event series. This could be corrected if verified bankfull discharges had been collected in each study catchment in intervals during urbanization. The return period of bankfull discharge events appears to be significantly reduced with urbanization, and for a subset of stations, approaches similar return frequency in a 1 to 2-month range.

Table 4.15: Field Verified Bankfull Return Periods for Selected Urban Catchments (Annable *et al.*, 2011)

StationID	Station Name	Catchment Area (km^2)	Percent Urban Change (1969-2008)	Field Observed Bankfull Discharge (m^3/s)
02HA014	Redhill Creek at Hamilton	56.3	33	13.8
02HC030	Etobicoke Creek below QEW	204	34	47.8
02HC033	Mimico Creek at Islington	70.6	39	18.4
02HC029	Little Don River at Don Mills	130	38	23.8
02HD013	Harmony Creek at Oshawa	41.6	25	12.5

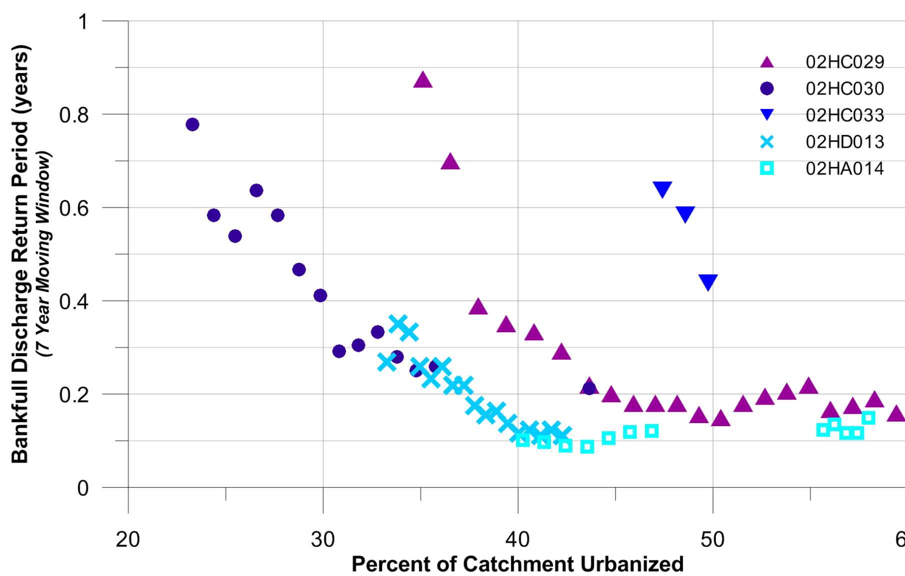

Figure 4.38: Change in Bankfull Return Period with Urbanization for selected Study Reaches

4.5.4 Summary

Considering each identified event peak as a continuous series allows estimates of return period and event frequency to be constructed. Urbanization is shown to affect high frequency events preferentially, as expected. Unexpectedly, some catchments demonstrate a reduction the magnitude of high frequency peak discharge. As a watershed urbanizes, the increase in impervious area generated larger runoff volumes while drainage efficiency increases the speed with which the flow moves through the catchment. This leads to a greater number of off runoff events reaching the stream gauge (Section 4.3.1) and an increase in the magnitude of these events. Large events are mitigated by stormwater management systems and the total conveyance of most drainage networks will reach an upper limit, retaining and delaying flood flows.

The inconsistent patterns and trends in frequency observed in neighbouring watersheds are the result of competing hydrologic and hydraulic processes which occur as a watershed transitions to an urban form. While an increase in impervious area increases runoff generation, the construction of stormwater management systems acts to detain a portion of each runoff event. The components of the drainage system also affect frequency response; online stormwater ponds would affect the runoff behaviour of high frequency (lower magnitude) events by storing event flow during the rising limb whereas offline ponds would store peak flow during larger events. Additionally, the structure and form of the drainage network varies by age. Drainage systems constructed before regulatory stormwater management standards were enforced will exhibit a different response from those constructed in the past decade. The spatial location of these systems will also lead to a dissimilar hydrologic response between neighbouring catchments with different built-out patterns.

Chapter 5

Conclusions

"Well-maintained data appreciate in value like a vintage car."
— Hamilton (2007)

Utilizing an automated computer code, runoff events were identified and parsed from high resolution hydrographs spanning a 40-year period of record in twelve urban, two urbanizing, and three rural watersheds of southern Ontario. Trends in the event time series were analyzed with the Mann-Kendall trend test. Increasing trends in event peak discharge were identified in all but one study catchment. Event volume was found to be consistently increasing in most of the urban watersheds, while trends in event duration were observed but with no clear increasing or decreasing trend. The lack of consistent trends in the timing and distribution of flow during runoff events suggests that build-out, drainage network design, and stormwater management systems play differing roles in the neighbouring urban catchments. The agricultural catchments introduced to serve as a control group show no consistent trends, supporting the conclusion that the trends observed in the urban watersheds are anthropogenic in nature.

An analysis of flow duration and peak exceedance plots indicates that urbanization affects peak event discharge differently for varying return periods. Estimates of event return periods can be generated with a moving window procedure to isolate and compare changes in event distribution with urbanization. This analysis confirmed that the magnitude of high frequency events is affected more than those of low frequency or flood events. The degree of variation between events of different frequency varied between stations. Some stations exhibited consistent increasing patterns across all return intervals, while at others change was only observed in a portion of the frequency distribution (i.e., from 1 to 6-months). Interestingly, the relative change in return frequency distribution is not consistent between catchments. Some heavily urbanized catchments exhibited minor changes in frequency, while others demonstrated large changes in magnitude. Unexpectedly, the peak discharge of some return periods appeared to decrease with urban development. This suggests that the increased detention brought with urban stormwater management systems can offset the increased runoff due to additional impervious area and improved drainage efficiency. A consistent relationship defining the change in geomorphically significant return periods (i.e., channel forming flow) with urbanization was developed for neighbouring urban catchments. It was observed that field calibrated bankfull return discharge at several urban stations trended towards a 1 to 3-month return period as the watershed urbanized.

The instantaneous hydrometric streamflow dataset provides a significant increase in temporal resolution compared to mean daily data. It was demonstrated that daily mean streamflow data does not have sufficient resolution to describe the change in hydrologic runoff characteristics at some urban stream gauges. Where an event based analysis of instantaneous hydrometric data reveals significant statistical trends corresponding with urbanization, an annual analysis of daily streamflow fails to show changes in flow or distribution. The demonstrated event parsing algorithm is relatively unsophisticated and still generates compelling results. The proposed event based analysis offers a method to distill large, cumbersome, high resolution, datasets down to small sets of hydrologically relevant data.

An objective of this study was to detect and quantify the change in hydraulic response with anthropogenic changes in land use; however, some trends were detected in the control catchments employed in this study. No consistent conclusion can be drawn between the small number of stations employed. Future work might involve the application of these methods to catchments with no major land use change to attempt to detect climate change signals. Several catchments in this study have been built-out to the watershed boundaries, it can be anticipated that the land use within these watersheds will remain unchanged for the foreseeable future. Barring channel maintenance, stream rehabilitation, or upgrades to existing storm drainage networks, the hydraulic response in these watersheds should also remain unchanged under current hydroclimatic conditions. With future changes to climate predicted (Parry *et al.*, 2007), these urban catchments can serve as indicator stations highly responsive to changes in event frequency, distribution, and duration. While WSCs Reference Hydrometric Basin Network (Brimley *et al.*, 1999) serves to track long term changes in pristine catchments (Burn *et al.*, 2012), the urban network is more sensitive to changes in frequency. Recent additions to the urban stream monitoring network in Ontario will aid in the measurement, prediction, and understanding of potential change. However, these stations must be well-funded and maintained long enough to develop a sufficient period of record. Additionally, further understanding of the variability and alteration of event frequencies in urban catchments will lead to improved rehabilitation and maintenance programs for urban streams.

5.1 Future Work

It is widely understood that the magnitude, shape, and timing of streamflow hydrographs are greatly influenced by the spatial and temporal variability in rainfall. Variability of intensity and pattern combined with direction and velocity of storm movement can have a dramatic effect on peak stream discharge (Singh, 1997). A detailed comparison of rainfall data to the identified runoff events would potentially explain some of the variability in the hydrograph parameters. Relating the instantaneous hydrometric dataset to a precipitation record of similar temporal resolution is a logical continuation of this study.

Inconsistent hydrologic patterns and trends were found in adjacent urban watersheds. More detailed, catchment specific studies may reveal additional insights into the observed hydrologic changes due to urbanization. Spatial build-out patterns and drainage network structure play an important role in determining post-urbanization runoff characteristics. Better linkages between runoff response and specific land-use or hydraulic changes made at the catchment scale will lead to a better understanding of how legacy infrastructure controls post-development runoff response.

Assumptions regarding the inherent error within the hydrometric record need to be better quantified, specifically for the instantaneous dataset. A mean daily error estimate of 5% may well be reasonable, but the assumption that the same confidence be placed on every measured stage and computed discharge value up the rising limb of an event hydrograph requires more rigorous testing.

A more detailed analysis of winter and spring runoff events is warranted. Urban streams stay ice-free for a longer portion of the year and provide detailed hydrographs during a period where rural stations are under the influence of ice and backwater. Changes to freshet timing and duration within the urban period of record should be analysed; results may present a further technique to detect climatic shifts. The automated event based analysis may not be appropriate in this context, but the instantaneous record is very helpful in manually identifying freshet timings.

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Appendices

Appendix A

ArkWSC: Automating the Extraction of Instantaneous Data from archived STREAM Formats

ArkWSC:
Automating the Extraction of Instantaneous Data from archived STREAM Formats

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Summary

The Water Survey of Canada has been collecting and publishing stream flow and water level data since 1908. Data processing techniques making use of computer programs were first introduced in 1968. Early computing processes utilized paper card decks as input files created from manually digitized hydrograph charts. The main goal of these initial programs was to automate the average and peak daily stream flow calculations at river gauge stations while simultaneously reducing the number of person hours spent processing data and increasing data accuracy.

New research projects have created interest in accessing previously unpublished high resolution stream flow data. Digitized stream gauge data, along with the appropriate corrections have been preserved in the original electronic format for many stations. Due to several updates in hardware and processing software and the discontinued use of manual digitizing methods, a substantial portion of this data record has become difficult to access with current software. While most of this data can be extracted, it involves a cumbersome and complicated, manually labour intensive process.

Nearly three decades of stream data resides in this bulky, difficult to use format. With specific interest in urbanization and its direct watershed effects, an initiative was undertaken at the University of Waterloo (in conjunction with Ontario Water Survey) to automate the extraction of large quantities of instantaneous stream discharge data from its original format. Automation has not only increased the speed of extraction, but has allowed for extensive testing and verification of the generated data.

Development began on a program titled ArkWSC in June, 2007. Written in Visual Basic .NET (Microsoft Visual Studio 2005), ArkWSC works in tandem with a legacy program, HOURLY, part of the @WSC suite. ArkWSC automates the input and output of files for the HOURLY program which extracts archived instantaneous data. Instantaneous data refers to 15 minute or hourly time step data extracted from the HOURLY program. For each extracted point, HOURLY determines the effective water level at that exact point in time and calculates the discharge. The data is not averaged or summed across some time period, and each point represents the exact hydrograph. The HOURLY program requires individual extraction runs not only for each year, but for each rating curve, chart type, and unit type. ArkWSC breaks each archived saveset (a file containing a station years worth of data) into a series of extraction blocks, runs the HOURLY program, and collates the outputted 15 minute instantaneous data. Each day of data extracted is then tested against the published mean daily discharge values in HYDAT. In addition to the 15 minute instantaneous data, ArkWSC also processes the discrete water level points recorded in the saveset (a data set with irregular intervals primarily defined by the actions of the historical digitizer) and computes the effective gauge height and discharge for each chart point allowing the creation of a truly instantaneous dataset.

Expanded to include the entire Ontario-region archived data, the ArkWSC project has analyzed the region's 8,672 station-years of discharge data. Some savesets, approximately 83 (1%), are corrupted in some way, or crash either HOURLY or ArkWSC. Other savesets contain no discharge data or are missing stage discharge relationships (3%). Of the valid savesets, 2.1 million days of instantaneous data have been extracted and tested for quality. Nearly 99% of the instantaneous data matches the published mean daily discharge values to within 1%. Ongoing study suggests that the deviations in the remaining 1% are a result of missing information within the savesets (specifically gauge and shift corrections) or incorrect start/end dates on stage discharge curves.

The automated extraction methods developed for the Ontario region can be modified to extract archived data from the other national offices. Approximately 39,700 station years of data exist nationally in the HOURLY saveset format. A trial extraction was conducted with 5,400 Manitoba and Northwest Territory discharge savesets. Although there are some differences in formatting between the Ontario and Manitoba files, 4,360 (80%) produced instantaneous data, of which 95.5% matched published daily averages to within 1%. It is theorized that the larger error rate in these savesets is due to irregularities in the dating of archived rating curves. It is expected this rate can be lowered substantially with further study.

The following report outlines the history and formatting of the input data supplied to the STREAM and HOURLY programs. A brief outline of the methodology used by ArkWSC is presented, with details on the accuracy and quality checking approaches. The quality of the extracted Ontario region instantaneous discharge data is discussed, as is the application of the ArkWSC procedures to National data.

HOURLY Background and Development

The STREAM computer program was the first automated computer program implemented by WSC to obtain daily mean gauge heights and discharges. The original STREAM program was developed from 1966 to 1968 through the combined efforts of Mr. J.J. Therrien and Mr. D.E. Cass. STREAM was written in Plain Fortran, a specification created by the Inland Waters Branch. Closer to FORTAN II, but combining some features of FORTRAN IV, the specification ensured compatibility with a range of computing systems. Primarily deployed on Univac and IBM mainframes with little physical memory by modern standards, the first versions made use of punch cards to input programs and data. Water level recorder charts were manually coded on a digitized table (Figure 1) to obtain punched cards containing the X-Y co-ordinates of straight-line segments of the water level trace. These cards were then combined with card decks which defined the stage-discharge relationship and the gauge, shift and updating corrections and then submitted for computer processing.

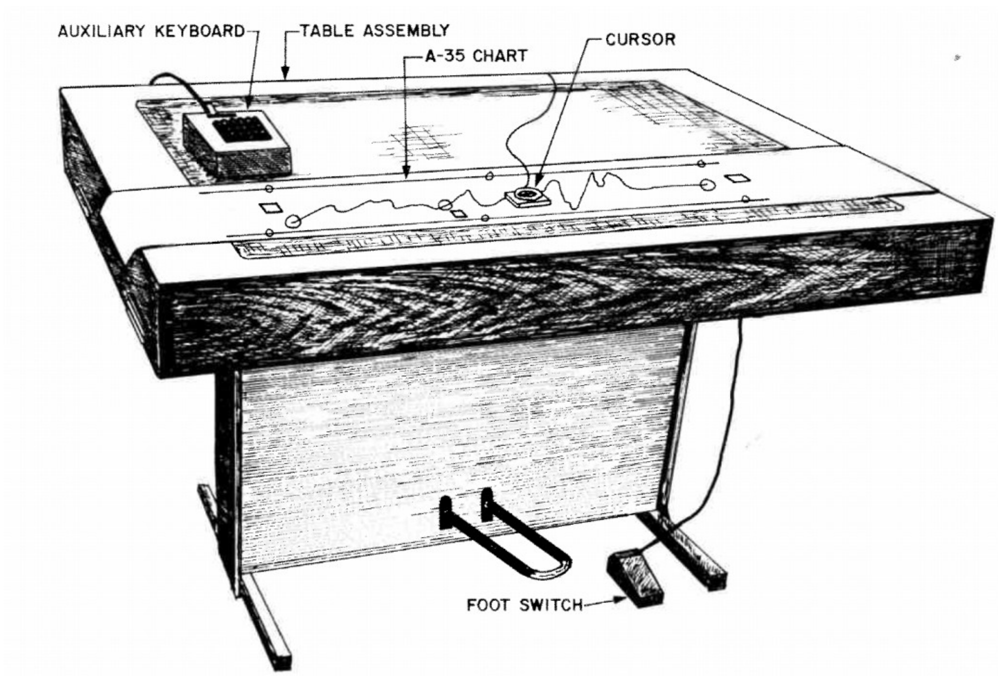

Figure 1 - Typical X,Y coordinate digitizing table

From 1968 to 1970 STREAM was implemented nationally, with an improved version arriving in 1973. The year 1975 saw the introduction of a program titled HOURLY. Derived almost entirely from STREAM source code, HOURLY was created to handle the output of instantaneous gauge heights and discharges at selected time intervals from the digitized water level traces. In addition, HOURLY also included the tidal computations which were formerly a part of STREAM. The card inputs for HOURLY were the same as were used with the STREAM program except for the initial “Options” or control card.

In 1976, some WSC hydrometric stations were converted to metric units, which prompted the development of an updated version of STREAM to handle the new input units. Through the 1980’s the STREAM and HOURLY programs were ported to the Fortran 77 programming language for use on a number of different operating systems and hardware, most commonly MicroVAX minicomputers. A new generation of digitizers led to a phasing out of the punch card inputs, however, the basic functioning of the program changed little from its origins. The input files were now entirely electronic, but the line by line formatting was identical to the card formats. STREAM and HOURLY, along with new programs to process sediment data and print hydrographs, were amalgamated into the @WSC hydrometric suite.

The early 1990's saw the introduction of CompuMOD, a graphical Windows based hydrometric suite which replaced STREAM in 1996 as the primary tool to compute daily average discharges. With a need to continue to digitize water level chart data, a version of HOURLY was ported to DOS to allow PC users to convert digitized water level data to a regular, instantaneous format for input into CompuMOD. Being outdated and redundant, no version of STREAM was ported to DOS. By the late 1990's water level chart recorders were quickly being replaced by digital recorders rendering HOURLY largely obsolete and unused by 2001.

Saveset Format

The formatting of the archived savesets follows the input card sequence used by the original STREAM program used to compute daily averages. Conceptually, every line within a saveset represents the information stored on a single punch card. Most cards were coded with the station ID and sequentially numbered to avoid sequence errors. An example saveset from 02GB008, Whiteman's Creek near Mount Vernon, for a portion of the year 1990, is provided for discussion. The paper water level chart for this period is provided in Appendix A. A brief description of the card types and saveset format is given as the various inputs provide some insight into the computational process used by HOURLY. A more detailed explanation of the various card types, their use and formatting can be found in "Automated Hydrometric Computation Procedures" dated 1977.

Saveset files contain blocks of data, inputted in the following order:

Update Corrections;
Rating Curve (if discharge is required);
Gauge Corrections;
Shift Corrections;
Digitized Data.

Often the saveset files are a digital copy of the original card deck used to analyze a given station year and compute the daily discharges. In these cases the saveset may contain the full station name and a STREAM control card (a series of control options, followed by the time span for analysis) at the beginning of the file:

```
02GB008   WHITEMANS CREEK NEAR MOUNT VERNON
02GB00851                     3W
02GB008 JAN 01 1990 DEC 31 1990
```

If the saveset is a copy of the original deck, the file will also contain a series of "End of " cards:

```
02GB008                                     UC                            999
02GB008                  27                                               999
02GB008                       GC                                          999
02GB008                       SC                                          999
```

These "End of" cards signify the end of input card blocks. These cards break up the input data into meaningful pieces for HOURLY to process and are required for the program to run successfully. A discussion of saveset parsing is presented below.

Update Correction Cards

```
02GB008 JAN 06 1990                    2.22 B UC                             1
02GB008 JAN 07 1990                    2.34 B UC                             2
02GB008 JAN 08 1990                    2.65 B UC                             3
```

In HOURLY, update corrections override the output of instantaneous data for days where the stage-discharge relationship does not apply. In STREAM, update cards were used to input daily data for ice or backwater conditions so that all the daily data would appear on the printed computational output. These cards were also used to transfer data between computational runs if there were multiple rating curves used during the year. Since the update corrections remaining in the saveset may not represent the actual data, ArkWSC discards all the discharge overrides in the savesets and recreates the override deck from the discharge symbols in HYDAT. This ensures that no valid instantaneous data is discarded.

Rating Curve

```
02GB008    1.157          0  27 OCT 04 1990 JAN 01 1990 DEC 31 1990          1
02GB008     1.16       0.01  27                                              2
  …
  …
02GB008     2.10       36.0  27                                             39
02GB008     2.20       43.6  27                                             40
```

Shift/Gauge Correction Cards

```
02GB008   -0.015 1410 DEC 14 1989 SC   M/M                                   1
02GB008   -0.019 1200 JAN 09 1990 SC   M/M                                   2
```

Digitized Data

Digitized chart data are made up of blocks of dependent cards. Where correction cards can vary from none to several hundred and are largely independent of each other, the blocks of water level data require distinct orientation, initialization and reference cards to run as a whole. A breakdown of a sample card deck is provided:

```
02GB008 JAN 01 1990 D12506                                              90 0001  1
02GB008 0167261525672623496326334974014625780136018001260083O715        90 0002  2
02GB008 10001295000101                                                  90 0003  3
02GB008 0083071500840717009407220111072501220722012507320139073201550724 90 0004
02GB008 0269072803530727044507280541073106460731075907330908073310860729 90 0005
02GB008 1386074015190741165007391773074518660749195507512058075221350759 90 0006
02GB008 2201079022130791223807822258079222680798230708072366081824260829 90 0007
02GB008 2602083527100837278908562862087329400881300908823074088930810886 90 0008  4
02GB008 3121090031260895318408793272087833390884342208943497091335650927 90 0009
02GB008 3686091937480898379808893863089438820898391608883974089440420923 90 0010
02GB008 4107097541420984419909784276097643540969443109554515093845820934 90 0011
02GB008 4733093647990930487009324955093450460932512809265141092551520925 90 0012
02GB008 51520925                                                        90 0013
02GB008 90001389113009                                                  90 0014
97 J.P.                                                                          5
```

1 - ***Chart Initial Orientation Card (1 Line)***

Line 1 indicates the starting date and time of the first point of the chart segment. For the example above, 12:00AM on January 1st, 1990 is the start time and date. The drive mode at the beginning of the chart, either reverse or direct, is denoted, in this case by a "D" for direct. The vertical water level range and horizontal time scale of the chart are given as 1.25m and 6cm per day respectively. The three digit vertical range of this chart indicates that this is a metric chart; English charts had a two digit vertical range.

2 - ***Orientation Co-ordinate Card (1 Line)***

Provides seven sets of 4-digit x,y coordinates in tenths of millimeters, six of which denote the selected working area of the chart on the digitizer table (similar in appearance to a drafting table approximately 100cm square, see Figure 1). Because the recorder chart could have been placed randomly on the table at any angle, the HOURLY program uses the six orientation points to determine the amount of stretch or shrinkage of the chart and to determine the angle of rotation. The seventh set of coordinates is the first observed point on the chart. The orientation points are shown on Figure 2.

3 - ***Reference Point Card (1 Line)***

Provides information on the first observed point (in this case denoted by a "1" of the left most character), or in the case of sequential charts decks, an observed check point. For the above example, the water level was found to be 1.295m at 12:01AM (based on the 24-hour clock time of 0001), on the first day of the month (the two right most characters indicate the day of the month).

4 - ***Digitizer Co-ordinate Card (10 Lines)***

Each line contains eight sets of 4-digit x,y coordinates in tenth of millimeters digitized from the recorder chart. This digitized water level is relative to the six orientation points on the reference point card. The water level points are shown on Figure 2 in relation to the orientation points.

5 - ***Reference Point and End of Chart Cards (2 Lines)***

Provides information on the last observed point (in this case denoted by a “9” as the left-most character) in the digitized series. For the above example, the final water level was observed to be 1.389m during a site visit at 11:30AM (based on the 24-hour clock time of 1130), on the ninth day of the month (the two right most characters indicate the day of the month). The difference between the water level and time of the first and last reference points in the series are used to calculate any required paper and time corrections. The final reference point is followed by an “End of Chart” Card” (denoted by “97”) and the initials of the digitizer operator or person responsible for the computations.

The following figure illustrates the water level data contained within the example block of digitized data above. The water level chart points contained within the block are taken relative to the six initial orientation points, and have time and vertical axis units of tenths of a millimeter. From the initial and end reference points, with the known vertical range and time scale of the chart, the digitized data can be converted to water level data in units of meters and days.

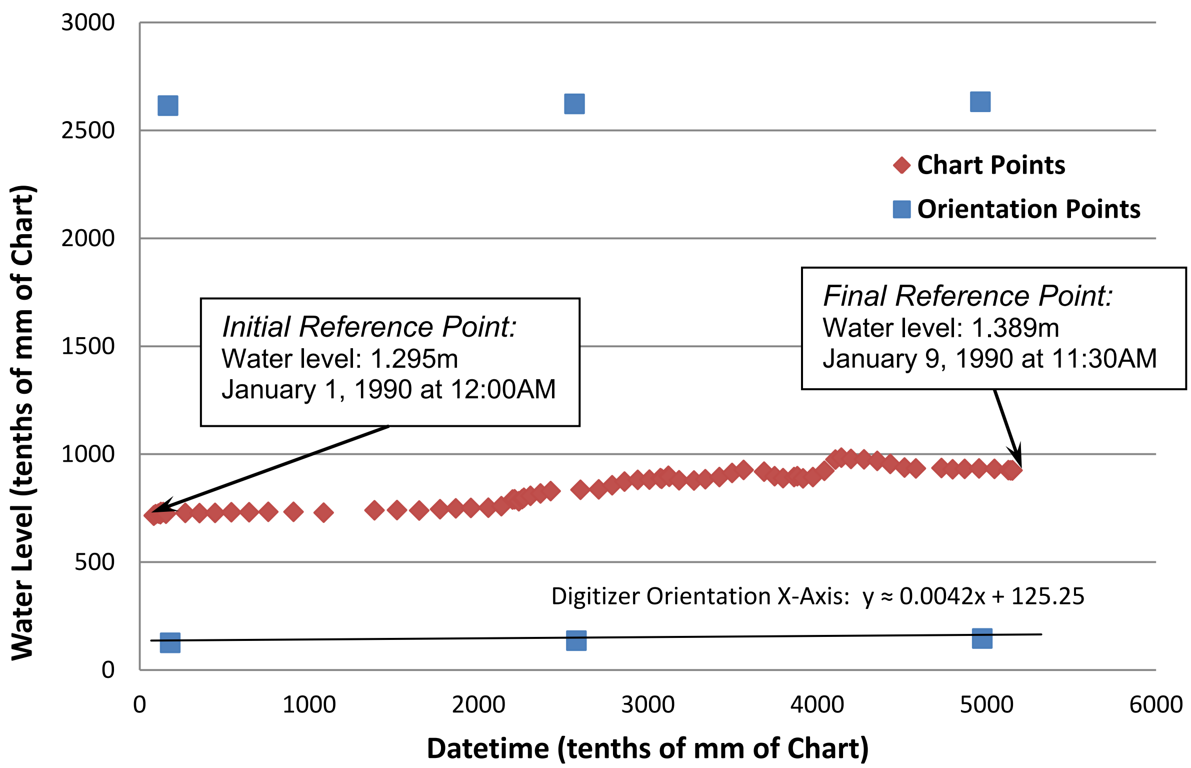

Figure 2 - Example digitized chart block

Figure 3 shows the computed 15 minute instantaneous water level and discharge data outputted by the HOURLY program for the block of digitized data from Figure 2. In addition to the 15 minute data, HOURLY also outputs the water level measurements taken directly off the water level chart, shown as blue points. Each point represents one pair of the 4-digit x,y coordinates in the block of digitized data. The gaps in the discharge data on January 6, 7 and 8 are the result of a backwater event. These data were overridden by the Update Correction cards described above.

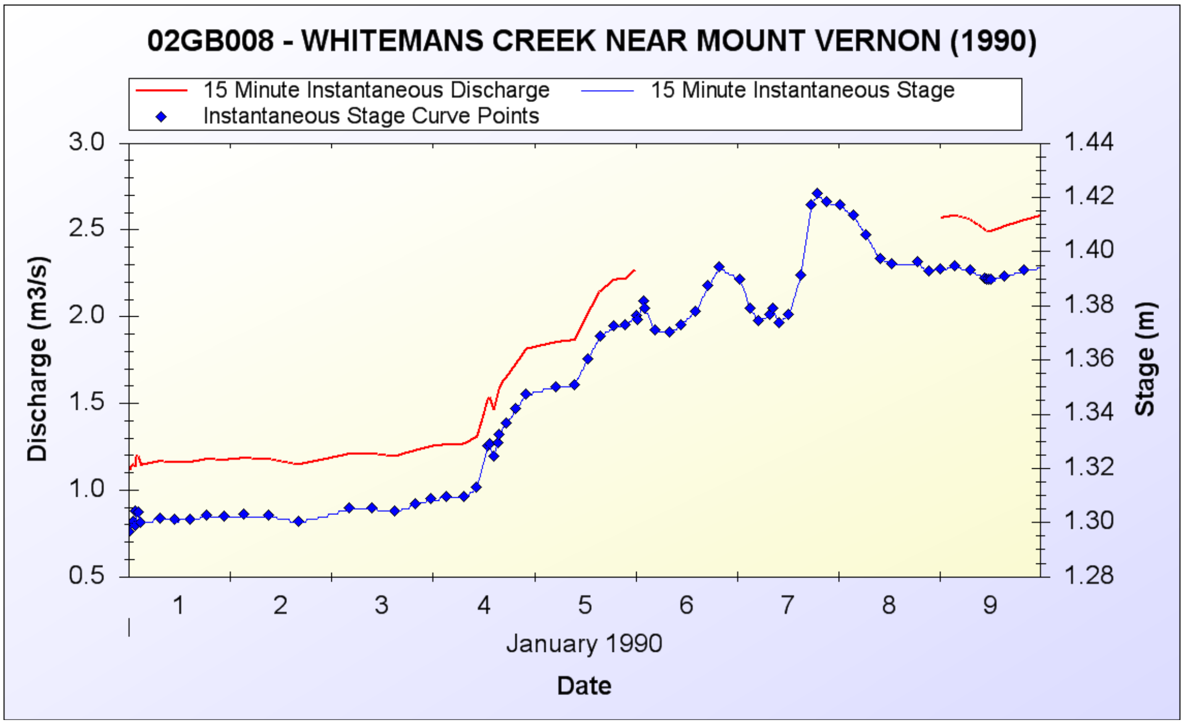

Figure 3 - Derived example instantaneous discharge and water levels

ArkWSC Program Methodology

The ArkWSC program consists of a series of subroutines written in the Visual Basic .NET programming language, compiled in Visual Studio 2005. ArkWSC works in concert with the DOS version of the HOURLY executable file; in programming parlance, ArkWSC acts as a “wrapper”. ArkWSC sorts through all of the saveset files and any rating curve files (*.TAB in the Ontario Region), collects information, creates the input files for HOURLY, runs HOURLY, then collates and analyzes the output. A description of the program is provided below. ArkWSC consists of several thousand lines of computer code, and while not overly complex, the detail cannot be completely summarized in the space allotted. A basic program flowchart is provided in Appendix B.

The following description outlines the function of the program when extracting Ontario data. In the Ontario region, all rating curves for a given station were stored in a specific file format (*.TAB). In most other regions, the rating curves were stored in the savesets themselves. Extracting these files would require a slightly more complicated setup although the approach would remain the same.

Setup and Extraction

- First, the user copies the files to be extracted into a single directory. Starting ArkWSC, the user inputs this directory into a text box and executes the program.
- ArkWSC checks every file in the input directory and sorts the files by station ID.
- For each found station, the program reads through every file in its entirety. It can be determined if there is valid water level trace data in a file by searching for the Chart Initial Orientation Card for each block of digitized data. ArkWSC notes the vertical range and time scale of each block of data. From this information, the units of the saveset can be determined. For metric conversion years, which required two runs for each unit type, the conversion date is recorded.
- The rating curves are loaded into memory for the requested station. The program then determines the units of each rating curve based on the curve start date and the relative change in magnitude of the discharge values between curves.
- Now that ArkWSC knows which files are valid, and has all of the rating curves in memory, it creates a series of extraction blocks for each station year. An extraction block details the start and end dates of the required run, the recorder units, and the rating curve for each block of yearly data to be run through HOURLY. The start and end dates of each block are based on the input requirements of HOURLY. Each run must have consistent units, and a single rating curve, requiring a new extraction block for each new stage discharge relationship. In some cases, both straight-line and curvilinear (Manitoba Pressure System) recorders were employed in the same year. HOURLY requires these differing chart types be run separately. Most commonly however, multiple runs are required to handle a new mid-year rating curve. Every metric conversion year also requires multiple runs to handle the change in chart units. ArkWSC determines the extraction blocks before moving, copying, or parsing any data.
- ArkWSC now processes the required extraction blocks one year (one saveset) at a time. Each saveset is parsed into distinct files containing the digitized data and the gauge corrections and shift corrections if available.
- The update corrections were originally coded as a means to output all the average daily values onto a single printout sheet, separating values between the various STREAM computational runs. Update Corrections prevent HOURLY from outputting instantaneous data for the day (regardless of the comment symbol), and many Update Corrections in the savesets are merely placeholders. As such, ArkWSC discards all the discharge Update Corrections in each saveset, (water level corrections are preserved). Every station year of daily discharge and water level information was extracted from the HYDAT CD, and parsed into individual station files. ArkWSC uses these files to recreate the Update Correction cards containing only days with valid overrides (e.g. due to backwater, ice, estimates etc.).
- ArkWSC then outputs the rating curve to a separate file in the appropriate card format. If a unit conversion is required, for example when a metric curve is to be applied to Imperial chart data, ArkWSC makes the necessary conversion.

- With the saveset parsed, and in the correct format for input to HOURLY, each extraction block for the year is processed. Firstly, the final input file, "Hourly.DAT", is created. The first lines contain the station information, which ArkWSC pulls from the station reference index. Then the HOURLY control card is created. The control card passes setup information to HOURLY, including the extraction dates, input and output units, the time interval, and if the chart data is from a curvilinear recorder. During a manual run, the user would input this information at the @WSC HOURLY options screen, which would then be used to create the options control card. This options menu represented a user friendly method of inputting the control parameters and its full function has been replicated by ArkWSC. A description of the HOURLY options card format is available in "*Automated Hydrometric Computation Procedures"*, 1977.
- Each block of data (*Update Corrections, Rating Curve, Gauge Corrections, Shift Corrections, Digitized Data*) is then appended to the Hourly.DAT file.
- ArkWSC calls the HOURLY executable , which processes the Hourly.DAT file.
- After HOURLY has executed, ArkWSC renames the outputted data.
- If there are multiple extractions required for each year, a new Hourly.DAT input file is created for each extraction block, and HOURLY is called again. The outputted data is renamed and organized by date.

Post Processing and Quality Checking

- After all the required HOURLY extraction runs are complete, ArkWSC collates the outputted water level and discharge data from the various runs, and moves it to a user specified output directory organized by station. ArkWSC also backs up the HOURLY log file (*.LST) and input file (Hourly.DAT) to this directory. For years requiring multiple runs, the input and log files are denoted with a letter to indicate their sequence.
- The water level and discharge data is then converted to a more user friendly format, either a column based text file or a *.CSV format.
- The irregular dataset based on the actual digitized data points is then sorted, and the effective water level and discharge calculated for each point based on the corrections and rating curve from its respective extraction block.
- Each day of instantaneous data is then checked against the published mean daily discharge, and deviations are noted in an Extraction Log. Both the quality checking and logging are discussed below.

Multi-Year, Multi-Station Processing

- The above operations are repeated for each station year (saveset) and for each stations worth of supplied data.

Appendix C outlines some of the systematic issues or errors that ArkWSC corrects. It is important to note that when a saveset does not extract correctly or does not match the published averages exactly that there may be nothing wrong with the archived files. HOURLY and STREAM were regularly updated over the 27 years the programs were in active service. File formats were changed (as in the case of the Update Correction Cards), and the computational rigor increased alongside the processing power of computers.

Quality Checking Against Published Data and Error Logging

The published daily average discharge (from HYDAT) was used to verify the quality of extracted instantaneous data. The average daily flow was calculated from the output of ArkWSC then compared to the historical data for that day. If a deviation was noted, it was logged in that stations Extraction Log file for the user to determine the validity of the data. This was required not only to verify the integrity of the archived saveset, but also to provide a rigorous quality assurance process for the ArkWSC program. *Every day of instantaneous data is compared against the historical values published in HYDAT.*

Two methods to calculate the mean daily average from instantaneous data were employed. Firstly, the sum of the 15 minute discharge measurements for each day was calculated. For most station years after 1980 this average is identical to the published values in HYDAT. For stations prior to 1980, the calculated values occasionally did not match the published data so exactly. Often only varying by one tenth of the trailing significant digit, and testing below the 1% deviation level, these perceived "errors" are minor. However, in an attempt to explain these deviations, subroutines similar to those used to calculate the daily averages during this period were coded into ArkWSC.

The STREAM program, employed on machines lacking in memory and processing power, utilized a subdivision method to calculate the daily average discharge which minimized computational requirements. The STREAM/HOURLY dataset is comprised of a series of irregular straight line measurements taken from the water level recorder trace. Knowing that minor changes in water level will cause only minor changes in discharge, a series of categories were developed to control when, and how often a straight line water level trace should be subdivided to calculate the discharge the segment. These categories and the subdivision method are outlined in "*Automated Hydrometric Computation Procedures"* (Ades, 1977), and with greater detail in "*Stream Programmer's Manual"* (Stewart & Comeau, 1974).

The subdivision method was coded into ArkWSC in an attempt to explain the minor variances in data from the 1970's. This method resolves some errors in the calculated daily averages; mostly for days with no change in water level. However, minor variances between the calculated and published daily averages remained. After detailed study of original paper charts, and many hundreds of savesets, it was concluded that this deviation was the result of some minor change in the STREAM program between its inception in 1968, and the 1978-80 version. Most likely a result of a change in the number of subdivisions required, or change to the way data-rounding was handled in the program. It has been theorized that early versions of STREAM attempted to emulate the operations a technician would have used to manually calculate a daily discharge value.

From the detailed study of the above problem, it was determined that a measurement calculated from the instantaneous data should be considered identical to the published value when the difference is zero or less than or equal to one tenth of the trailing significant digit. For example, for a day with a published daily value of 420 m^3/s, a calculated daily average from the instantaneous data could be 419, 420, or 421 m^3/s to be considered identical.

For each year, ArkWSC creates a log file detailing the extraction blocks for each year. The dates, rating curve number and units, as well as the chart units are logged. Every day that deviates from the published data is logged into this file. Figure 4 presents a typical log file for a station-year extraction. Note that the published (historical) daily average is provided, with the two calculated values based on the instantaneous dataset for suspect days.

```
Year = 1975

     Extraction Period: JAN 01 1975 to APR 20 1975
     Stage Discharge Curve #14
     Stage Discharge Curve Units: Imperial
     Saveset Units: Imperial

     Extraction Period: APR 21 1975 to DEC 31 1975
     Stage Discharge Curve #15
     Stage Discharge Curve Units: Imperial
     Saveset Units: Imperial
           ERROR - 21/03/1975     ACCURACY CODE = B   Historical = 32.80
                                                      ExtractedQQ = 33.00
                                                      ExtractedSD = 33.00

     Days of Complete Data: 339      Days with Complete Chart Data: 337
     Days on the Historical Record: 339
```

Figure 4 - Typical station-year extraction log

A summary log file is created for each station, which incorporates the log files from each year. Every day of data that deviates from the published values is logged in the master file. A brief discussion of the accuracy code as well as a legal disclaimer are provided with each station's data. A copy of this text is provided in Appendix D.

Accuracy Code

It has become apparent from the study of the archived files in the Ontario region that some savesets are not identical to those used to calculate the published mean daily average discharges. The deviations in the extracted instantaneous data are most often a result of 1) incorrect period of use dates on the rating curves; 2) missing rating curves; and 3) missing shift or gauge corrections. Missing rating curves and period of use dates can be obtained from the paper archive. In Ontario, the rating curves of approximately 50 stations were manually reentered from file copies.

Shift and gauge corrections are missing or erroneous in some cases where the saveset that was archived electronically was not the final version used for the yearly computations. This is more common with years requiring multiple extraction runs. In other cases, data has been revised years later without backing up a copy of the saveset used in the revised computations. To reliably reproduce missing shift corrections, a paper copy of the original STREAM computational run is usually required. The archived paper copy of the computer run sometimes does not include the shift corrections that were used during the final run. In these cases it is nearly impossible to reproduce the missing shift corrections. In the case of erroneous shift or gauge corrections, without the final version of the paper log it is impossible to determine if the corrections are actually the problem.

Ultimately, this means that some savesets can never be restored to their original condition. Two options exist to handle instantaneous data that do not produce a match with the published dailies. Firstly, the data could be discarded. Looking to retain as much data as possible, it was proposed to classify each 15 minute instantaneous point with an accuracy code representing the deviation from the published averages. These codes would inform the user of the quality of the instantaneous data.

Accuracy codes are used by the United States Geological Survey (USGS) (http://ida.water.usgs.gov/ida), who has made considerable effort over the past decade to provide a historical instantaneous dataset, which now includes over 9000 stations. An example output is provided in Appendix E. In the US, the electronic files used in the calculation of daily data were routinely discarded after use until the late 1980's. Some earlier data archived on paper charts is being processed manually. Water Survey is fortunate to have had the prudence and forethought to preserve the saveset archive, and can boast an instantaneous database that now spans over 40 years.

The accuracy codes and categories currently employed by the ArkWSC program are defined as follows:

- **A** - The daily mean discharge calculated with the instantaneous data from this day is **identical** to the published value plus or minus one tenth of the trailing significant digit.
- **B** - The daily mean discharge calculated with the instantaneous data from this day matches the published value to within **1 percent**.
- **C** - The daily mean discharge calculated with the instantaneous data from this day matches the published value to within **1** to **5 percent**.
- **D** - The daily mean discharge calculated with the instantaneous data from this day matches the published value within **5** to **10 percent**.
- **E** - The daily mean discharge calculated with the instantaneous data from this day matches the published value with **10** to **30 percent**.
- **F** - The daily mean discharge calculated with the instantaneous data from this day exceeded the published value by over **30 percent**. No instantaneous data has been outputted for this day.
- **N** - No valid instantaneous data exists for this day.

An alphabetic indicator (e.g. “A”) rather than a numerical type (e.g. “1”) was chosen to represent to the error codes. When manually reviewing large volumes of data, it was consistently easier to comprehend that “E” or “F” was poor data, as compared to numerical codes like “5” or “6”. All modern programming languages and spreadsheets now have functions that easily convert between character codes and their string equivalent (in Excel, the CODE and CHAR functions) for bulk computer analysis. While there may be some overlap with existing discharge comment codes, keeping the error codes simple and human readable was considered a priority. Providing the actual percent deviation was also considered, but it was found that breaking poor data into ranges was required for the bulk quality analysis of the ArkWSC project, and this option was not implemented.

The selection of the tolerance ranges used with the error codes was somewhat arbitrary. A deviation of less than 1 percent has been considered ideal since this projects inception, but even this value is arbitrary. Fortunately, most data (~99%) in the Ontario region falls into the best accuracy category; however, detailed peer review of the error code concept, practicality, and implementation is recommended.

Ontario Instantaneous Data Quality

Table 1 outlines the extraction of Ontario region savesets at present. 8,672 savesets theoretically contain discharge data, with ArkWSC able to extract data from 96%. Some savesets lacked rating curves for all or portions of their operating history and therefore cannot produce discharge data. This is to be expected as some stations were treated as water level only for the first few years of operation or alternated between water level and discharge operation. Water level only stations are, at present, outside of the scope of the ArkWSC project. In other cases, rating curves are missing from the electronic and paper archives.

Table 1 - Breakdown of Ontario saveset quality

	Number of Savesets	Percent
Ontario Savesets with Discharge Data	8 672	--
Savesets with Insignificant Errors	7 978	92.0%
Savesets with Significant Errors	381	4.39%
Savesets with no Apparent Data	83	0.96%
Savesets with no Rating Curves	170	1.96%
Savesets that crash ArkWSC	60	0.69%

The instantaneous data outputted from the 8,359 savesets that did extract were sorted into the accuracy categories outlined in the previous section. Of the valid savesets, 2.1 million days of instantaneous data were extracted and tested for quality. Nearly 99% of the instantaneous data matches the published mean daily discharge values to within 1%. The instantaneous data quality is summarized on Table 2. (Accuracy code B has been split into two subcategories for the purposes of quality checking the various extraction runs.)

Table 2 - Breakdown of Ontario instantaneous data quality

Accuracy Code	Description	Number of Days	Percent
A	No Deviation	2 105 127	98.22%
B	Between 0.1% and 0.5% Deviation	3 877	0.18%
B	Between 0.5% and 1% Deviation	2 275	0.11%
C	Between 1% and 5% Deviation	10 012	0.47%
D	Between 5% and 10% Deviation	6 198	0.29%
E	Between 10% and 30% Deviation	8 802	0.41%
F	Greater than 30 % Deviation (no data outputted)	6 988	0.33%
	TOTAL	**2 143 279**	

Output Formatting

HOURLY outputs 15 minute water level and discharge data in a fixed column, table format. The ArkWSC accuracy subroutines read and sort this data. Currently, ArkWSC outputs data to a human readable text column format similar to that from Compumod, as shown in Figure 5 as well as comma separated values (Figure 6).

```
2010-07-26 02:21:29     Pete Thompson, University of Waterloo

Interpolated Data for station: 02GB008 WHITEMANS CREEK NEAR MOUNT VERNON


Data from 1990-01-01 to 1990-12-31.
Interval: 15 Minutes

Corrections have been applied.
Metric Units - Water Level (m) & Discharge (m3/s)


Date/Time           Water Level              Discharge          Accuracy Code

1990-01-01 00:00:00  1.297                    1.11                 A
1990-01-01 00:15:00  1.299                    1.13                 A
1990-01-01 00:30:00  1.299                    1.14                 A
1990-01-01 00:45:00  1.3                      1.15                 A
1990-01-01 01:00:00  1.3                      1.14                 A
1990-01-01 01:15:00  1.299                    1.13                 A
1990-01-01 01:30:00  1.303                    1.19                 A
1990-01-01 01:45:00  1.303                    1.19                 A
1990-01-01 02:00:00  1.303                    1.19                 A
1990-01-01 02:15:00  1.302                    1.18                 A
```

Figure 5 - Example of ArkWSC text output format

```
Date,Time,Water_Level,Discharge,Accuracy_Code
1990-01-01,00:00:00,1.297,1.11,A
1990-01-01,00:15:00,1.299,1.13,A
1990-01-01,00:30:00,1.299,1.14,A
1990-01-01,00:45:00,1.3,1.15,A
1990-01-01,01:00:00,1.3,1.14,A
1990-01-01,01:15:00,1.299,1.13,A
1990-01-01,01:30:00,1.303,1.19,A
1990-01-01,01:45:00,1.303,1.19,A
1990-01-01,02:00:00,1.303,1.19,A
1990-01-01,02:15:00,1.302,1.18,A
```

Figure 6 - Example of ArkWSC comma separated value output

The data output from ArkWSC can be easily converted into any format. The Ontario instantaneous discharge data extracted with ArkWSC easily can be modified to suit any format requirements.

Resolution Comparison - Mean Daily vs. Instantaneous Data

Accurate, high resolution hydrograph data is essential for many types of analysis. Estimating the return period of flood events in an urban or flashy watershed requires information about all of the major events that occur during a year, not just a single instantaneous peak. Tracking the subtle changes to an urbanizing watershed also requires detailed data, not just for a single year, but ideally for the entire period of record. In addition, base flow analysis and hydrograph separation methods rely upon accurate data from the receding limb of a storm event. The recessional limb is often obfuscated, or hidden altogether in the daily mean time series.

There can be a substantial increase in hydrograph resolution between mean daily and instantaneous time series. Figure 7 and Figure 8 illustrate the relative difference in data resolution between mean daily and instantaneous data for an urban watershed. While the daily volume is equivalent between the daily mean and instantaneous hydrographs, a significant amount of resolution is lost. Distinct events on the instantaneous hydrograph are shown as a single event on the daily hydrograph. Figure 9 illustrates a mid-summer hydrograph from a seasonal gauge near the Peyto Glacier in Alberta. The diurnal effect on stream flow from glacial melt water is completely obscured on the mean daily hydrograph.

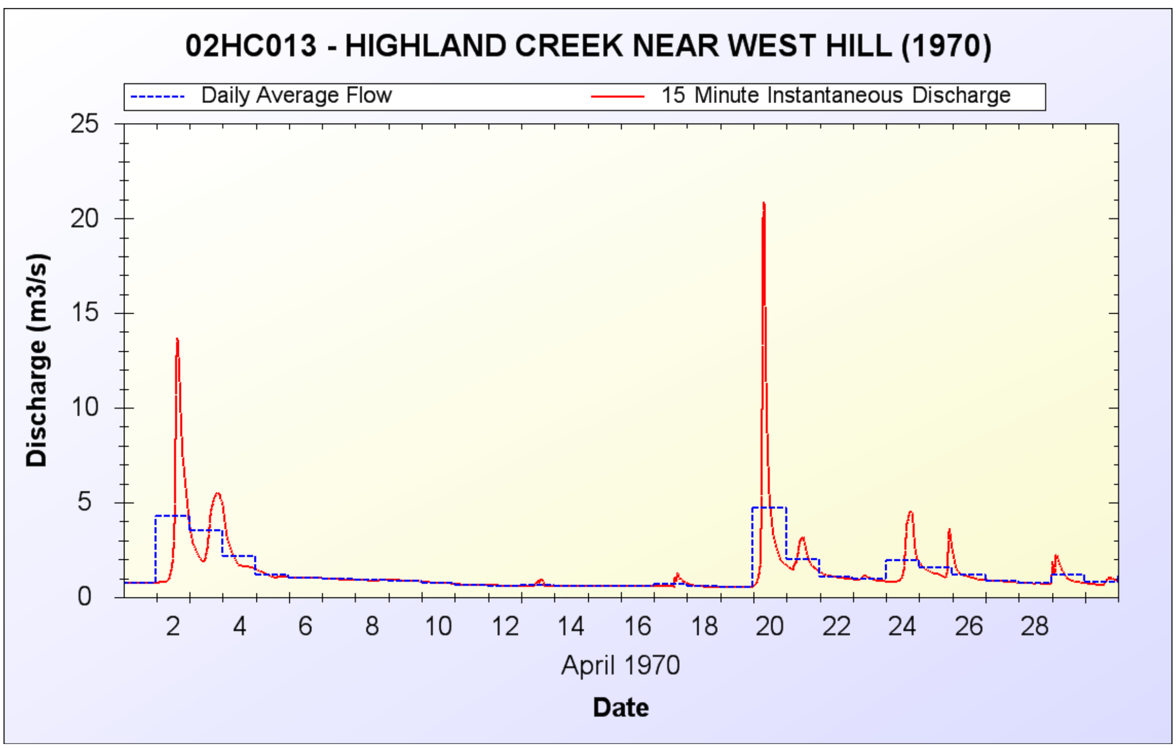

Figure 7 - Mean Daily vs. Instantaneous hydrograph comparison - Urban Ontario

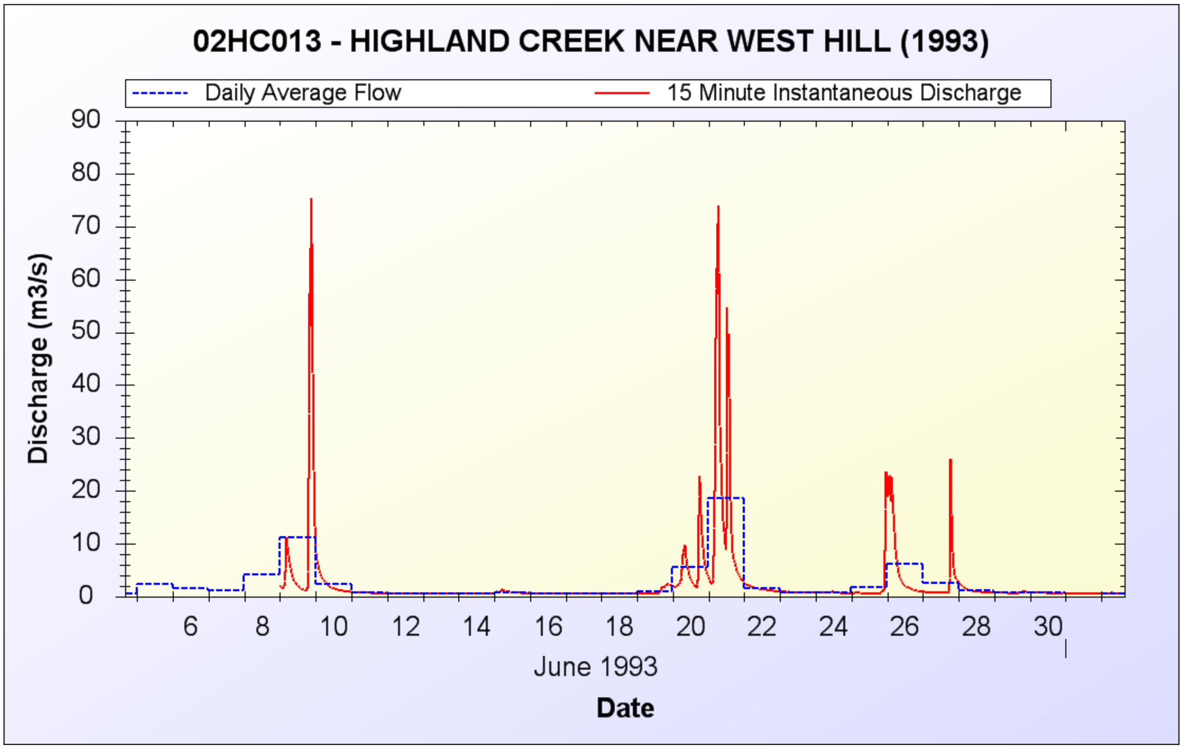

Figure 8 - Mean Daily vs. Instantaneous hydrograph comparison - Urban Ontario

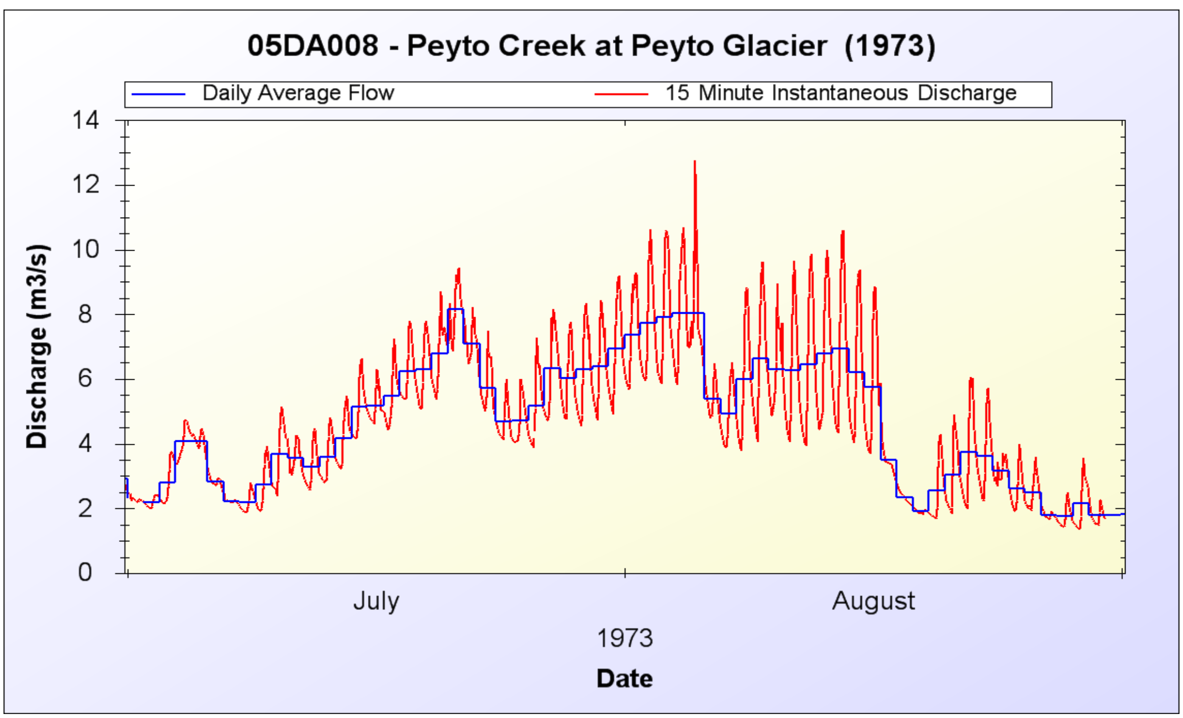

Figure 9 - Mean Daily vs. Instantaneous hydrograph comparison - Glacial runoff

National Archived Saveset Data

In early 2010, a request was sent to each Water Survey region to submit any available archived saveset data for analysis. With a focus on completing the extraction of Ontario data, the national savesets have been considered a secondary priority. However, the submitted data has been screened to determine the number of station-years of data. Each submitted file was checked for usable recorder water level data. Savesets that can be extracted with the ArkWSC methodology are summarized by office in Table 3.

Table 3 – Preliminary saveset breakdown by National Office

Office	Number of Savesets	Discharge Savesets	Water Level Savesets
Alberta	10 473	9 715	758
Atlantic	5 316	4 811	505
Manitoba	7 335	5 197	2 138
NWT	441	309	132
Ontario	8 815	8 390	425
PYR	0	0	0
Quebec	62	18	44
Regina	7 210	5 880	1 330
TOTAL	**39 652**	**34 320**	**5 332**

In the savesets from the western provinces, the rating curve is often contained within the saveset itself, as opposed to a separate file as in Ontario. The ArkWSC code was modified to test the quality of the saveset data from these regions.

A trial extraction was conducted with 5,400 Manitoba and Northwest Territory discharge savesets. Although there are some differences in formatting between the Ontario and Manitoba files, 4,360 (80%) produced instantaneous data, of which 95.5% matched published daily averages to with 1%. It is theorized that the larger error rate in these savesets is due to irregularities in the dating of archived rating curves. It is expected this error rate can be lowered substantially with further investigation.

Irregular Instantaneous Time Series

To the modern observer, the benefits of pressure transducers and data loggers relegate analog chart recorders to the past; however, chart recorders have one advantage over modern loggers. Chart recorders produce a continuous water level trace, free of gaps due to a prescribed sampling interval. While operating correctly, the recorder is constantly collecting data, capturing every peak and the break in slope of every event regardless of duration or intensity.

As discussed in previous sections, the HOURLY program makes use of the digitized water level chart data to calculate daily mean values. This irregular series of captured points is outputted by HOURLY as corrected water level. Since ArkWSC reads the rating curves and shift corrections into memory for each saveset into memory, it is a possible to calculate the effective water level (by applying the shift corrections) and discharge (by applying the rating curve) for each of these points. As discussed above, the production of this irregular discharge series was required to calculate the daily mean discharge by the subdivision method. Figure 10 illustrates the irregular water level and discharge points for a typical urban storm event.

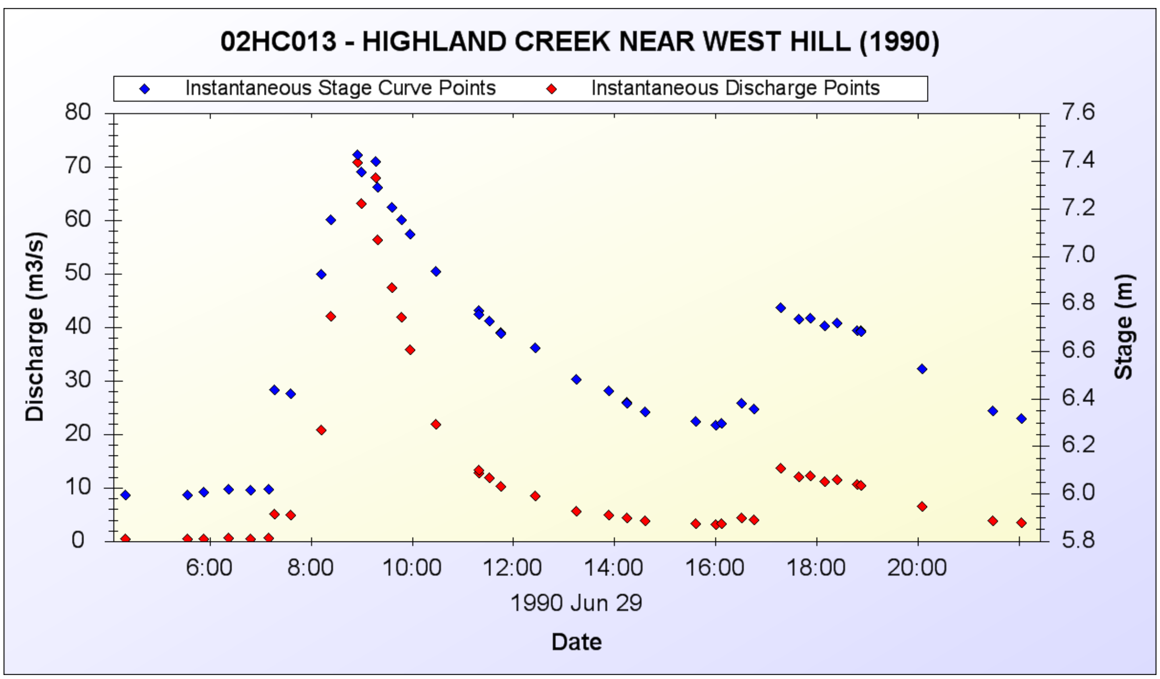

Figure 10 – Peak event showing discretely computed discharge values

With this detailed record, a unique instantaneous dataset can be created, which in some cases offers a higher resolution than 15 minute or hourly data. Figure 11 compares the irregular discharge dataset with 15 minute time series output from HOURLY for a large urban storm event. It is apparent that the digitized savesets can offer a higher degree of resolution for some events than even a 15 minute time series.

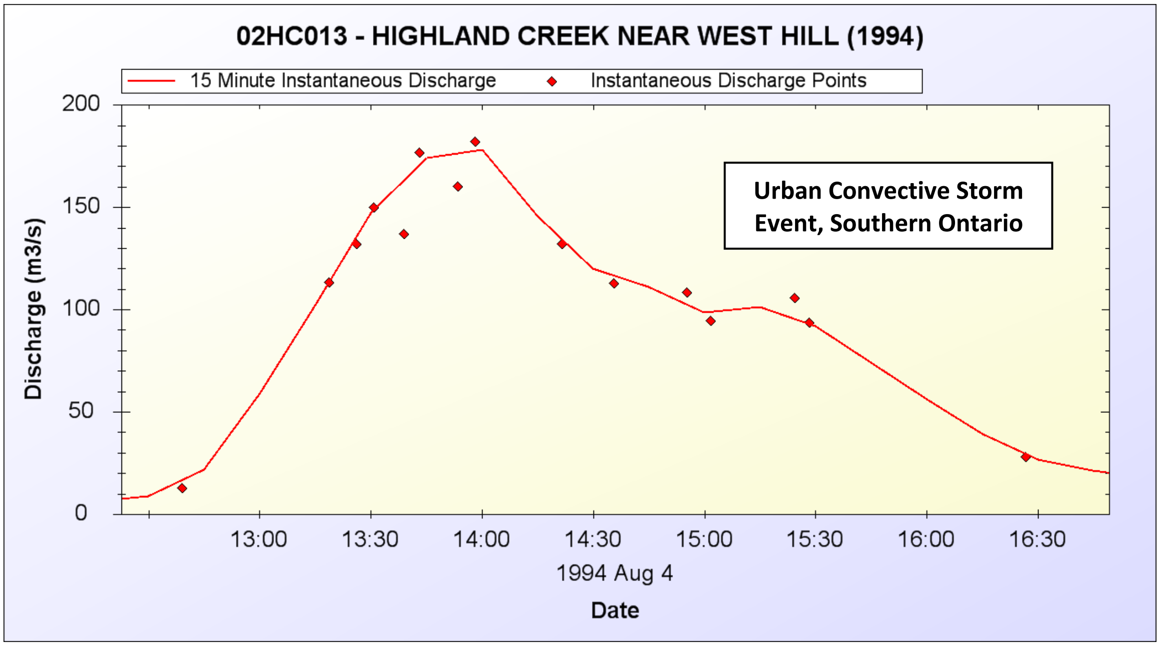

Figure 11 - Comparison of recorded discharge points versus interpolated 15 minute values

Figure 12 shows the irregular output for the rising limb of the urban event shown on Figure 11. An appropriate output format for irregular water level and discharge time series has yet to be developed. ArkWSC does not output discharge points for days with override corrections (due to ice or backwater) which leads to gaps in the data series. With sequential 15 minute or hourly data, each data point is accounted for, either with valid data or a null placeholder (-999.999). With irregular data, gaps in the dataset are continuous, and it may be unclear to the user that periods between points of data represent null values. When a line is drawn between two points (possible through a gap in the data series), it is easy to assume that the data between those points fits the line. A data format that efficiently accounts for gaps in the time series must be developed and documented before this dataset can be publically distributed.

DateTime	Waterlevel	Discharge
04/08/1994 10:51:27	5.992	0.365
04/08/1994 11:05:51	5.996	0.385
04/08/1994 12:05:02	6.512	6.22
04/08/1994 12:21:44	6.504	6.06
04/08/1994 12:39:01	6.743	12.7
04/08/1994 13:18:46	7.821	113
04/08/1994 13:26:15	7.990	132
04/08/1994 13:30:43	8.154	150
04/08/1994 13:38:55	8.035	137
04/08/1994 13:43:14	8.398	177
04/08/1994 13:53:28	8.246	160
04/08/1994 13:58:13	8.446	182

Figure 12 - Example output, irregular dataset

ArkWSC Project History

During the mid-Summer of 2006, Dr. Bill Annable of the Eco-Hydraulics Lab, Department of Civil and Environmental Engineering, University of Waterloo approached the Ontario Region of the Water Survey Division to obtain 15 minute or hourly time step instantaneous data for several urban watersheds in southern Ontario. Pete Thompson became involved in the fall of 2006 as a research assistant, and manually extracted a number of stations with @WSC under the supervision of Tom Arsenault.

In June 2007, Dr. Annable expanded his research to include selected rural Ontario stations. Recognizing a need to automate the extraction of data from @WSC, Pete Thompson began programming a method in Visual Basic to accomplish this task. Data verification and quality checking algorithms were coded during early 2008 at the suggestion of Tom Arsenault. Funding for the development of automated extraction methods during this period was provided by the Natural Sciences and Engineering Research Council of Canada, Discovery Grants program and by Dr. Bill Annable.

Hired as a casual WSD employee, the ArkWSC extraction process was expanded to include the entire Ontario Region in 2009 by the author. Further quality checking algorithms were added, and much of the previous extraction code was rewritten for clarity and efficiency. Development of the irregular dataset as a method of quality checking began in February of 2010.

Instantaneous data from this project has formed the basis of the following research papers:

Annable, W.K., Lounder, V.G. and Watson, C.C., Estimating channel-forming discharge in urban watercourses. *River Research and Applications*, n/a. doi: 10.1002/rra.1391

Annable, W.K., Watson, C.C. and Thompson, P.J., Quasi-equilibrium conditions of urban gravel-bed stream channels in southern Ontario, Canada. *River Research and Applications*. (In Press)

Conclusions and Future Work

The ArkWSC project has completed the entire extraction of Ontario archived instantaneous discharge data. The methods employed are systematic, consistent, and reproducible. The outputted data (as a 15 minute regular data set or an irregular digitized data set) has been verified against the original published daily mean values. Little deviation between the outputted instantaneous data and the published averages has been observed (less that 1% of the data extracted). The quality of the data is high, as the input files are identical to those used in the original computations. The HOURLY program was employed for over 30 years; ArkWSC adapts for changes within input formats and units, and documents errors or deviations from the published averages.

The most important advantage gained by the automated ArkWSC approach is consistency. Thousands upon thousands of extraction blocks are compiled, extracted, and tested in exactly the same way. Each bulk extraction run can be reproduced in a matter of hours and operator error is minimized. The user is removed from the selection, copying, extraction, and collating of files; as is potential introduction of human error.

An executable version of ArkWSC has not been compiled as of present. There are a number of subtle variations between savesets that can cause ArkWSC to crash. Most extraction runs are completed in Visual Studio's debugging mode in order to trace the nature of an error or crash, with manual modifications of the savesets often required. Currently ArkWSC is operated as a series of macros, rather than a fully functioning, stand alone program. Direct operator oversight is *always* required to fully diagnose saveset problems and quality check the outputted data.

In the Ontario region, the next goal is to expand the ArkWSC program to include the water level only station years. While only encompassing ~5% of the saveset data in the region, the extraction and testing methodology would be similar to the discharge stations.

The ArkWSC program has already been employed with considerable success to the Manitoba and Northwest Territories dataset. The process could easily be expanded to include all national savesets. In the Ontario region, approximately 100 savesets required manual alteration to run correctly, with many hundreds of stage discharge curves requiring manual entry or modification of curve dates. To obtain the same level of accuracy in the other regions, modifications to the ArkWSC program and extensive time with the paper station archives may be required to achieve the same level of success that has been met in the Ontario Region.

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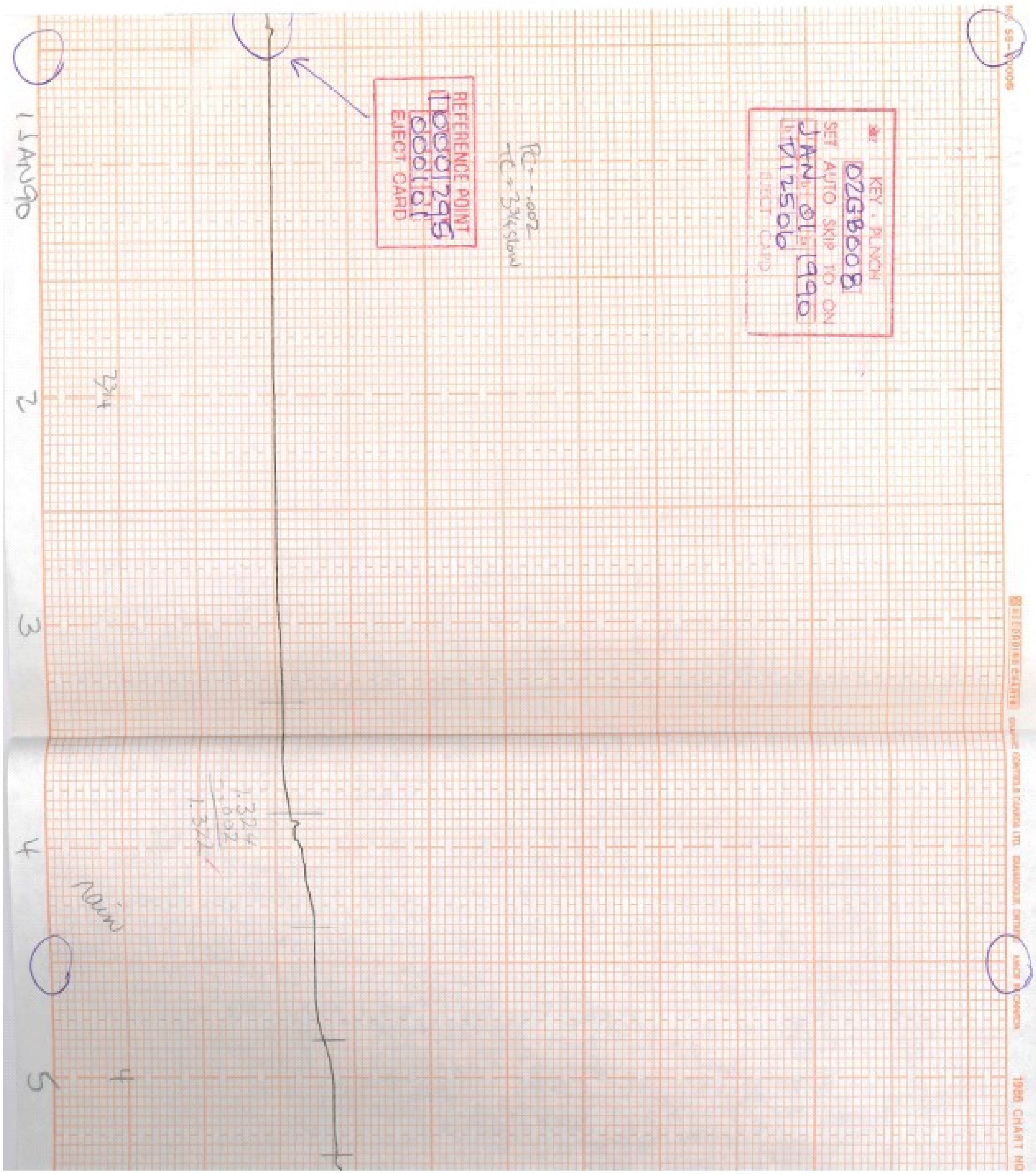
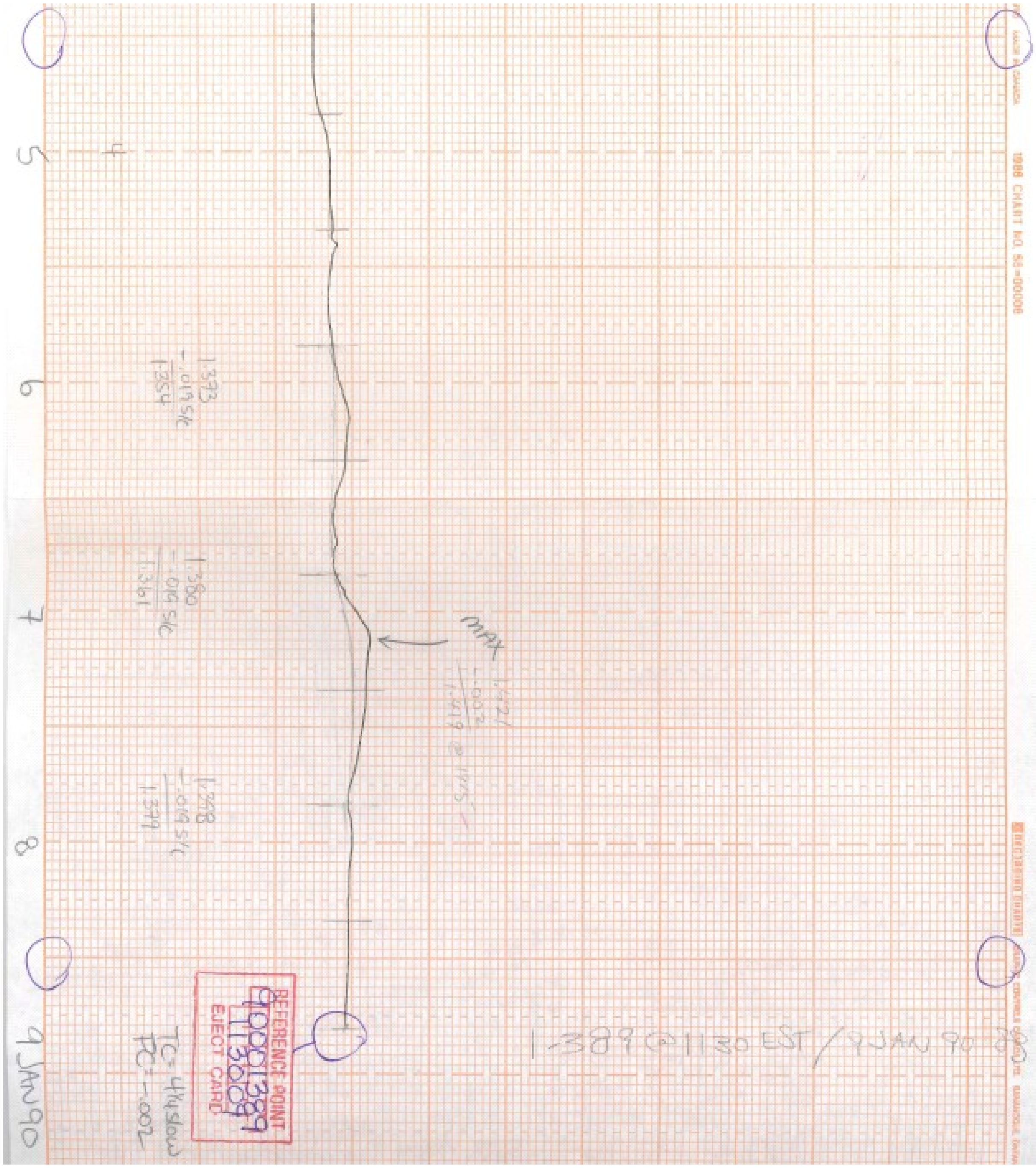
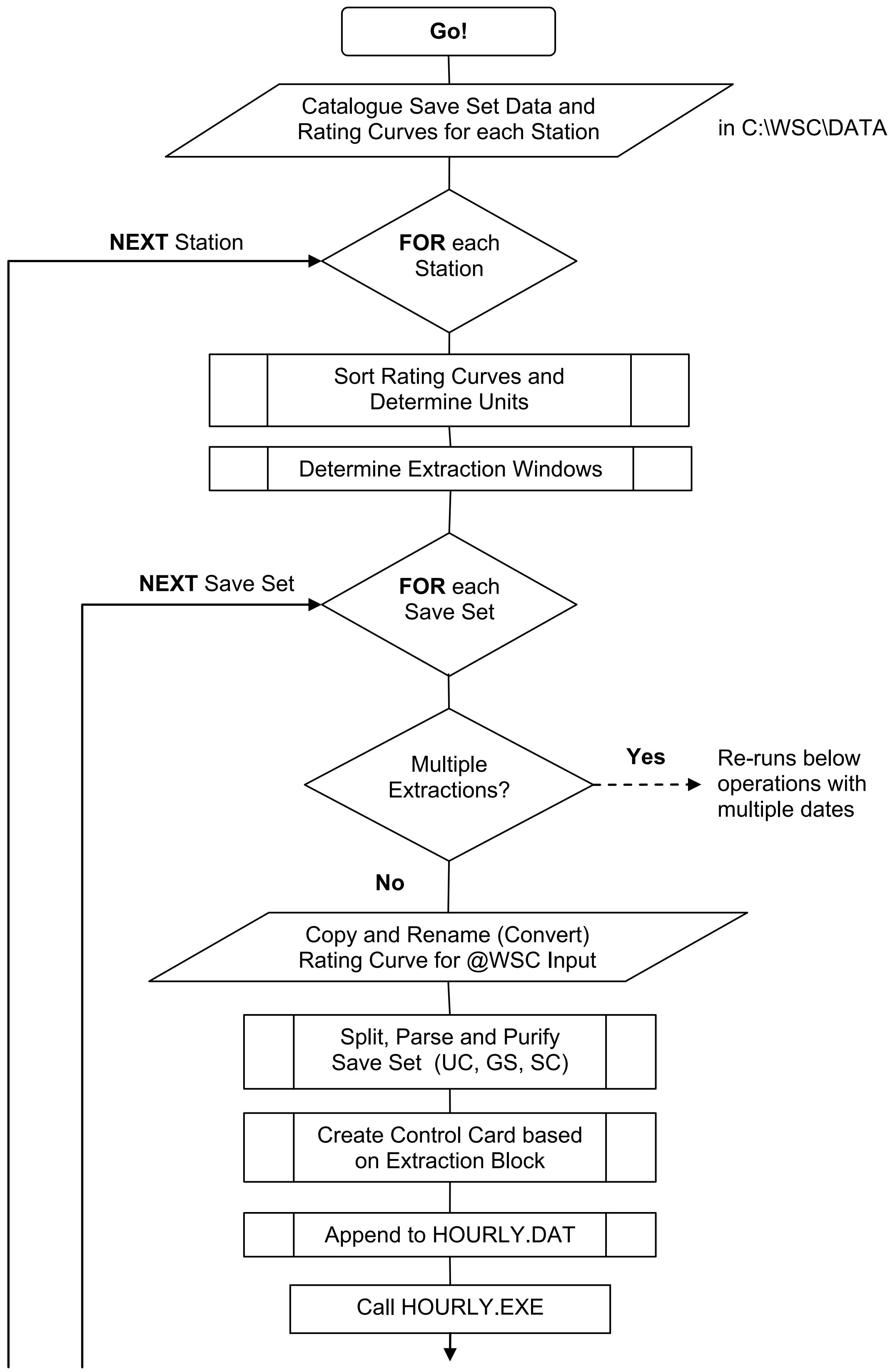
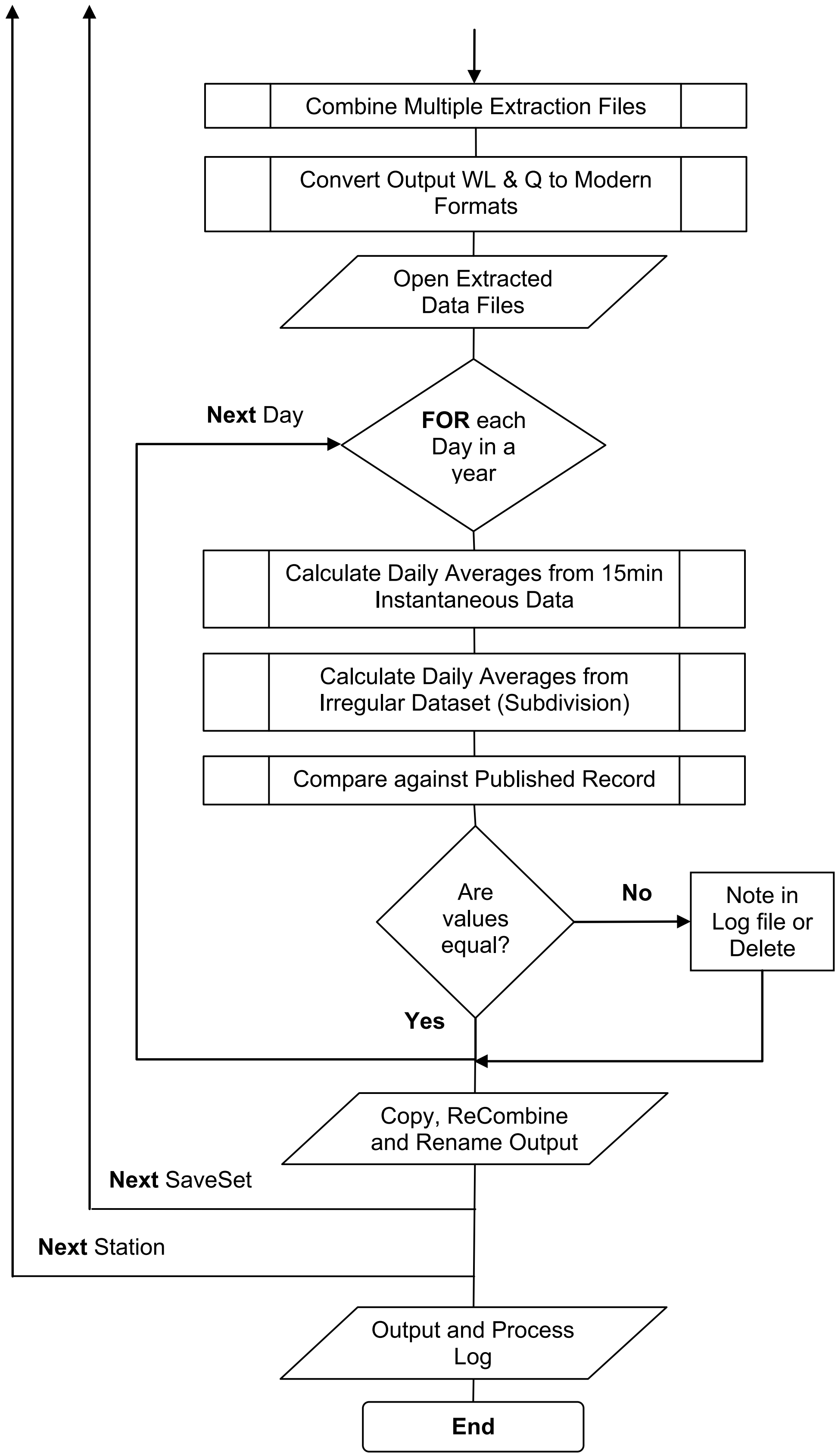
Appendix A – Example Water Level Chart (02GB008 – 1990)




MAX
REFERENCE POINT
EJECT CARD
9 JAN 90

Appendix B – Simplified ArkWSC Program Flowchart (Ontario)




Combine Multiple Extraction Files
Convert Output WL & Q to Modern Formats
Open Extracted Data Files
Next Day
FOR each Day in a year
Calculate Daily Averages from 15min Instantaneous Data
Calculate Daily Averages from Irregular Dataset (Subdivision)
Compare against Published Record
Are values equal?
No
Note in Log file or Delete
Yes
Copy, ReCombine and Rename Output
Next SaveSet
Next Station
Output and Process Log
End

Appendix C – Corrected @WSC Saveset Issues

Extracting data via @WSC can appear complicated due to the rigid formatting conditions in the original code and significant care must be taken to observe proper syntax and execution. However, this rigid formatting makes it possible to correct systematic errors in the savesets with automated computer code. Below are examples of issues that have been accounted for within ArkWSC.

Convoluted Process to Replicate UNIVAC "End of Table" Card

The @WSC HOURLY program was ported directly from UNIX. The DOS program that emulated the original version still required the input files to be in a similar form as the original card files. The system used specific cards to indicate the end of a chart deck or a correction table. These End of Chart or End of Run cards are replicated in the current version when "97", "98", or "999" are placed on a single line.

The "Save File Extractor" program within @WSC parsed the saveset's into the appropriate sections (*.HQ files) based on indicators placed through the file. The HOURLY program inputs the parsed data as *.DAT files (appended *.HQ files), not as whole savesets. With some savesets missing the proper indicator values, and the Extractor prone to the occasional unknown crash, the parsing subroutine was rewritten in ArkWSC and given a more robust method for breaking up the various files. (Based on identifying characters or chart codes given on each line or with each block of data, rather than the "99" cards) The "End of …" 99 and 999 cards are replaced when the various files are combined into HOURLY.DAT for input.

Improper Units within Update Correction File

The original HOURLY program was written in the late 1960's with only Imperial units in mind. When Canada adopted the Metric system, the program was revised. A code column was incorporated into the Update Correction table (a card file at the time) indicating the appropriate units. Imperial update corrections required a "1" in column 76 of each line, while metric corrections left the column blank. Files created before the metric conversion year (generally 1978 or 1979 for hydrometric data) don't have this code, as it wasn't required at the time. This results in an error with Imperial savesets as @WSC cannot reconcile the Imperial chart data with the apparently metric update corrections. This can be overcome by the user, if when prompted the option "Metric Updating Units" is selected.

To correctly extract this data, ArkWSC first determines the chart unit (from the various Chart Initial Orientation Card's), and then inserts the required code (1) in the Update Correction file when imperial data is detected.

Incorrectly Coded Update Corrections

When multiple rating curves were employed in @WSC for a given year, multiple runs would be required as the program could only work with one curve at a time. To compensate, the operator would run each curve separately, calculating the daily averages for the entire year in blocks. To produce a single computation summary with all the daily averages for a given year in one report, the operator would insert the calculated averages as update corrections. The presence of an update correction prevents the extraction of instantaneous data, as @WSC assumes the rating curve is invalid (backwater, assumption, or estimate).

While @WSC will run and produce data; not all available, valid data will be extracted. ArkWSC compares the update correction values and code to those within HYDAT and removes any erroneous codes. ArkWSC runs each curve separately then combines all of the runs in a given year into single files negating the need for these extra update corrections. Occasionally, overrides exist with HYDAT and not the saveset, in this case the overrides are added to the saveset.

Incorrect Sequence Number within Correction Files

The precursor card file system required each card to be number sequentially to avoid sequence errors. In the modern version of @WSC each card is represented as a line of text within an input file. Each line must be numbered sequential as with the card files. Often within the data sets, this numbering will be incorrect, especially when multiple runs were required within a single year and the operator combined the various input files for storage. An incorrect sequence number will result in a crash of the original @WSC HOURLY program. ArkWSC renumbers each correction (update, gauge, or shift (in fact, renumbers all the input files)) to avoid this error.

Systematic Character Repetition

In the Ontario rating curve files, a systematic repetition of some characters was discovered. It is unclear whether this was due to a read/write error from paper card to magnetic tape or from magnetic tape to some other format or perhaps some form of data corruption. Regardless, the current electronic versions of many rating curves from the 1970's do not match the originals used for the computations. An algorithm was written to test and correct the rating curve files.

Ampersand (&)

A peculiarity of UNIVAC addition/subtraction circuitry was that the ampersand symbol was occasionally treated as a numeric character. As such, several ampersands exist within the Save Sets that are actually a null value. The ArkWSC parses all ampersands.

Weir Code – Outputting Data to Four Significant Digits

In 1981 the STREAM and HOURLY programs were modified to provide an option for computing discharges to a fourth decimal point. Since this capability is mostly required for low flow weir stations, the option is invoked by the use of a "W" on the option card. The computed data will be shown as follows:

0.0001
0.0011
0.0111
0.111
1.11
11.1 111 1110 etc.

While it is possible to output data to four significant figures, it is not possible to recompute the historical data in many cases (for these low flow stations) to a fourth decimal point because the stage-discharge curves had been rounded to three places and would therefore give erroneous results. The weir code is only applied when the STREAM control card at the beginning of a saveset indicates the historical daily average was calculated to four significant digits. Future coding will call the historical daily averages from HYDAT to make this determination, and parse the saveset appropriately.

Differing Units on the Shift/Gauge Corrections during the Conversion Year

The @WSC HOURLY program does not prompt the user to indicate the units of shift and gauge corrections. The shift and gauge correction cards hold no information regarding the units of the correction, and rely on the user to only input metric corrections for metric chart data. During the metric conversion year, the units on the correction cards must match the units on the water level trace. The Update Corrections are pulled from HYDAT making the conversion a simple one; however, a more complex algorithm is employed to parse and convert the shift and gauge corrections to the appropriate units. In many savesets for the metric conversion year, shift and gauge corrections exist in both metric and imperial units. Sometimes these values overlap or are repeated in the file for both units. Overlapping shift/gauge correction dates cause a crash in HOURLY. To resolve this ArkWSC first attempts to separate the corrections by block. Next, it sorts corrections by date, and then attempts to parse them by magnitude. The shift/gauge correction cards contain no information about the units of the corrections, and user intervention is occasionally required to accurately parse the corrections.

Any and all other Issues

Other errors may exist within the savesets or the automation program may incorrectly deal with the above issues. In these cases, the accuracy check against the daily average values will flag the suspect data for a manual inspection.

Appendix D – Instantaneous Data Background and Disclaimer

WATER SURVEY OF CANADA – INSTANTANEOUS HYDROMETRIC DATASET (AUGUST 2010)

BACKGROUND

The collection and publication of stream flow information by Environment Canada has primarily focused on daily mean (or average) values as a final product. Standard computerized methods for calculating these daily values which made use of detailed instantaneous measurements have been in place since 1969. Fortunately, most of the computer files originally used to calculate the daily mean discharge or water level for a given year have been preserved in an electronic form. Where possible, instantaneous 15 minute data has been extracted from these archived files. The software employed to obtain this data was nearly identical to the same software originally used for daily calculations.

ACCURACY CODE

While derived from original records, over time some information in the archived files may have been lost or corrupted. To provide a basic level of review and quality assurance of these data the daily average discharge of each days worth of generated instantaneous data has been automatically checked against the published values in the HYDAT database. An accuracy code is provided in the dataset for each instantaneous value to inform the user of any deviation from the published values. Although significant effort has been made to ensure the instantaneous data provided is valid, there may still be significant error in any individual value. USERS ARE ADVISED TO REVIEW ALL DATA CAREFULLY BEFORE USE.

A summary file outlining the data available for each station is provided with a list of days that deviate from the published values broken down by year.

The following accuracy codes have been assigned to represent the deviation in instantaneous value from the daily mean:

A - The daily mean discharge calculated with the instantaneous data from this day is identical to the published value plus or minus one tenth of the smallest significant digit.
B - The daily mean discharge calculated with the instantaneous data from this day matches the published value to within 1 percent.
C - The daily mean discharge calculated with the instantaneous data from this day matches the published value to within 1 to 5 percent.
D - The daily mean discharge calculated with the instantaneous data from this day matches the published value within 5 to 10 percent.
E - The daily mean discharge calculated with the instantaneous data from this day matches the published value with 10 to 30 percent.
F - The daily mean discharge calculated with the instantaneous data from this day exceeded the published value by over 30 percent. No instantaneous data was generated for this day.
N - No published daily value exists to compare this instantaneous data against.

Note: Instantaneous discharge may not be available for periods influenced by ice or backwater conditions or for intervals where there was no measured data available. Consult the daily data symbols available in HYDAT for more information regarding a specific period with no instantaneous data.

Appendix E – Example USGS Instantaneous Data Format

```
# retrieved: 2009-08-05 16:30:06 CST
#
# Data for the following station is contained in this file
# ---------------------------------------------------------
#  USGS 01348000 EAST CANADA CREEK AT EAST CREEK NY
#
# This data file was retrieved from the USGS
# instantaneous data archive at
# http://ida.water.usgs.gov
#
# ---------------------WARNING---------------------
# The instantaneous data you have obtained from
# this automated U.S. Geological Survey database
# may or may not have been the basis for the published
# daily mean discharges for this station. Although
# automated filtering has been used to compare these
# data to the published daily mean values and to remove
# obviously bad data, there may still be significant
# error in individual values. Users are strongly
# encouraged to review all data carefully prior to use.
# These data are released on the condition that neither
# the USGS nor the United States Government may be held
# liable for any damages resulting from its use.
#
# This file consists of tab-separated columns of the
# following fields.
#
# column       column definition
# -----------  -----------------------------------------
# site_no      USGS site identification number
# date_time     date and time in format (YYYYMMDDhhmmss)
# tz_cd        time zone
# dd           internal USGS sensor designation (''data descriptor'')
# accuracy_cd  accuracy code
#                   0 - A daily mean discharge calculated from the instantaneous
#                       data on this day is 0.01 cubic feet per second
#                       or less and the published daily mean is zero.
#                   1 - A daily mean discharge calculated from the instantaneous
#                       data on this day matches the published daily mean
#                       within 1 percent.
#                   2 - A daily mean discharge calculated from the instantaneous
#                       data on this day matches the published daily mean
#                       from greater than 1 to 5 percent.
#                   3 - A daily mean discharge calculated from the instantaneous
#                       values on this day matches the published daily mean
#                       from greater than 5 to 10 percent.
#                   9 - The instantaneous value is considered correct by the
#                       collecting USGS Water Science Center. A published daily
#                       mean value does not exist and/or no comparison was made.
# value        discharge in cubic feet per second
# precision    digits of precision in the discharge
# remark       optional remark code
#                 Remark  Explanation
#                   <     Actual value is known to be less than reported value.
#                   >     Actual value is known to be greater than reported value.
#                   &     Value is affected by unspecified reasons.
#                   A     Value is affected by ice at the measurement site.
#                   B     Value is affected by backwater at the measurement site.
#                   e     Value has been estimated by USGS personnel.
#                   E     Value was computed from an estimated value.
#                   F     Value was modified due to automated filtering.
#                   K     Value is affected by instrument calibration drift.
#                   R     Rating is undefined for this value.
#
#
site_no date_time       tz_cd   dd      accuracy_cd     value   prec    remark
15N     14N     6S      2N      5S      16N     1S      1S
01348000        19910101000000  EST     1       1       2930    3
01348000        19910101001500  EST     1       1       2920    3
01348000        19910101003000  EST     1       1       2920    3
…
```

Appendix B

Event Parsing Algorithm - Source Code

The following source code was written in Microsoft Visual Basic 2005 (.NET Framework 2.0) for the purpose of identifying storm events within high resolution hydrograph data. Key functions and classes have been included. The ZedGraph class library is required to deploy the code as written below. The ZedGrpah library is open source and publicly available at http://sourceforge.net/projects/zedgraph/.

```
Private Function FindValley(ByRef zppData As PointPairList, ByRef inStart As Integer) As Integer

    'FYI, this sub won't account for missing data,

    Dim dtPrev As DateTime
    Dim dtCurr As DateTime
    Dim dtNext As DateTime

    Dim dbDiffBack As Double
    Dim dbDiffForw As Double

    Dim sgDischargeSigFig As Single = 0.00105

    For inForwardValleyFinding As Integer = inStart + 1 To zppData.Count - 5

        'Get the Dates of the points in the sweep
        Dim ZedsDatePrev As XDate = zppData(inForwardValleyFinding - 1).X
        dtPrev = ZedsDatePrev.DateTime

        Dim ZedsDateCurr As XDate = zppData(inForwardValleyFinding).X
        dtCurr = ZedsDateCurr.DateTime

        Dim ZedsDateNext As XDate = zppData(inForwardValleyFinding + 1).X
        dtNext = ZedsDateNext.DateTime

        'Diff(1-2)
        dbDiffBack = (zppData(inForwardValleyFinding).Y - zppData(inForwardValleyFinding - 1).Y)
             / dtCurr.Subtract(dtPrev).TotalDays
        'Diff(2-3)
        dbDiffForw = (zppData(inForwardValleyFinding + 1).Y - zppData(inForwardValleyFinding).Y)
             / dtNext.Subtract(dtCurr).TotalDays

        If dbDiffBack < sgDischargeSigFig / dtCurr.Subtract(dtPrev).TotalDays And dbDiffForw >
            sgDischargeSigFig / dtNext.Subtract(dtCurr).TotalDays Then

            FindValley = inForwardValleyFinding
            Exit Function

        End If

    Next

    'No valley was found found....
    FindValley = -9999

End Function
```

```
Private Function FindPeak(ByRef zppData As PointPairList, ByRef inStart As Integer, ByVal inEnd
    As Integer) As Integer

    Dim dbTestforPeak As Double = zppData(inStart).Y
    Dim inPeakLocation As Integer = Nothing

    For inForwardPeakFinding As Integer = inStart + 1 To inEnd - 1

        If zppData(inForwardPeakFinding).Y > dbTestforPeak Then

            dbTestforPeak = zppData(inForwardPeakFinding).Y
            inPeakLocation = inForwardPeakFinding

        End If

    Next

    FindPeak = inPeakLocation

End Function
```

```
Private Sub PeakFinder(ByVal zppInput As PointPairList, ByRef listEvents As List(Of ObjEvent), ByRef
    listExtraCurves As List(Of objZedCurve), ByVal stStationID As String, ByVal inYear As Integer)

'Ver 4. - Nov 2011 - PJT Mod for baseflow preconditioning, disabled for urban analysis.  Required
    for ALT, MAN, NWT analysis

        'Base threshold constants used by the PeakFinding Algorithm, read CSV for catchment specific
             values
        'The minimum peak discharge (m^3/s) required for an identified peak to be considered an
            event
        Dim dbThresholdMinimumDischarge As Double = 2
        'The minimum number of points required to constitute an event
        'MEASURED points, independent of time step.  Are there enough measured points to define an
            event?
        Dim inThresholdMinimumNumberofPoints As Integer = 6
        'A percent value that determines when to create a new primary event
        Dim sgThresholdPercentThresholdtoEndEvent As Single = 0.25

        'Read in any predefined thresholds from file for study catchments
        Dim stInput As String
        Dim stSplitLine() As String

        Dim stDelim As String = ","
        Dim chDelimiter As Char() = stDelim.ToCharArray()

        Using srCheck As StreamReader = File.OpenText("C:\FlowData\Peak_Finding_Constants.csv")

            Do Until srCheck.EndOfStream

                stInput = srCheck.ReadLine()
                stSplitLine = stInput.Split(chDelimiter, 10)

                If stSplitLine(0) = stStationID Then

                    If stSplitLine(1) <= inYear And stSplitLine(2) >= inYear Then

                        If stSplitLine(3) <> "" Then
                            dbThresholdMinimumDischarge = stSplitLine(3)
                        End If

                        If stSplitLine(4) <> "" Then
                            sgThresholdPercentThresholdtoEndEvent = stSplitLine(4)
                        End If

                        If stSplitLine(7) <> "" Then
                            inThresholdMinimumNumberofPoints = stSplitLine(7)
                        End If

                    End If

                End If

            Loop

        End Using


        'Prefer the user entered variables on the form if available
        If IsNumeric(txtEndofEventThreshold.Text) Then
            sgThresholdPercentThresholdtoEndEvent = CSng(txtEndofEventThreshold.Text)
        End If

        If IsNumeric(txtbxMinDischarge.Text) Then
            dbThresholdMinimumDischarge = CSng(txtbxMinDischarge.Text)
        End If



        'Get Daily Mean Data
        Dim zppYearlyData As New PointPairList
        GetDailyRecord(stStationID, inYear, zppYearlyData, 0, False)
        Dim inWindowsSizeDays As Integer = 5


        'Create a 5-Day UKIH Baseflow Hydrograph
        Dim zppYearlyBaseflowHydrograph As New PointPairList
        Dim zppYearlyTurningPoints As New PointPairList

        Baseflow.UKIH(zppYearlyData, zppYearlyBaseflowHydrograph, zppYearlyTurningPoints,
            inWindowsSizeDays)


        'Use ReturnInstBaseflowDischarge to interpolate between turning points. Disabled for urban
            analysis.
```

```
'Loop through the entire dataset, hopping from valley to valley
For inI As Integer = 1 To zppInput.Count


    'Accounts for missing sections of data by fast forwarding the search when a gap are
         encountered in the dataset
    If zppInput(inI - 1).IsMissing = True Or zppInput(inI).IsMissing = True Or zppInput(inI
         + 1).IsMissing = True Then

        For inIMissingData As Integer = inI To zppInput.Count - 10
            If zppInput(inIMissingData).IsMissing = False Then

                inI = inIMissingData + 1
                Exit For

            End If
        Next
    End If


    'Find the next valley in the time series
    Dim inValleyStart As Integer = FindValley(zppInput, inI)


    'Have we hit the end of the dataset?
    If inValleyStart > 0 Then

        inI = inValleyStart

        Dim CurrentEvent As New ObjEvent
        CurrentEvent.zppValleyStart = zppInput(inI)

        Dim bnEventOver As Boolean = False

        'Look forward to the next valley, determine if an event has occurred and store
        Do Until bnEventOver = True

            'Find the next valley
            Dim inFoundValley As Integer = FindValley(zppInput, inI)


            'Find the relevant peaks
            Dim inFoundPeak As Integer = FindPeak(zppInput, inI, inFoundValley)
            Dim inPrimePeak As Integer

            If inI = inValleyStart Then
                inPrimePeak = inFoundPeak
            Else
                inPrimePeak = FindPeak(zppInput, inValleyStart, inFoundValley)
            End If


            'Account for missing data as it is very possible that there may be a gap in the
                 data during an event
            'Only complete events will be retained (eg. have a start, peak, then return to
                 25\% (sgThresholdPercentThresholdtoEndEvent) of the initial discharge.
                 Ideally we only want to keep events that have  gaps in the recessional limb
                  after the event is considered over
            'If the event is over, store the event
            For inMissingData As Integer = inI To inFoundValley
                If zppInput(inMissingData).IsMissing = True Then
                    If zppInput(inMissingData).Y >= (zppInput(inPrimePeak).Y - zppInput(
                         inValleyStart).Y) * sgThresholdPercentThresholdtoEndEvent +
                         zppInput(inValleyStart).Y Then
                        Exit Do
                    Else
                        bnEventOver = True
                    End If

                End If
            Next


            'There is no data left in the trace, exit the loop and Finder
            If inFoundValley < 0 Then
                'Bail, don't save any data
                inI = zppInput.Count
                Exit Do
            End If
```

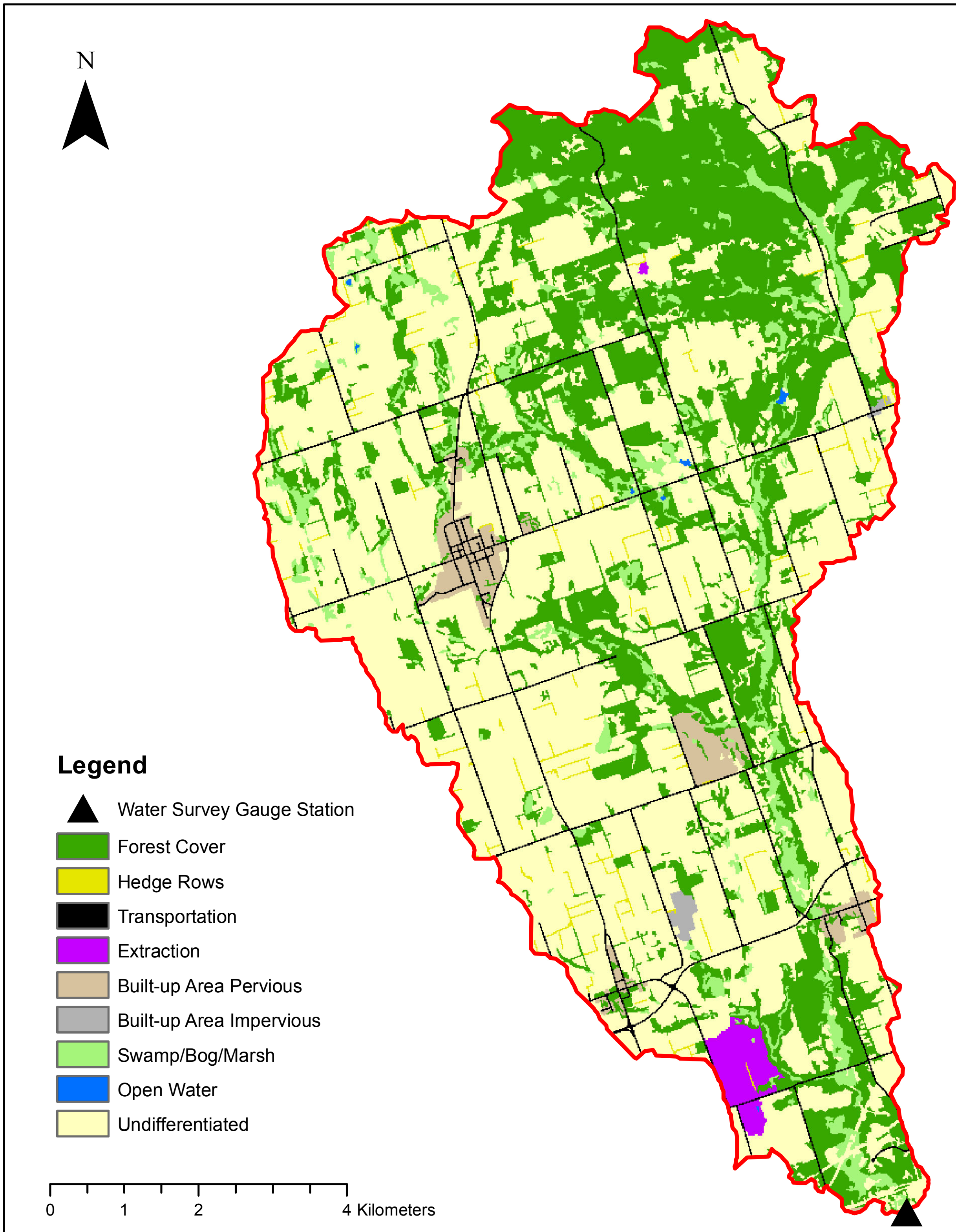
```
'Check to see if this is actually an event, look ahead for a valley at a lower
     discharge with no peak in between
If zppInput(inPrimePeak).Y - zppInput(inValleyStart).Y <
     dbThresholdMinimumDischarge Then
     ' 'This is not an event, restart with inI = last found valley + 1

     inI = inFoundValley - 2
     Exit Do

End If



'Is the event technically over? (If its not, we have to keep searching for the
     next valley)
If zppInput(inFoundValley).Y >= (zppInput(inPrimePeak).Y - zppInput(
     inValleyStart).Y) * sgThresholdPercentThresholdtoEndEvent + zppInput(
     inValleyStart).Y Then

     'No, the event is not over, store peak and look forward for next peak
     CurrentEvent.listPeaks.Add(zppInput(inFoundPeak))
     inI = inFoundValley

Else
     'The event is over, and this is the last valley
     bnEventOver = True

End If


If bnEventOver = True Then

     'This is the end of the event, store variables and end loop

     'Was there found peak?
     If zppInput(inPrimePeak).Y > zppInput(inValleyStart).Y Then
         If zppInput(inPrimePeak).Y - zppInput(inValleyStart).Y >
              dbThresholdMinimumDischarge Then

              'Are there enough points in this hydrograph to constitute an event
              If inFoundValley - inValleyStart >= inThresholdMinimumNumberofPoints
                   Then


              Dim ZedsDateTest1 As XDate = zppInput(inValleyStart).X
              Dim dtTest1 As DateTime = ZedsDateTest1.DateTime

              If dtTest1.Month = 6 And dtTest1.Day = 17 Then
                  Dim test As Integer = 1
              End If


              'So we have found an event, but are we sure about the start and end
                   points of each event
              'Use ReturnInstBaseflowDischarge to interpolate between turning
                   points

              'Looking backward from the peak, attempt to find the point where
                   Discharge/Baseflow Discharge is Minimized
              'Tie in to Baseflow package for preconditioning hydrographs, not
                   deployed for urban stations
              'If inValleyStart >= 25 Then

                  'Dim dbBFIRatio As Double = 0
                  'Dim inNewValleyStart As Integer = inValleyStart

                  'For inJ As Integer = inValleyStart To inValleyStart - 6 * 4
                       Step -1

                      'Dim dbBFDischarge As Double = ReturnInstBaseflowDischarge(
                           zppYearlyTurningPoints, zppInput(inJ))

                      'Dim dbDischarge As Double = zppInput(inJ).Y
                      'Dim dbNewBFI As Double = dbBFDischarge / zppInput(inJ).Y

                      'If dbBFIRatio < dbBFDischarge / zppInput(inJ).Y Then

                          'dbBFIRatio = dbBFDischarge / zppInput(inJ).Y
                          'inNewValleyStart = inJ

                      'End If


                  'Next
```

```
                                        'Does the difference between the new and the old start points
                                            worth keeping?
                                        'Dim dbOldBFStartDischarge As Double =
                                            ReturnInstBaseflowDischarge(zppYearlyTurningPoints,
                                            zppInput(inValleyStart))
                                        'Dim dbOldBFRatio As Double = dbOldBFStartDischarge / zppInput(
                                            inValleyStart).Y

                                        'If dbBFIRatio - dbOldBFRatio > 0.2 Then
                                        '    CurrentEvent.zppValleyStartNew = zppInput(inNewValleyStart)
                                        'Else
                                        '    CurrentEvent.zppValleyStartNew = zppInput(inValleyStart)
                                        'End If

                                        'CurrentEvent.zppValleyStartNew = zppInput(inValleyStart)
                                        'If dbBFIRatio - dbOldBFRatio > 0.2 Then
                                            'CurrentEvent.zppValleyStart = zppInput(inNewValleyStart)
                                            'CurrentEvent.zppValleyStartNew = zppInput(inNewValleyStart)
                                        'End If

                                    'End If

                                    CurrentEvent.zppPeak = zppInput(inPrimePeak)

                                    CurrentEvent.listPeaks.Add(zppInput(inFoundPeak))
                                    If inFoundPeak <> inPrimePeak Then
                                        'CurrentEvent.listPeaks.Add(zppInput(inPrimePeak))
                                    End If

                                    CurrentEvent.listSecondaryPeaks.AddRange(CurrentEvent.listPeaks)
                                    CurrentEvent.listSecondaryPeaks.Remove(zppInput(inPrimePeak))

                                    CurrentEvent.zppValleyEnd = zppInput(inFoundValley)


                                End If
                            End If
                        End If
                    End If

                Loop  'Loop until end of event

            End If   'Checks that the loop hasn't hit the end of the dataset

            '********************** TEMPORARY MEASURE, forces the finder
            '                            to quit at the end of the trace
            'If inI = zppInput.Count - 4 Then
            '    'End of File
            '    Exit For
            'End If

        Next  'Loops through the dataset, jumping from valley to valley

        listExtraCurves.Clear()

        'So we've got our events temporally defined, call the EventAnalyzer to parameterize
        EventAnalyzer(zppInput, listEvents, sgThresholdPercentThresholdtoEndEvent)

    End Sub
```

```
Public Class ObjEvent

    Public stStationID As String
    Public inYear As Integer  'Used for colourizing plots

    'Datetime stored within ZedGraph Pointpair classes
    Public zppPeak As PointPair

    Public zppValleyStart As PointPair
    Public zppValleyStartNew As PointPair
    Public zppValleyEnd As PointPair
    Public zppEventEnd As PointPair

    Public listPeaks As New List(Of PointPair)

    Public listSecondaryValleys As New List(Of PointPair)
    Public listSecondaryPeaks As New List(Of PointPair)

End Class
```

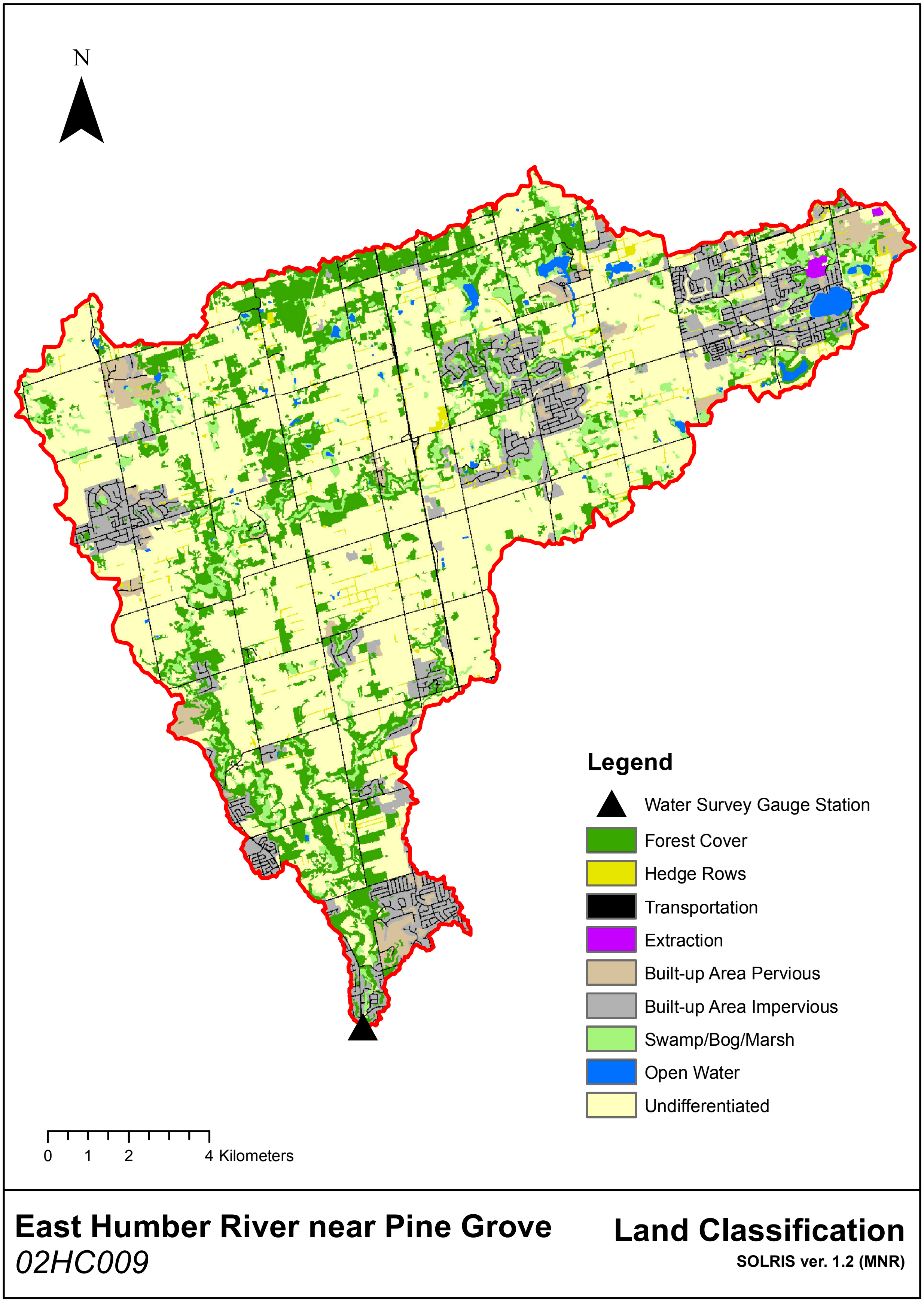
Appendix C

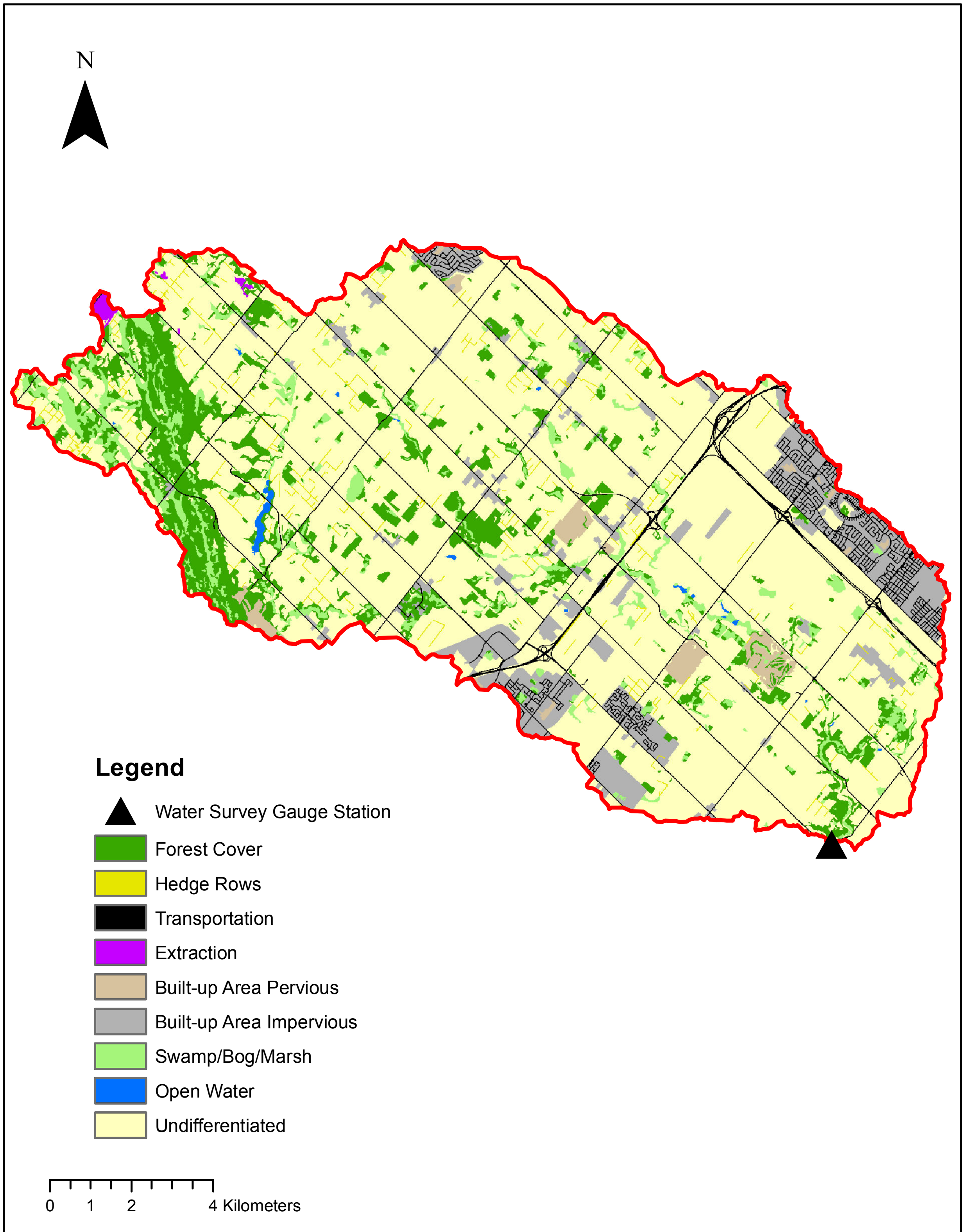
Aerial Photographic Analysis



Duffins Creek above Pickering
02HC019

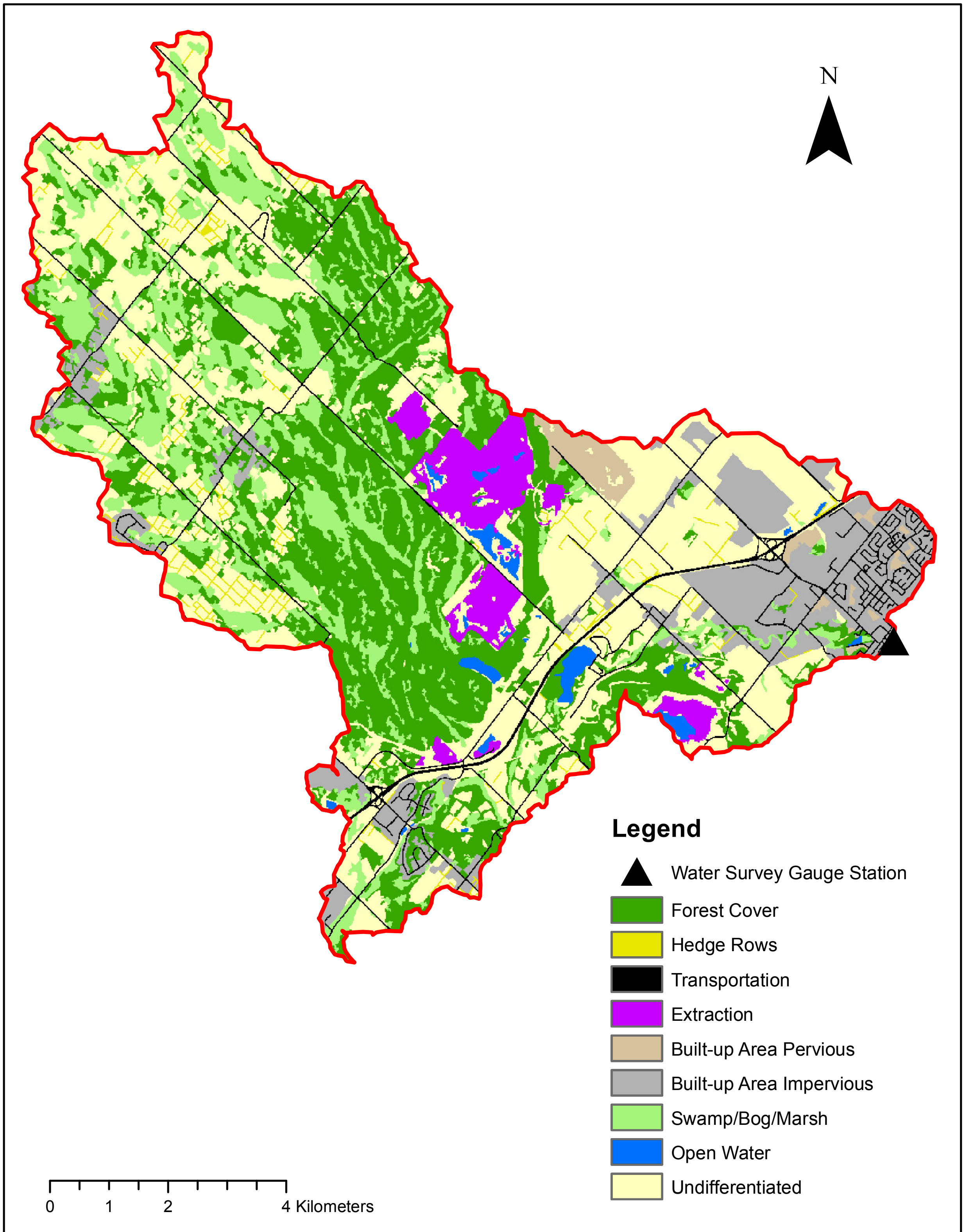
Land Classification
SOLRIS ver. 1.2 (MNR)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0 1 2 4 Kilometers
East Humber River near Pine Grove
02HC009
Land Classification
SOLRIS ver. 1.2 (MNR)



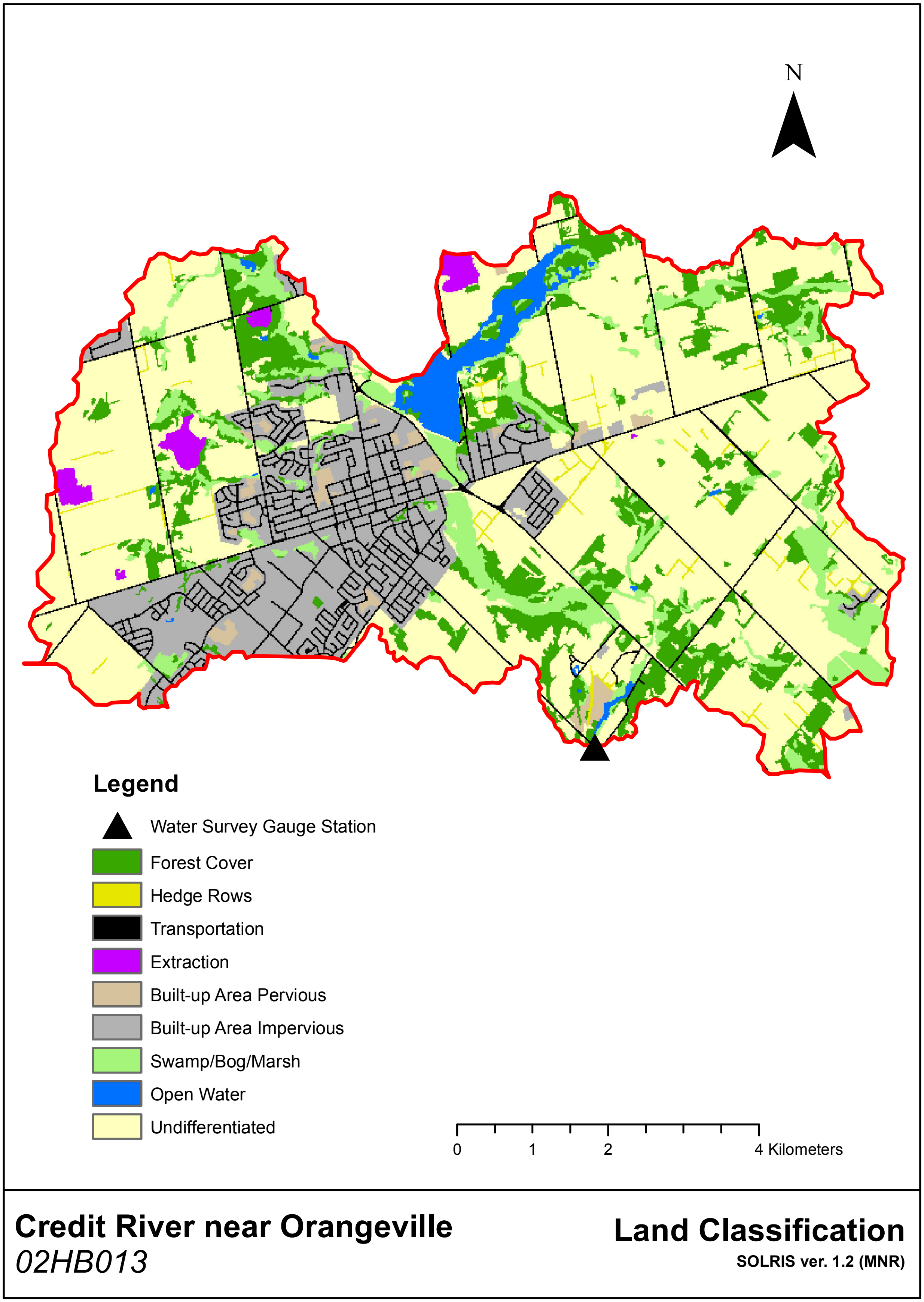
East Oakville Creek near Omagh
02HB004

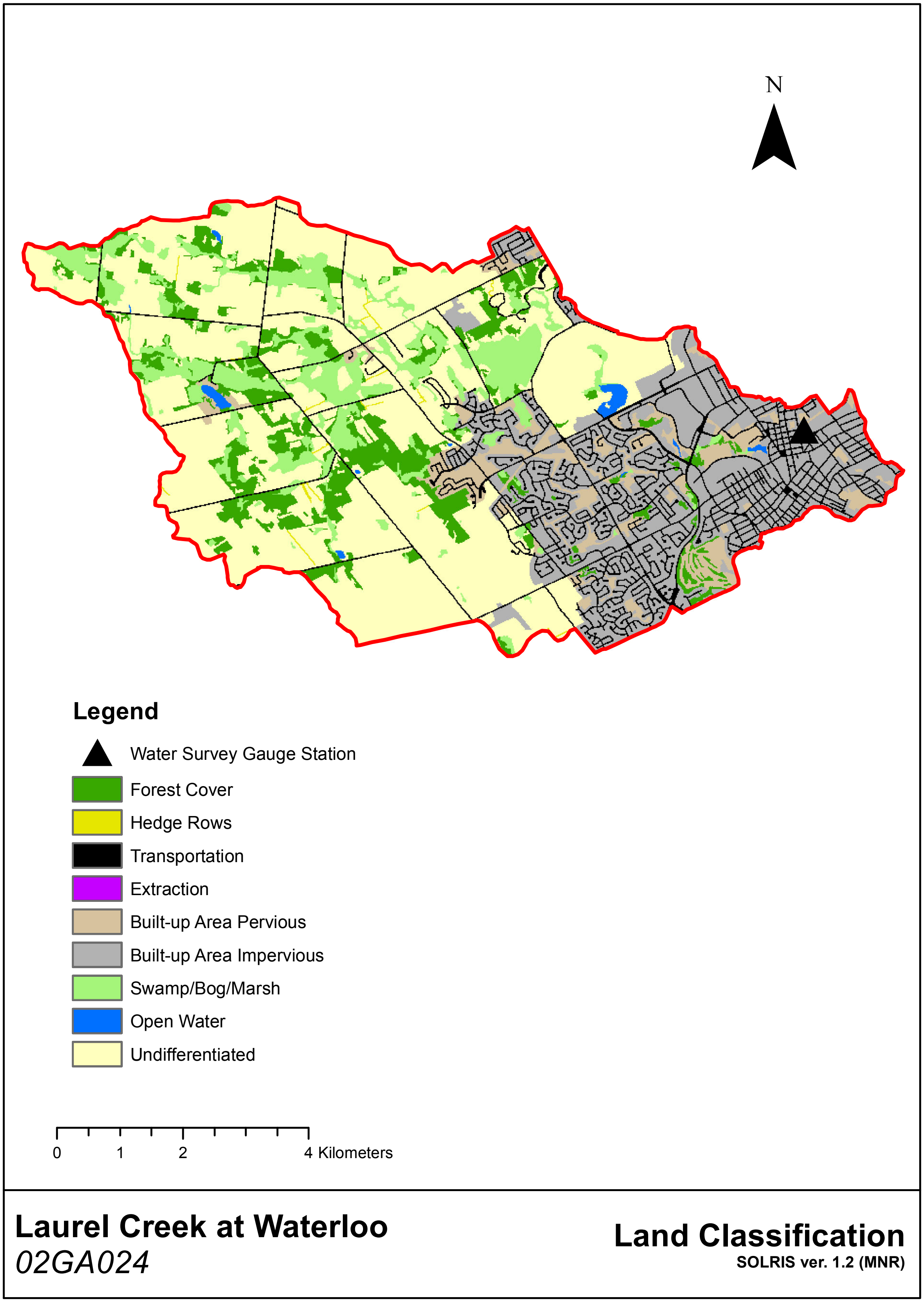
Land Classification
SOLRIS ver. 1.2 (MNR)

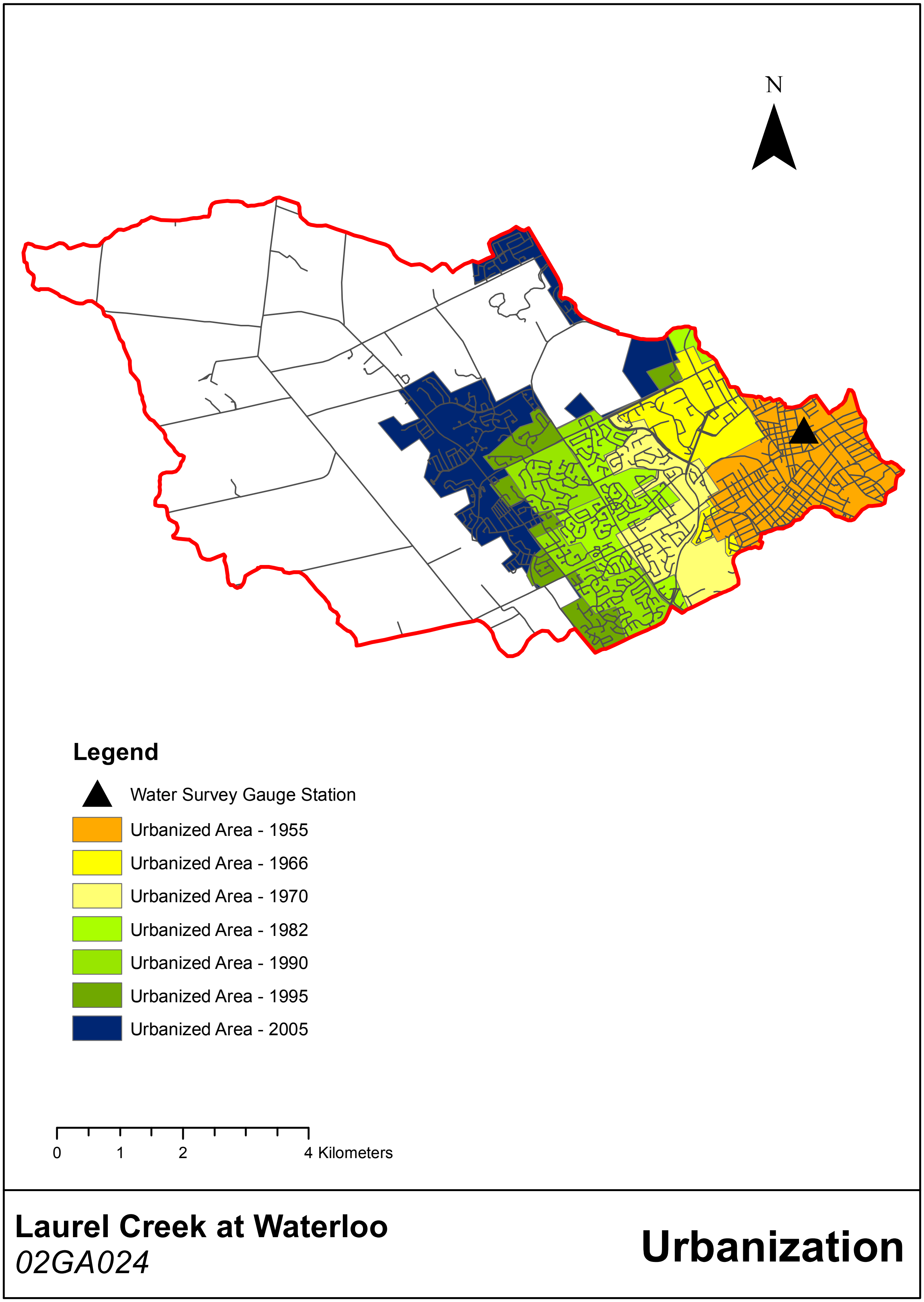


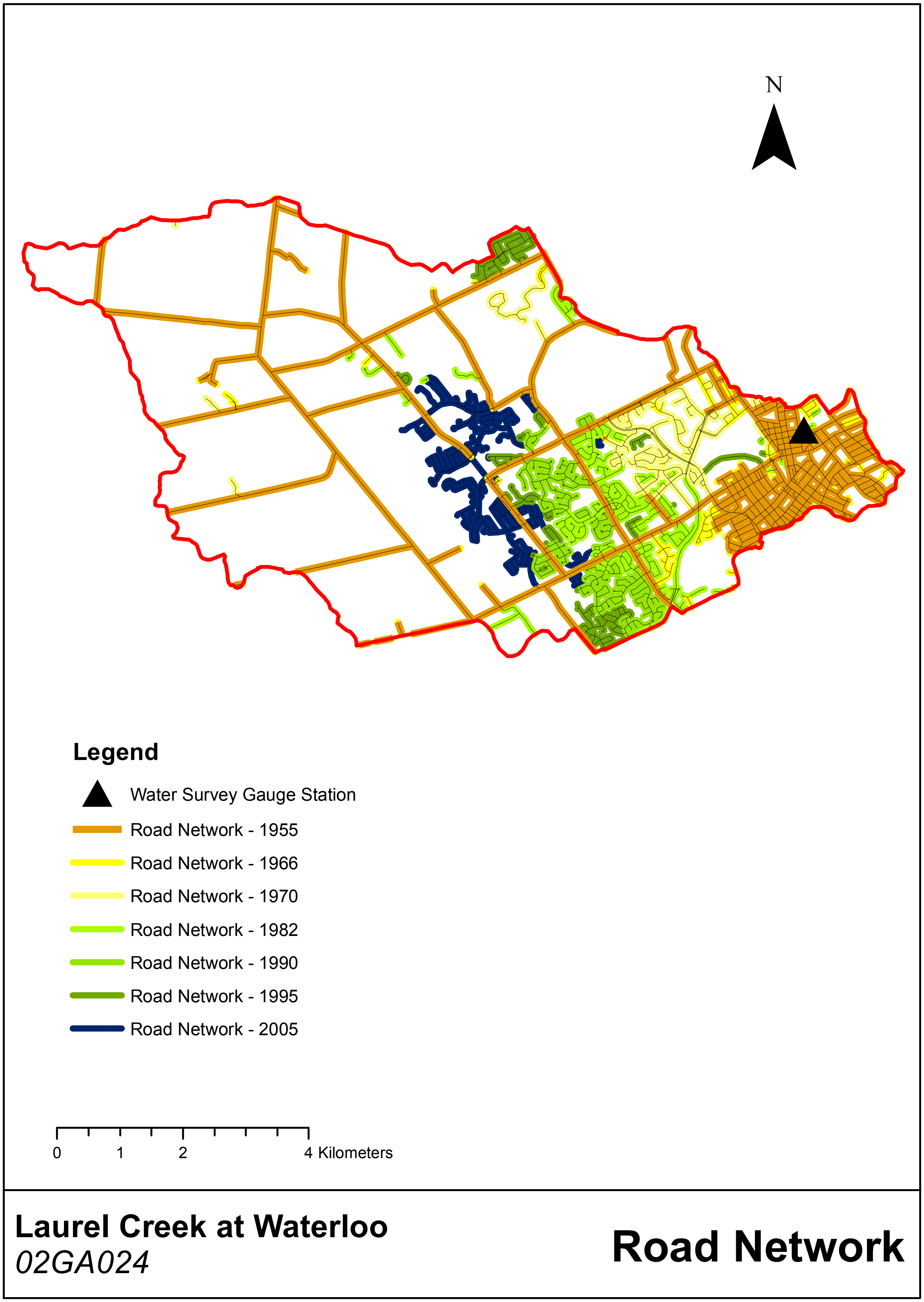
Oakville Creek at Milton
02HB005

Land Classification
SOLRIS ver. 1.2 (MNR)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0
1
2
4 Kilometers
Credit River near Orangeville
02HB013
Land Classification
SOLRIS ver. 1.2 (MNR)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0 1 2 4 Kilometers
Laurel Creek at Waterloo
02GA024
Land Classification
SOLRIS ver. 1.2 (MNR)


N
Legend
Water Survey Gauge Station
Urbanized Area - 1955
Urbanized Area - 1966
Urbanized Area - 1970
Urbanized Area - 1982
Urbanized Area - 1990
Urbanized Area - 1995
Urbanized Area - 2005
0
1
2
4 Kilometers
Laurel Creek at Waterloo
02GA024
Urbanization


N
Legend
Water Survey Gauge Station
Road Network - 1955
Road Network - 1966
Road Network - 1970
Road Network - 1982
Road Network - 1990
Road Network - 1995
Road Network - 2005
0
1
2
4 Kilometers
Laurel Creek at Waterloo
02GA024
Road Network

02GA024 - Laurel Creek at Waterloo

Topographic Catchment Area: 57.5 km^2

Table C.1: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1955	4.6	8	129	2.2	62.3	13.5
1966	7	12.2	140	2.4	87.9	12.5
1971	9.9	17.1	169	2.9	111.4	11.3
1982	12.4	21.5	204	3.6	139.5	11.3
1990	14.9	25.9	231	4	168.4	11.3
1995	16.6	28.9	249	4.3	181.9	10.9
2006	21.6	37.6	283	4.9	229.7	10.6

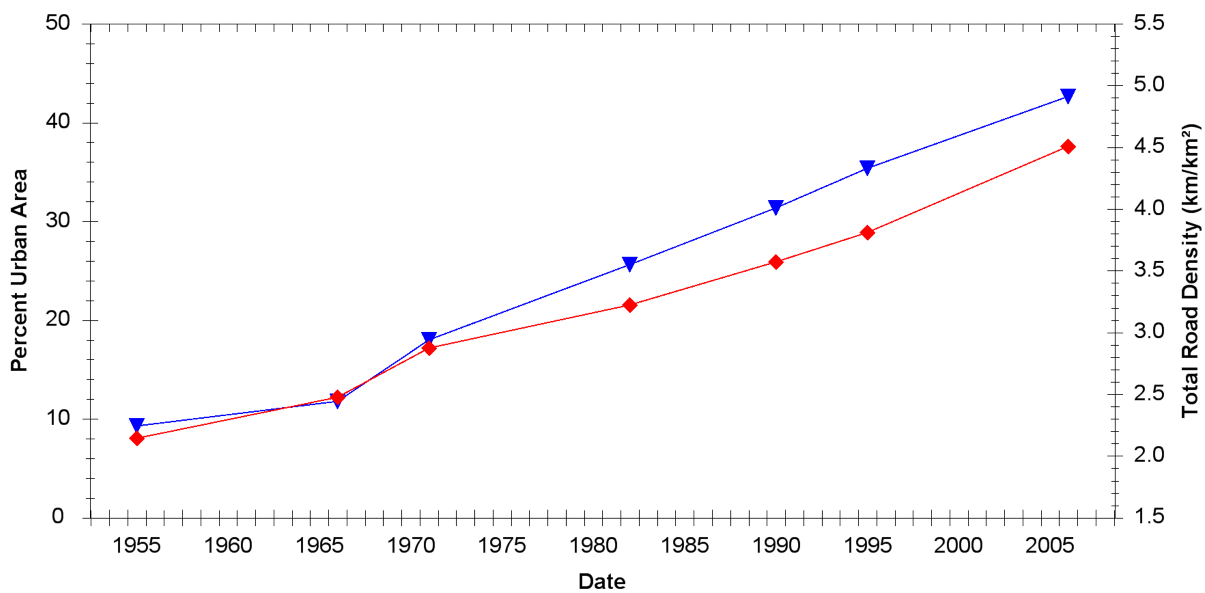
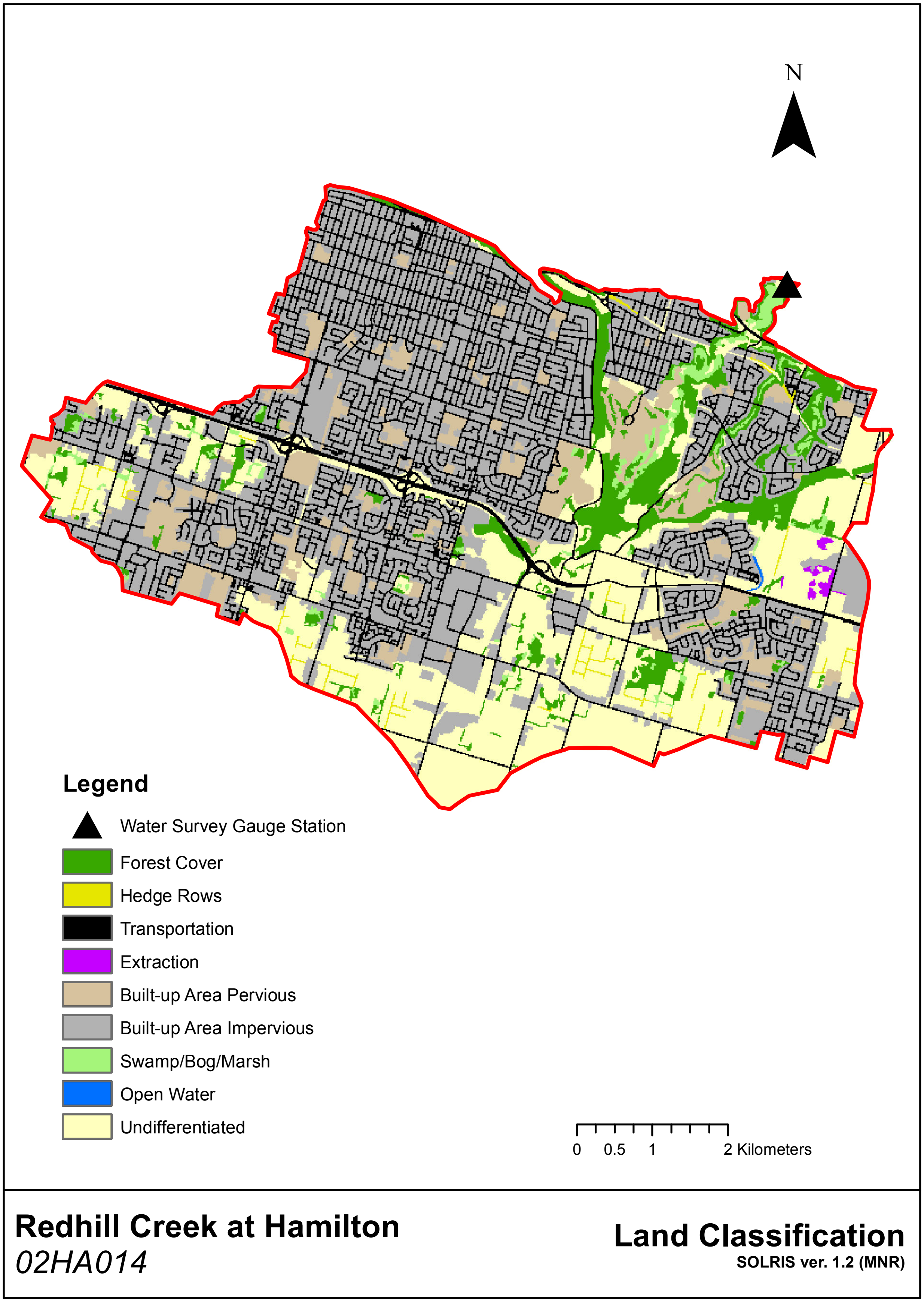
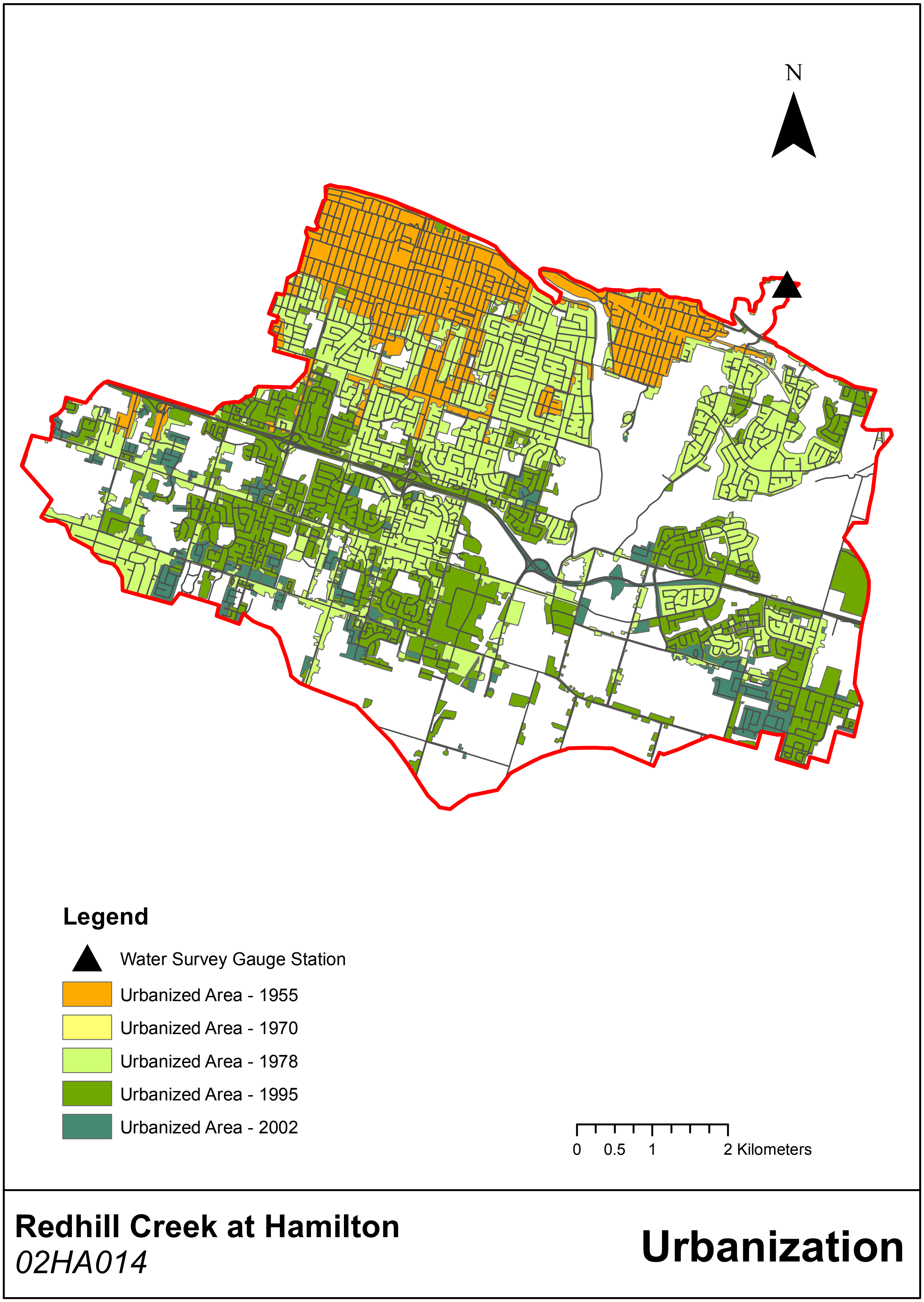
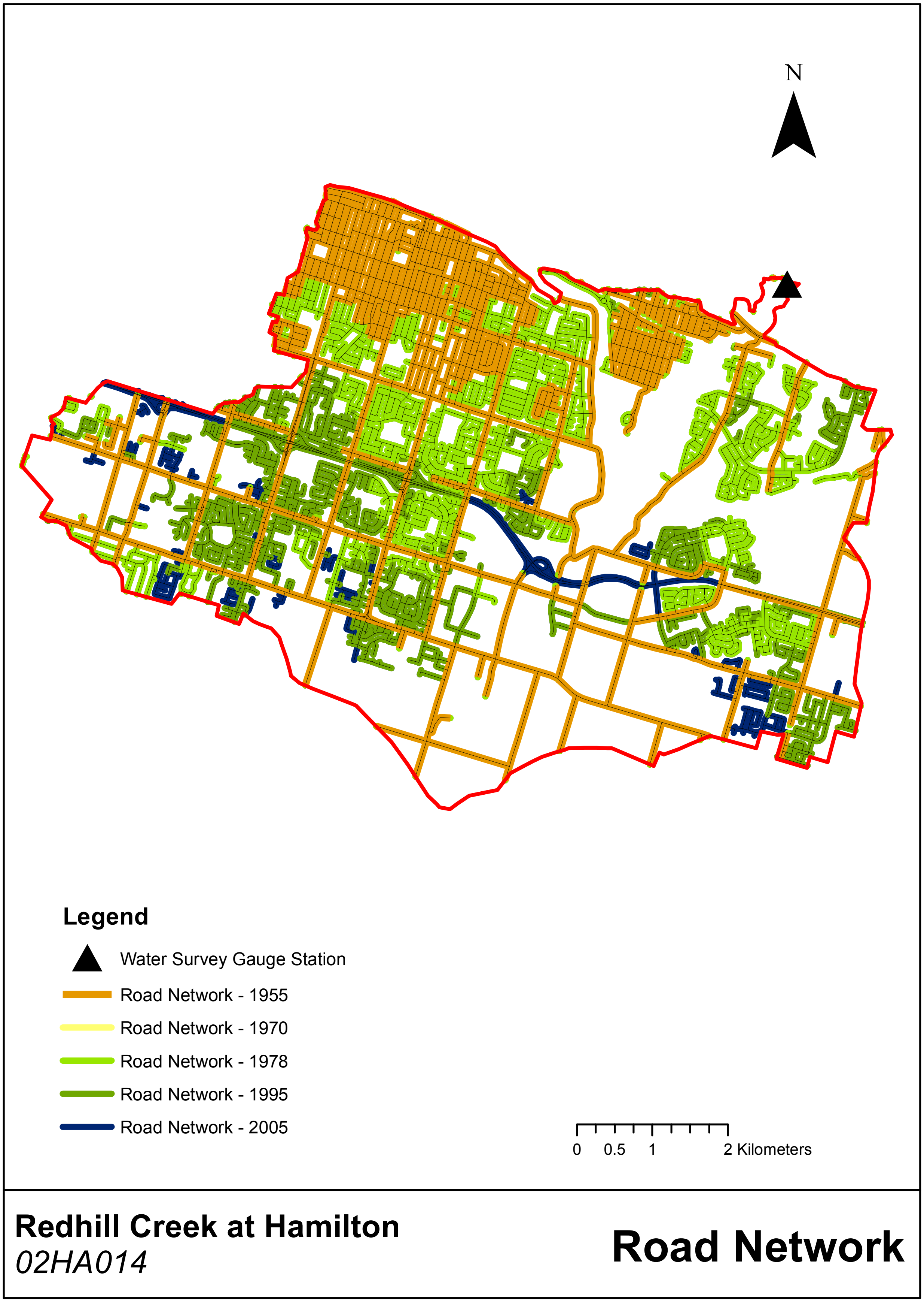


Figure C.1: Observed temporal change in urban area (red) and road density (blue)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0 0.5 1 2 Kilometers
Redhill Creek at Hamilton
02HA014
Land Classification
SOLRIS ver. 1.2 (MNR)



N
Legend
Water Survey Gauge Station
Urbanized Area - 1955
Urbanized Area - 1970
Urbanized Area - 1978
Urbanized Area - 1995
Urbanized Area - 2002
0 0.5 1 2 Kilometers
Redhill Creek at Hamilton
02HA014
Urbanization


N
Legend
Water Survey Gauge Station
Road Network - 1955
Road Network - 1970
Road Network - 1978
Road Network - 1995
Road Network - 2005
0
0.5
1
2 Kilometers
Redhill Creek at Hamilton
02HA014
Road Network

02HA014 - Red Hill Creek at Hamilton

Topographic Catchment Area: 57.0 km^2
Effective Catchment Area: 56.3 km^2

Table C.2: Observed Urban Coverage and Roadway Length

Year	**Urbanized Area (km^2)**	**Percent Urban Area**	**Total Roadway Length (km)**	**Total Roadway Density (km/km^2)**	**Urban Roadway Length (km)**	**Urban Roadway Density (km/km^2)**
1955	6.6	11.7	201	3.6	103.6	15.7
1978	20.8	36.9	340	6	305.3	14.7
1995	31.3	55.7	470	8.4	460.4	14.7
2002	33.6	59.7	505	9	497.6	14.8

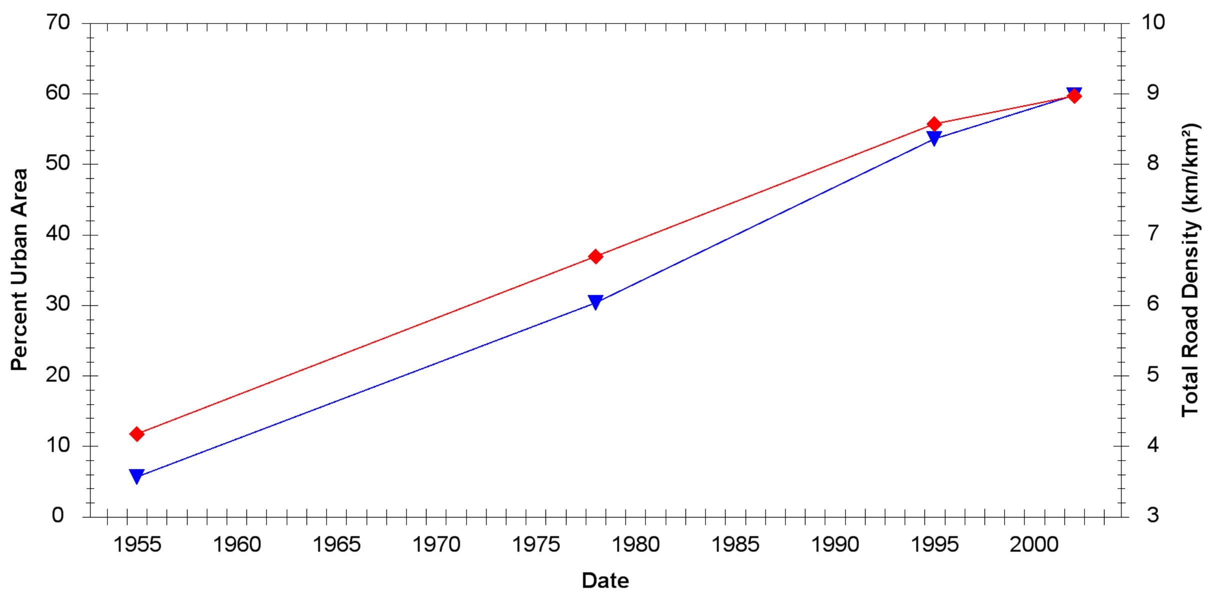
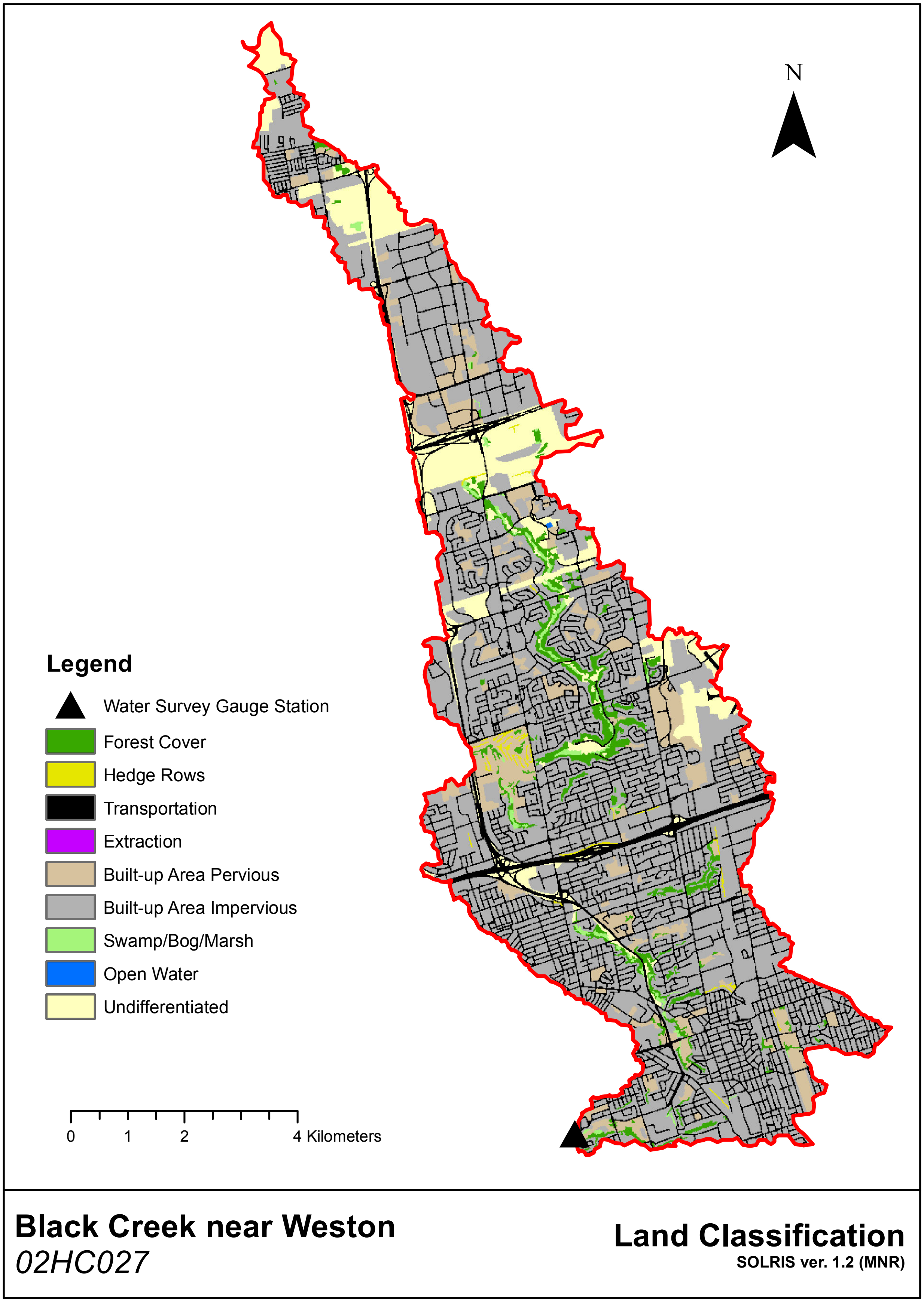
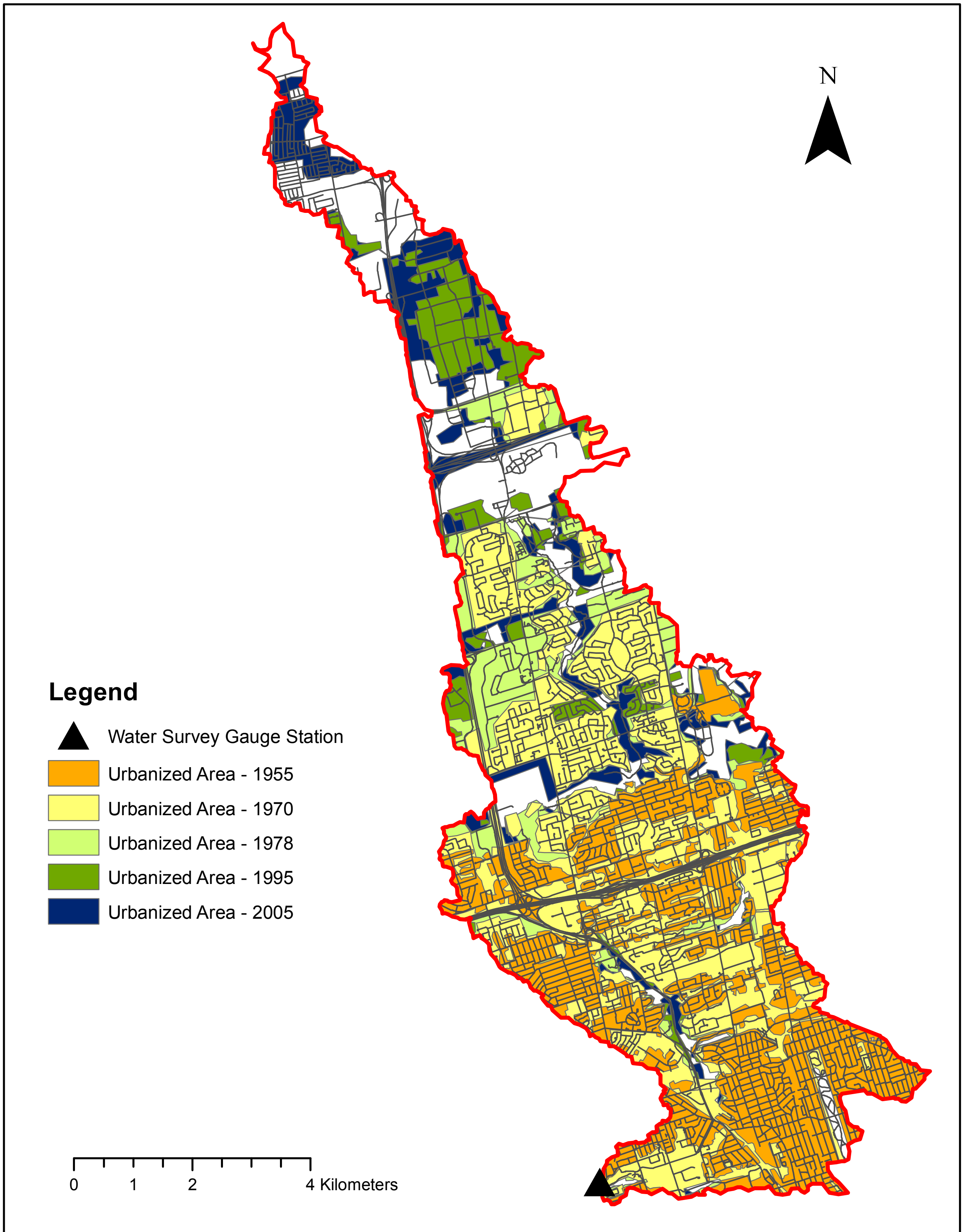


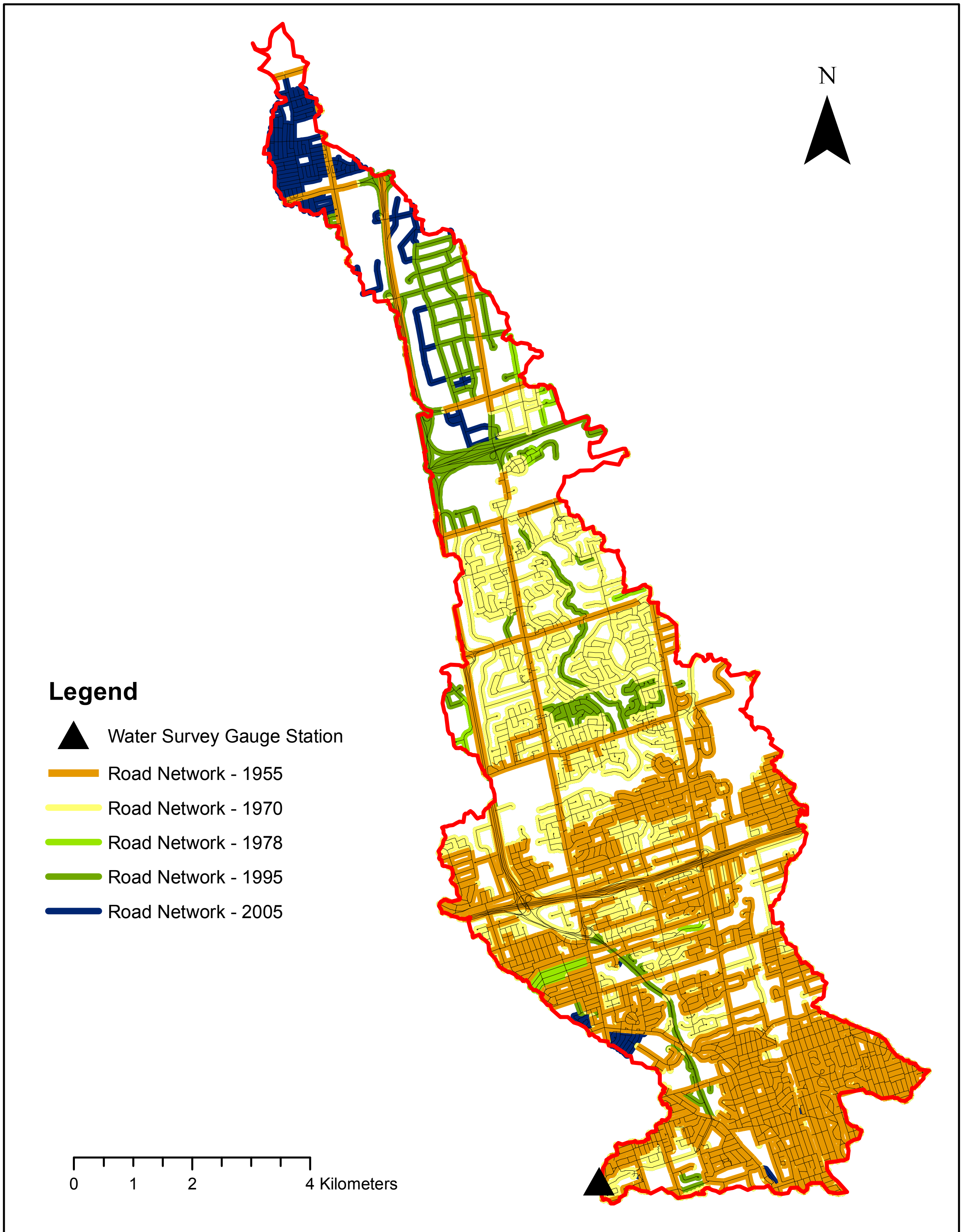
Figure C.2: Observed temporal change in urban area (red) and road density (blue)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0
1
2
4 Kilometers
Black Creek near Weston
02HC027
Land Classification
SOLRIS ver. 1.2 (MNR)



Black Creek near Weston
02HC027

Urbanization



Black Creek near Weston
02HC027

Road Network

02HC027 - Black Creek near Weston

Topographic Catchment Area: 66.0 km^2

Table C.3: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1954	18.9	28.6	349	5.3	277.9	14.7
1970	37.5	56.8	556	8.4	474.1	12.6
1978	42.9	65	565	8.6	524.5	12.2
1995	46.3	70.2	658	10	583.9	12.6
2005	51.3	77.8	705	10.7	634.3	12.4

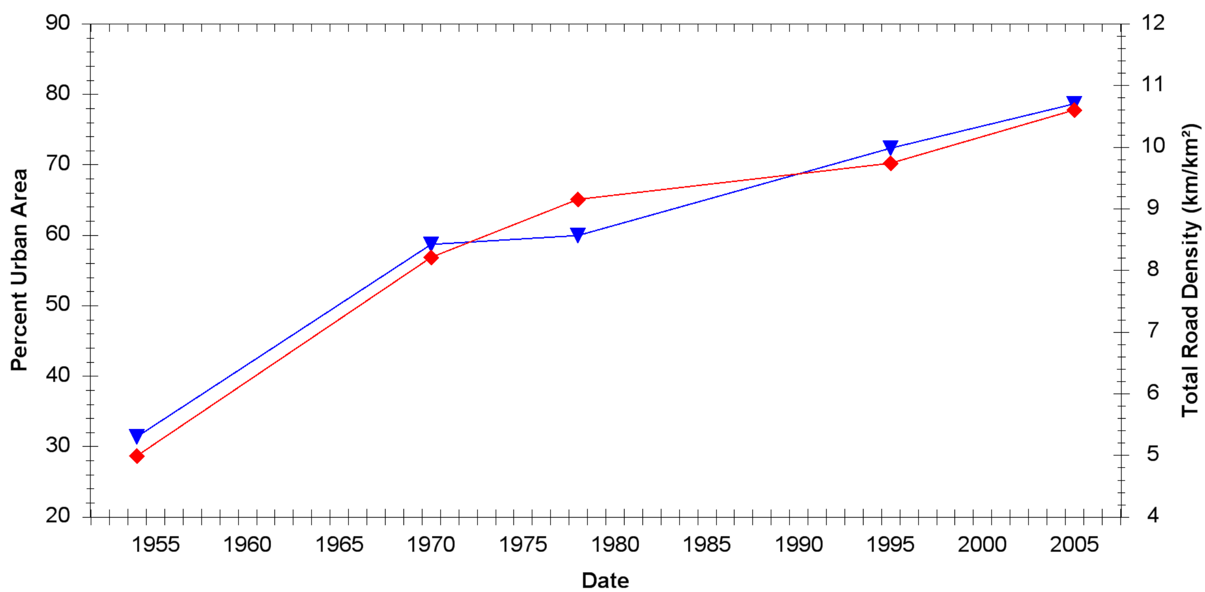
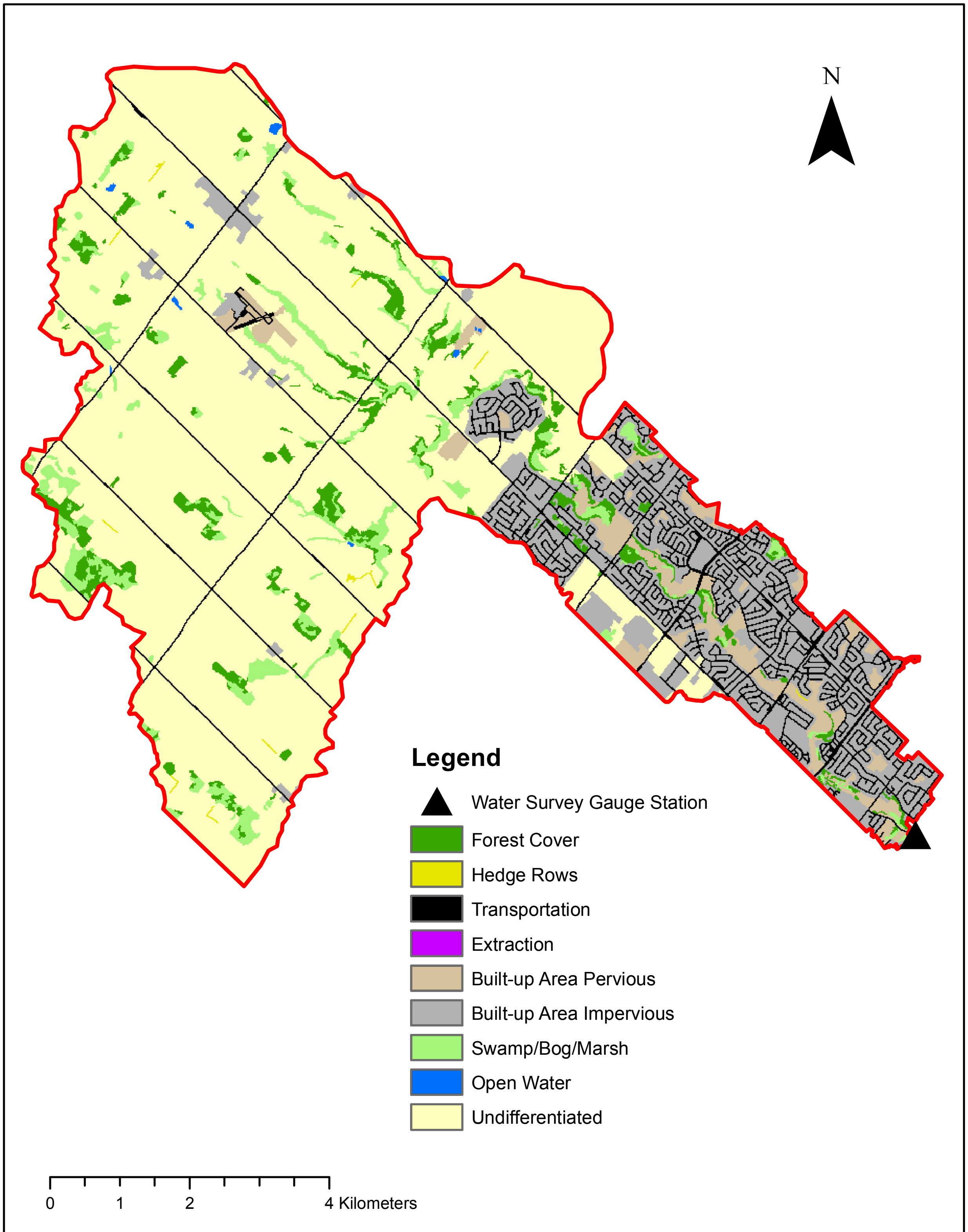
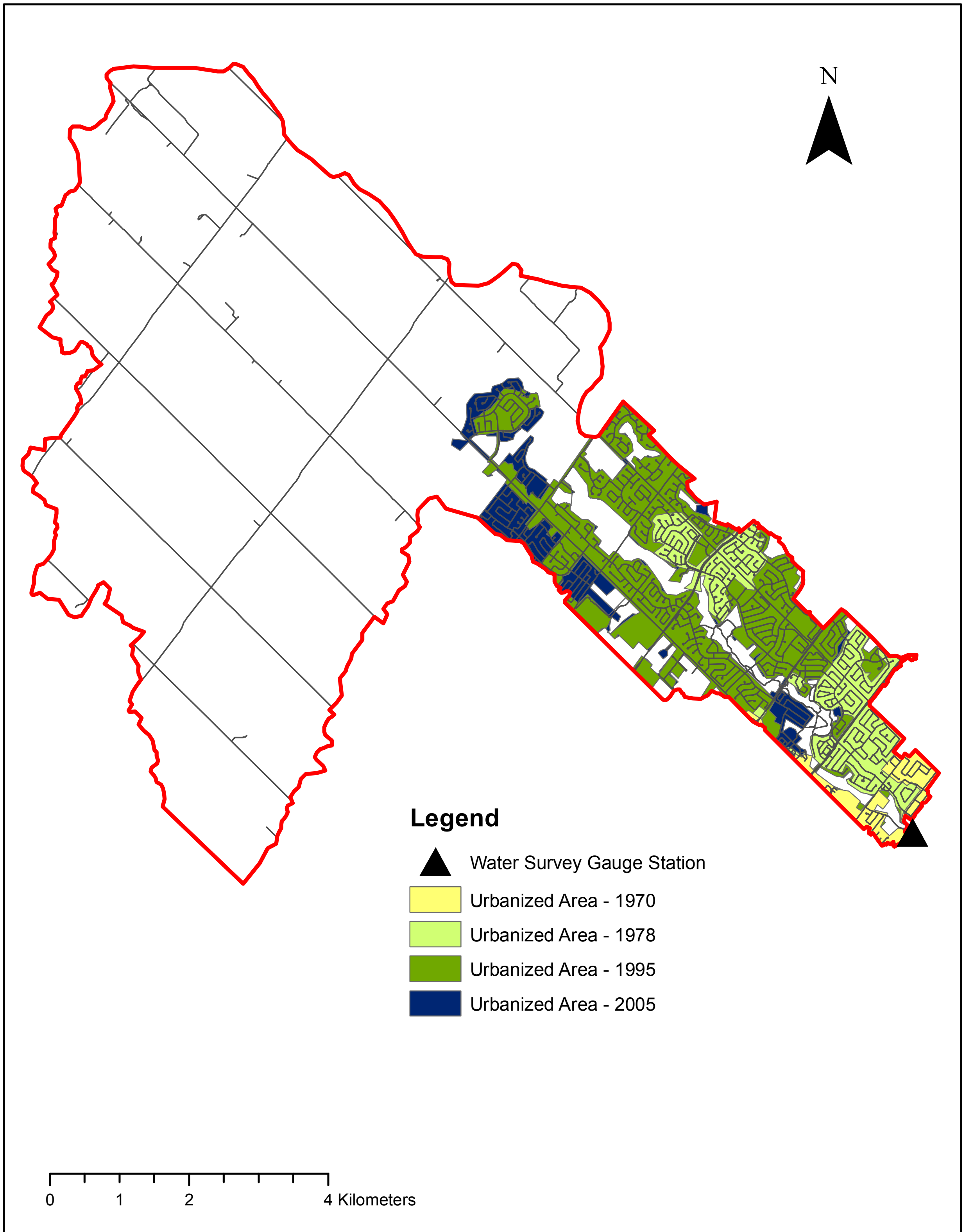


Figure C.3: Observed temporal change in urban area (red) and road density (blue)



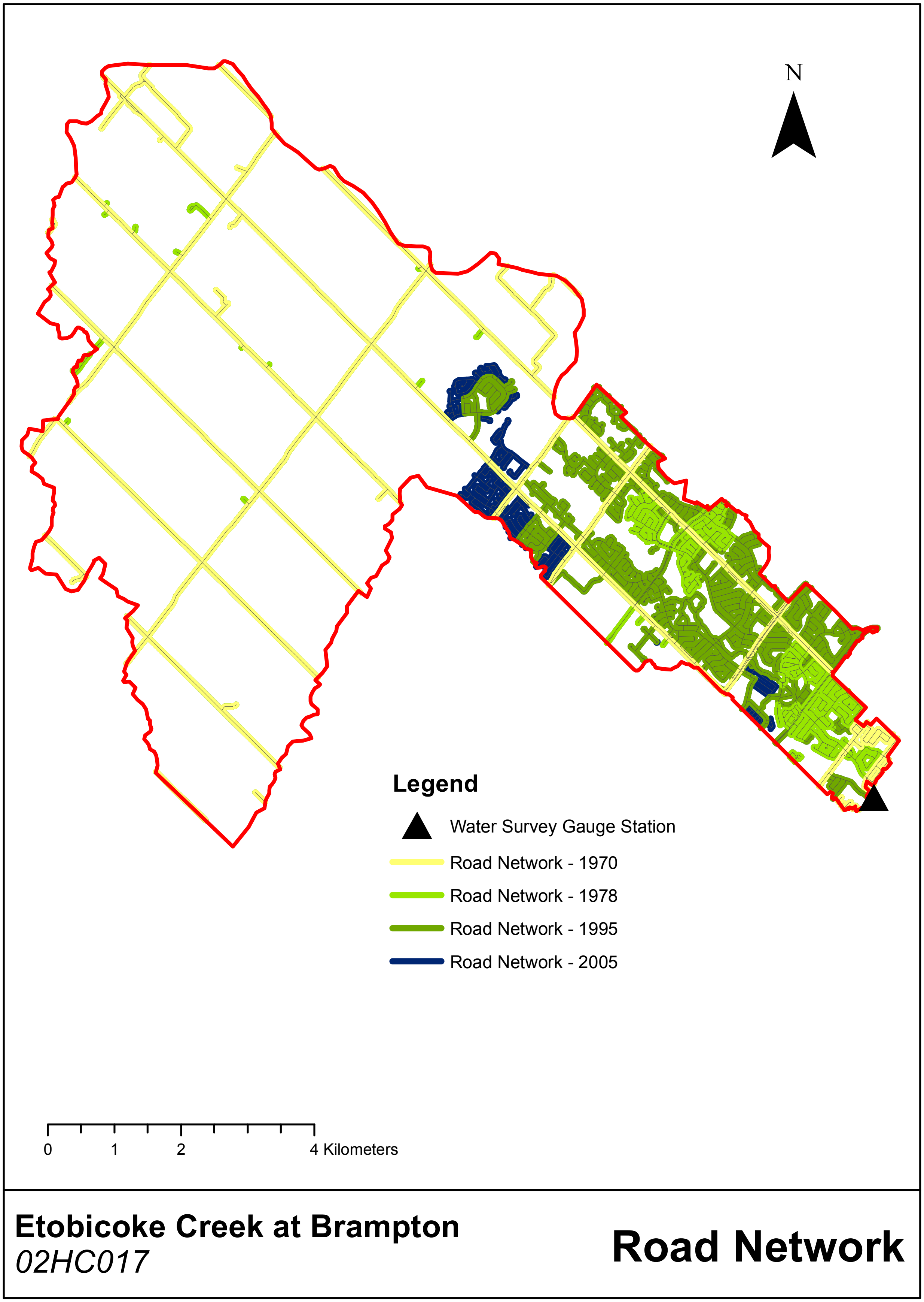
Etobicoke Creek at Brampton
02HC017

Land Classification
SOLRIS ver. 1.2 (MNR)



Etobicoke Creek at Brampton
02HC017

Urbanization


N
Legend
Water Survey Gauge Station
Road Network - 1970
Road Network - 1978
Road Network - 1995
Road Network - 2005
0
1
2
4 Kilometers
Etobicoke Creek at Brampton
02HC017
Road Network

02HC017 - Etobicoke Creek at Brampton

Topographic Catchment Area: 65.1 km^2
Effective Catchment Area: 67.7 km^2

Table C.4: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1970	0.8	1.2	101	1.5	7.3	9
1978	3.2	4.8	139	2.1	44.3	13.7
1995	11	16.2	240	3.5	156.1	14.2
2005	12.5	18.5	262	3.9	180.8	14.4

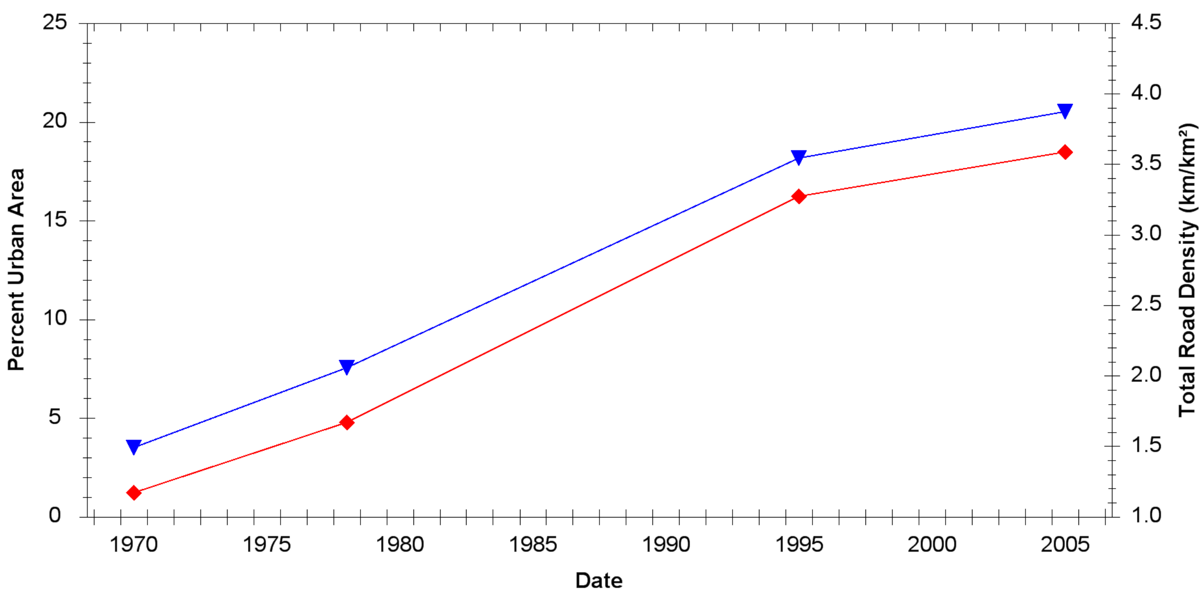
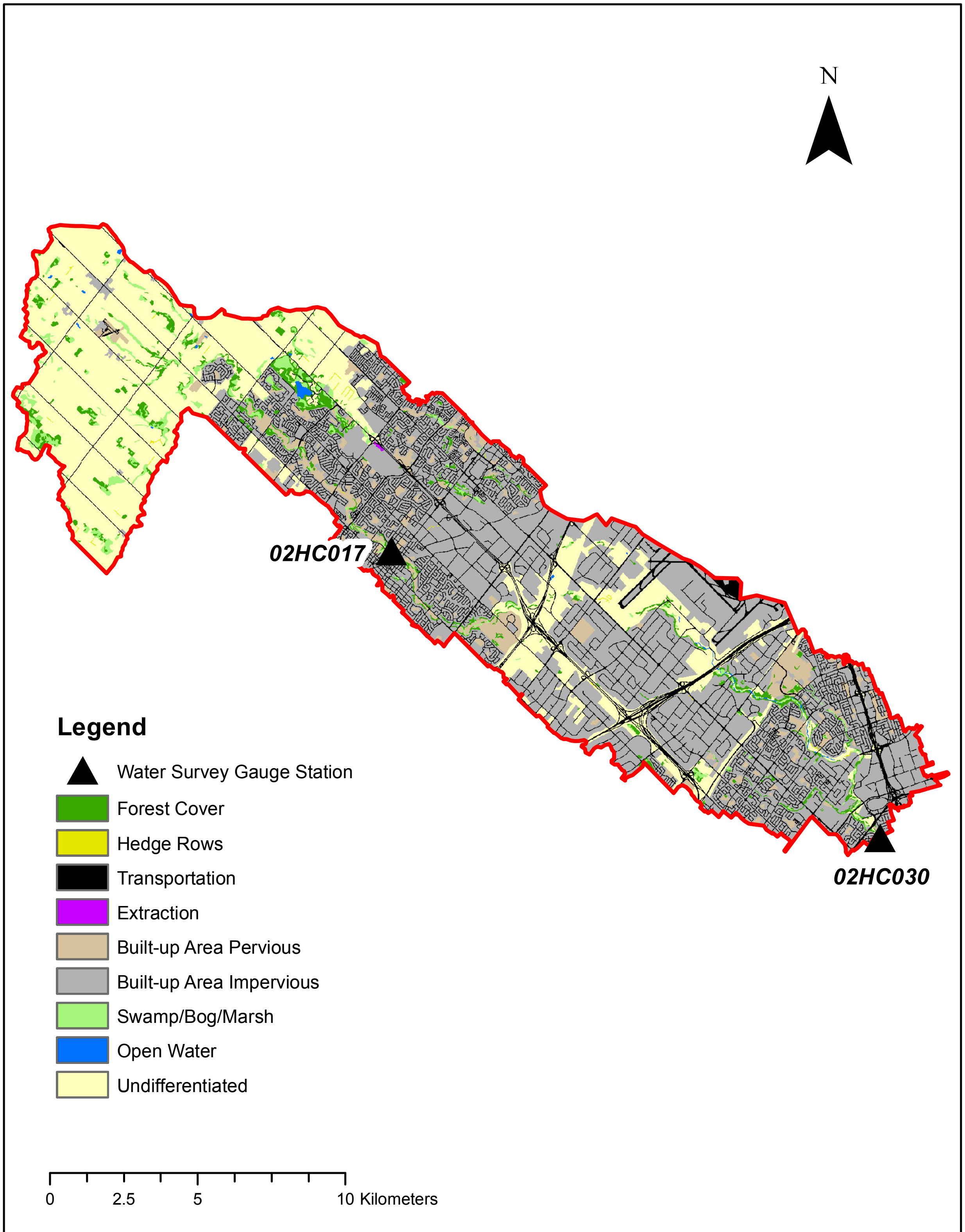
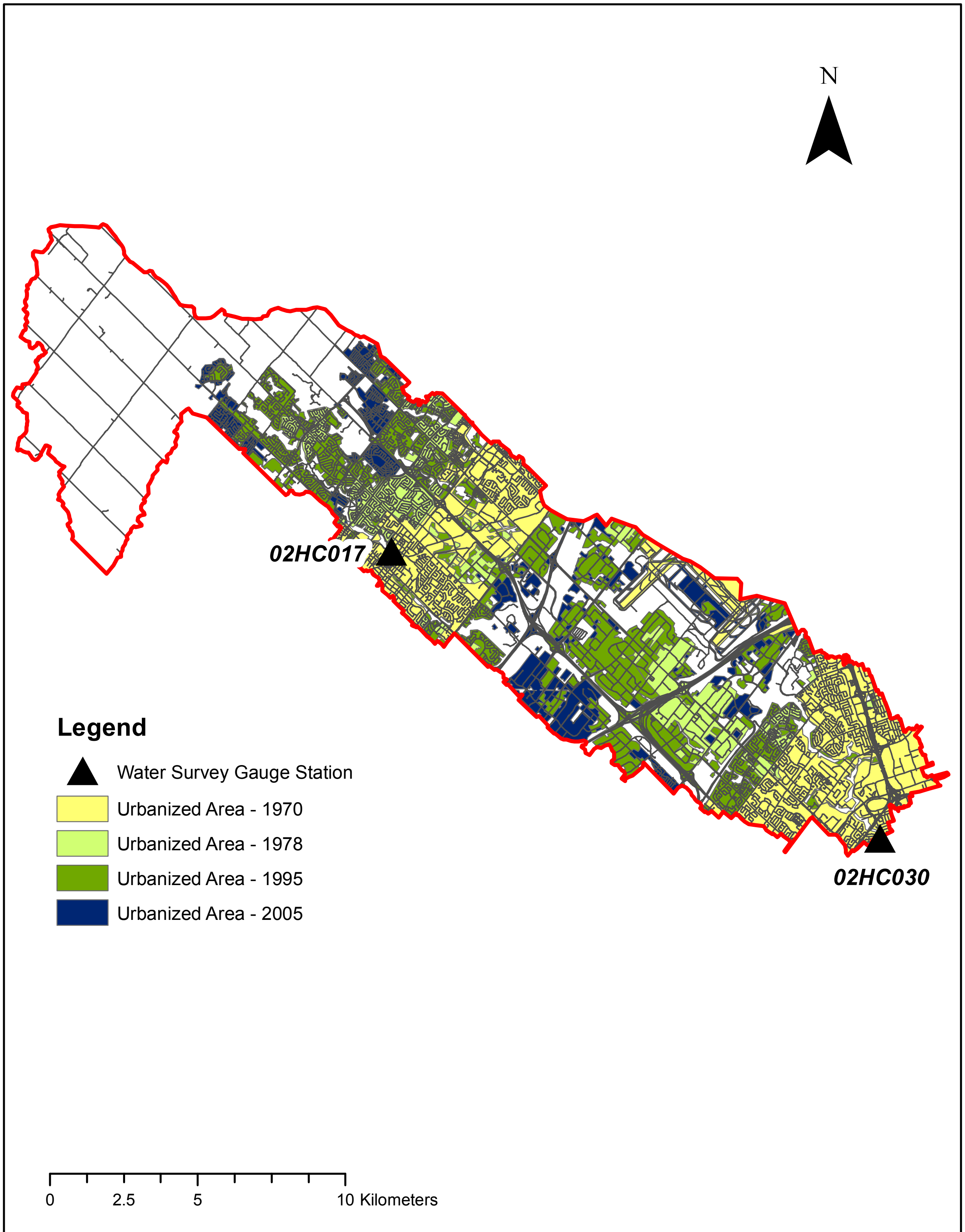


Figure C.4: Observed temporal change in urban area (red) and road density (blue)



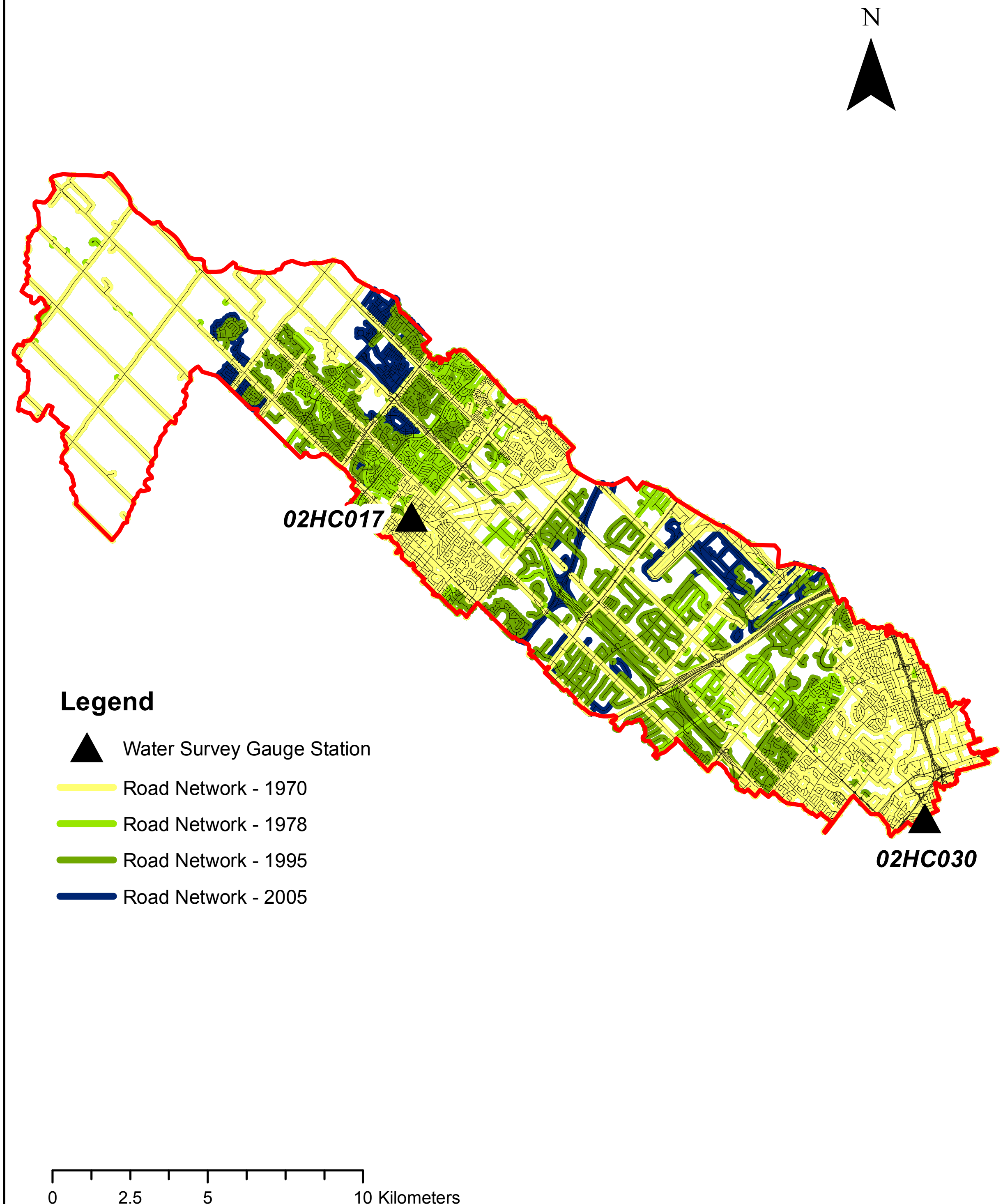
Etobicoke Creek below QEW
02HC030

Land Classification
SOLRIS ver. 1.2 (MNR)



Etobicoke Creek below QEW
02HC030

Urbanization



Etobicoke Creek below QEW
02HC030

Road Network

02HC030 - Etobicoke Creek below QEW

Topographic Catchment Area: 210.6 km^2
Effective Catchment Area: 215.2 km^2

Table C.5: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1970	45.5	21.1	718	3.3	493.6	10.9
1978	64.2	29.8	908	4.2	714.9	11.1
1995	100.3	46.6	1384	6.4	1220.5	12.2
2005	118.2	54.9	1538	7.1	1412.8	12

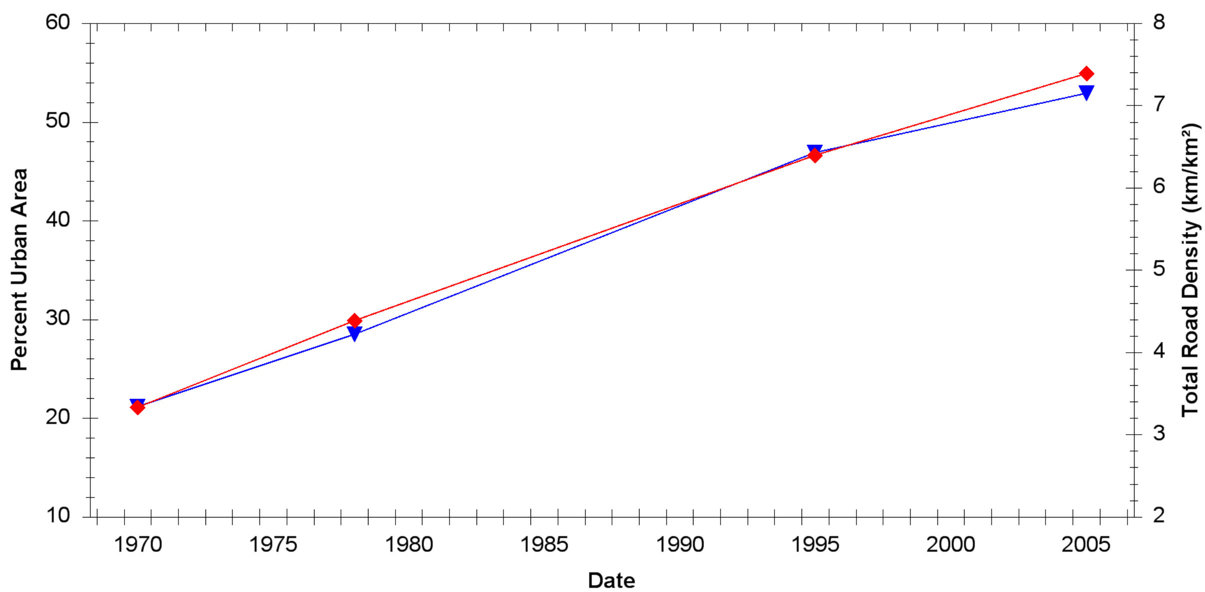
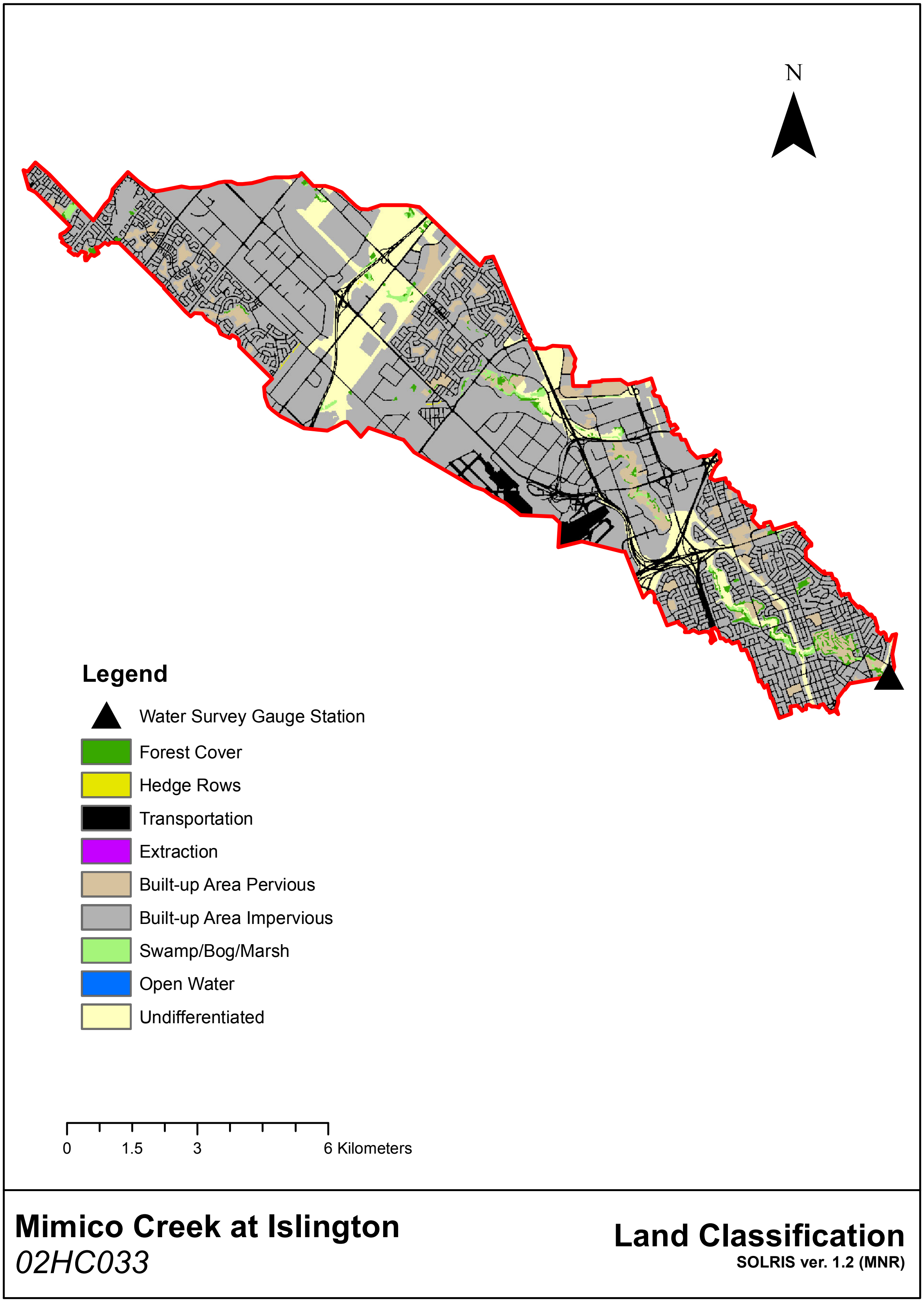
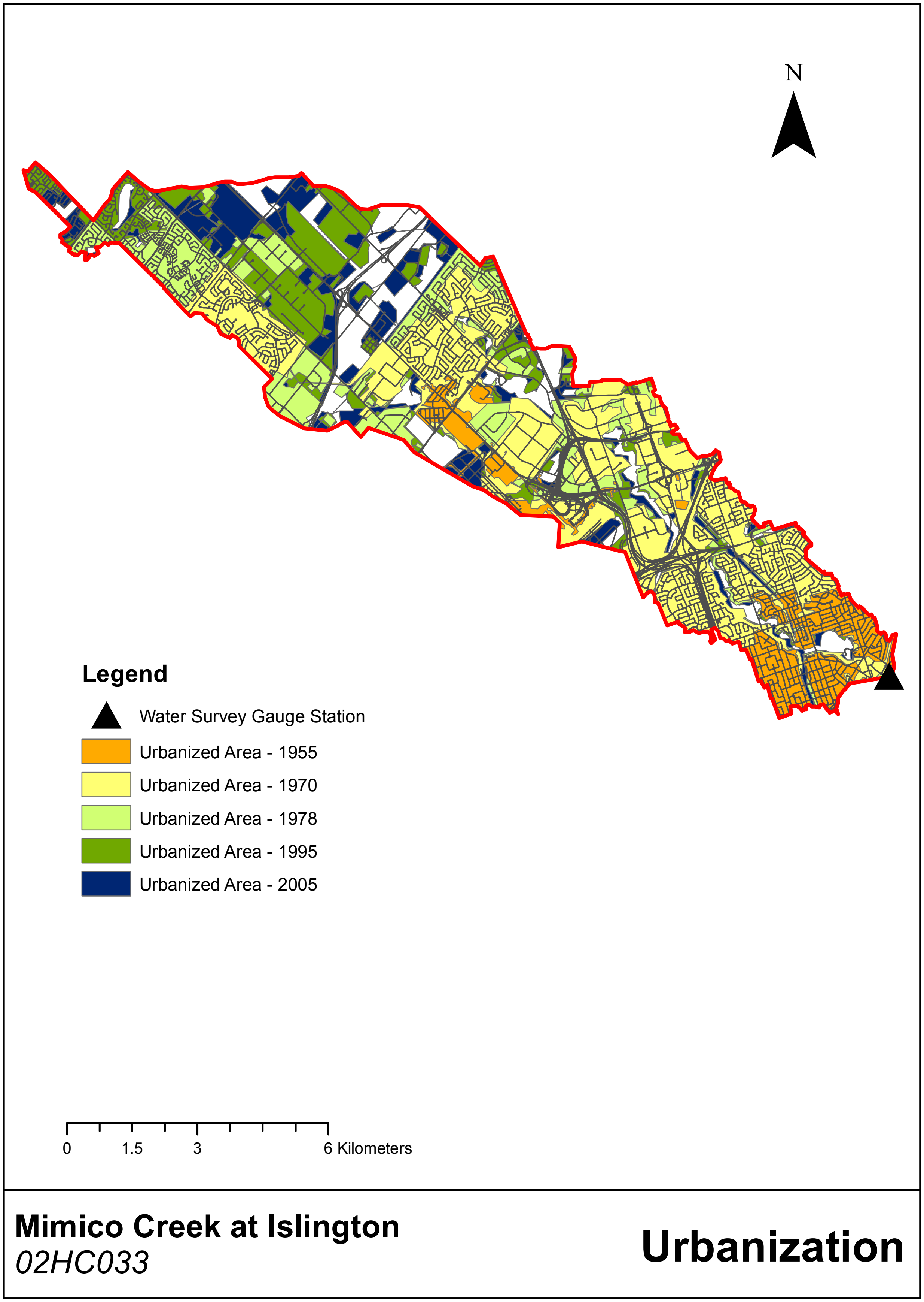
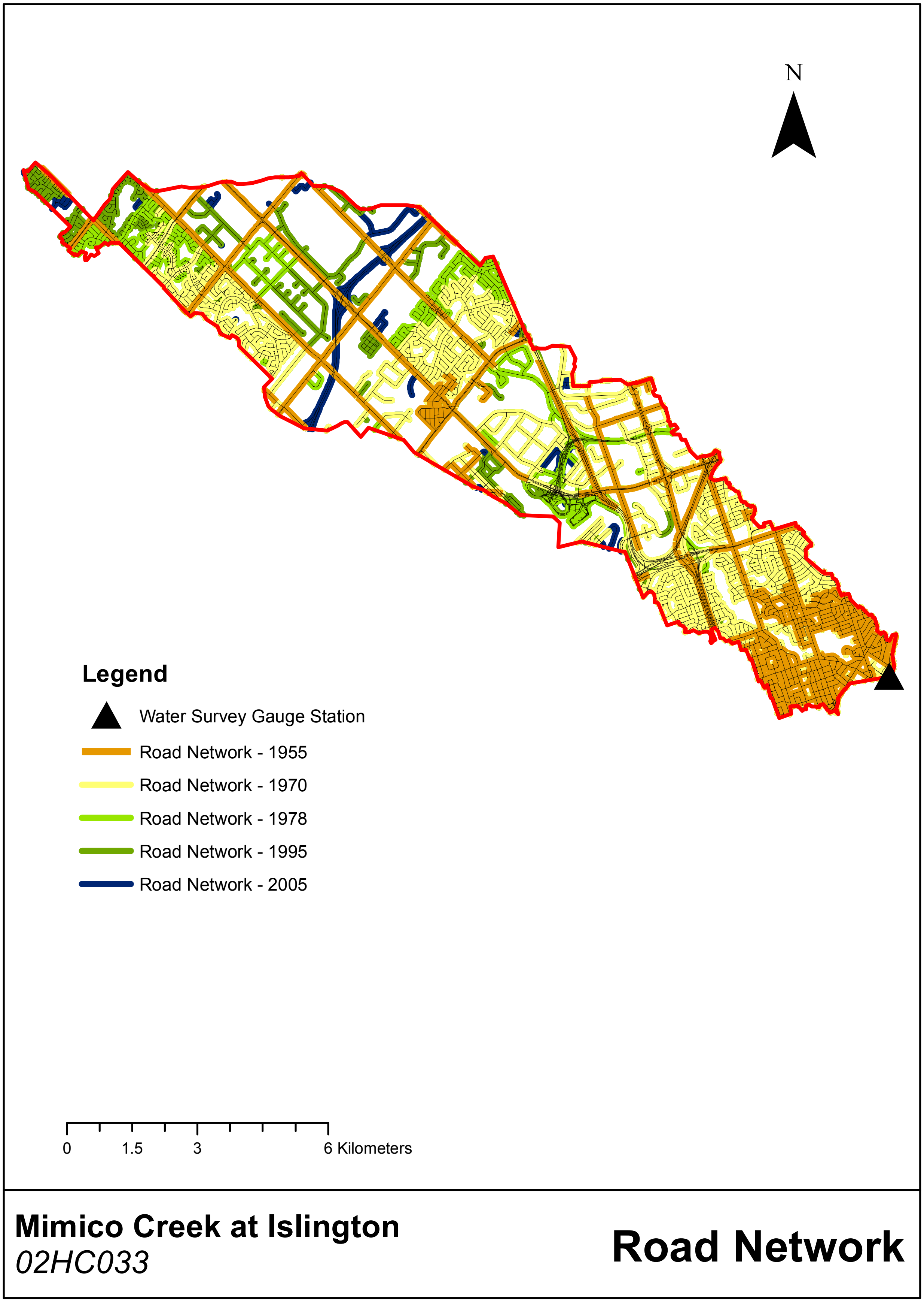


Figure C.5: Observed temporal change in urban area (red) and road density (blue)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0
1.5
3
6 Kilometers
Mimico Creek at Islington
02HC033
Land Classification
SOLRIS ver. 1.2 (MNR)


N
Legend
Water Survey Gauge Station
Urbanized Area - 1955
Urbanized Area - 1970
Urbanized Area - 1978
Urbanized Area - 1995
Urbanized Area - 2005
0
1.5
3
6 Kilometers
Mimico Creek at Islington
02HC033
Urbanization


N
Legend
Water Survey Gauge Station
Road Network - 1955
Road Network - 1970
Road Network - 1978
Road Network - 1995
Road Network - 2005
0
1.5
3
6 Kilometers
Mimico Creek at Islington
02HC033
Road Network

02HC033 - Mimico Creek at Islington

Topographic Catchment Area: 75.2 km^2
Effective Catchment Area: 73.8 km^2

Table C.6: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1955	7.4	10	177	2.4	85.8	11.6
1970	33.3	45.1	450	6.1	362.4	10.9
1978	40.2	54.5	553	7.5	454.8	11.3
1995	53	71.8	641	8.7	591.3	11.1
2005	60.2	81.5	683	9.3	639.4	10.6

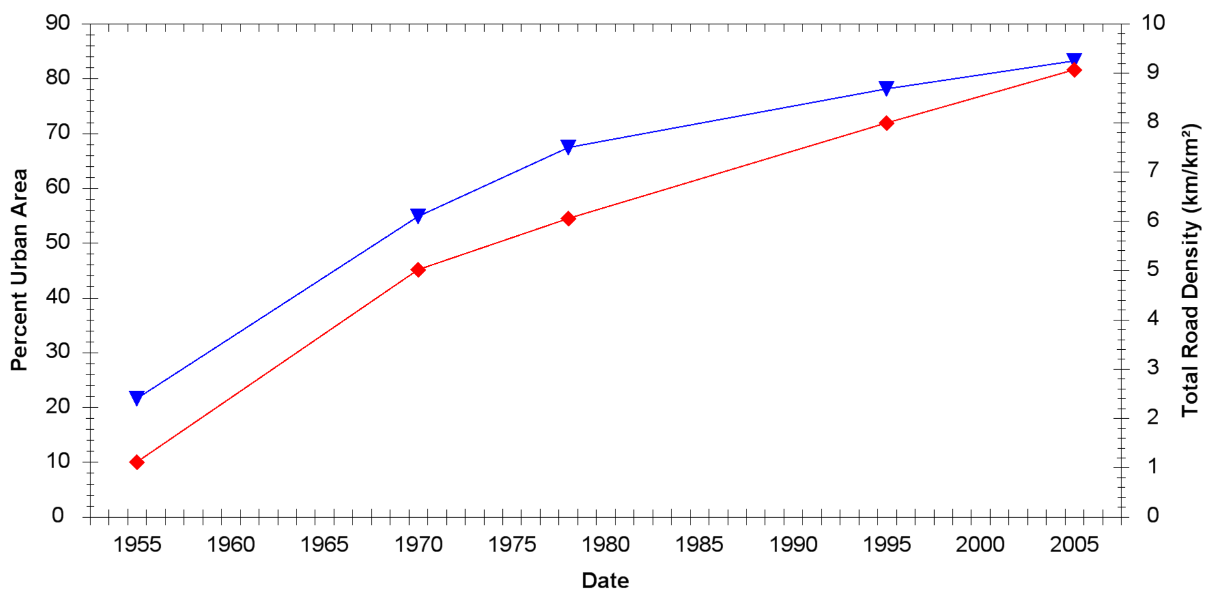
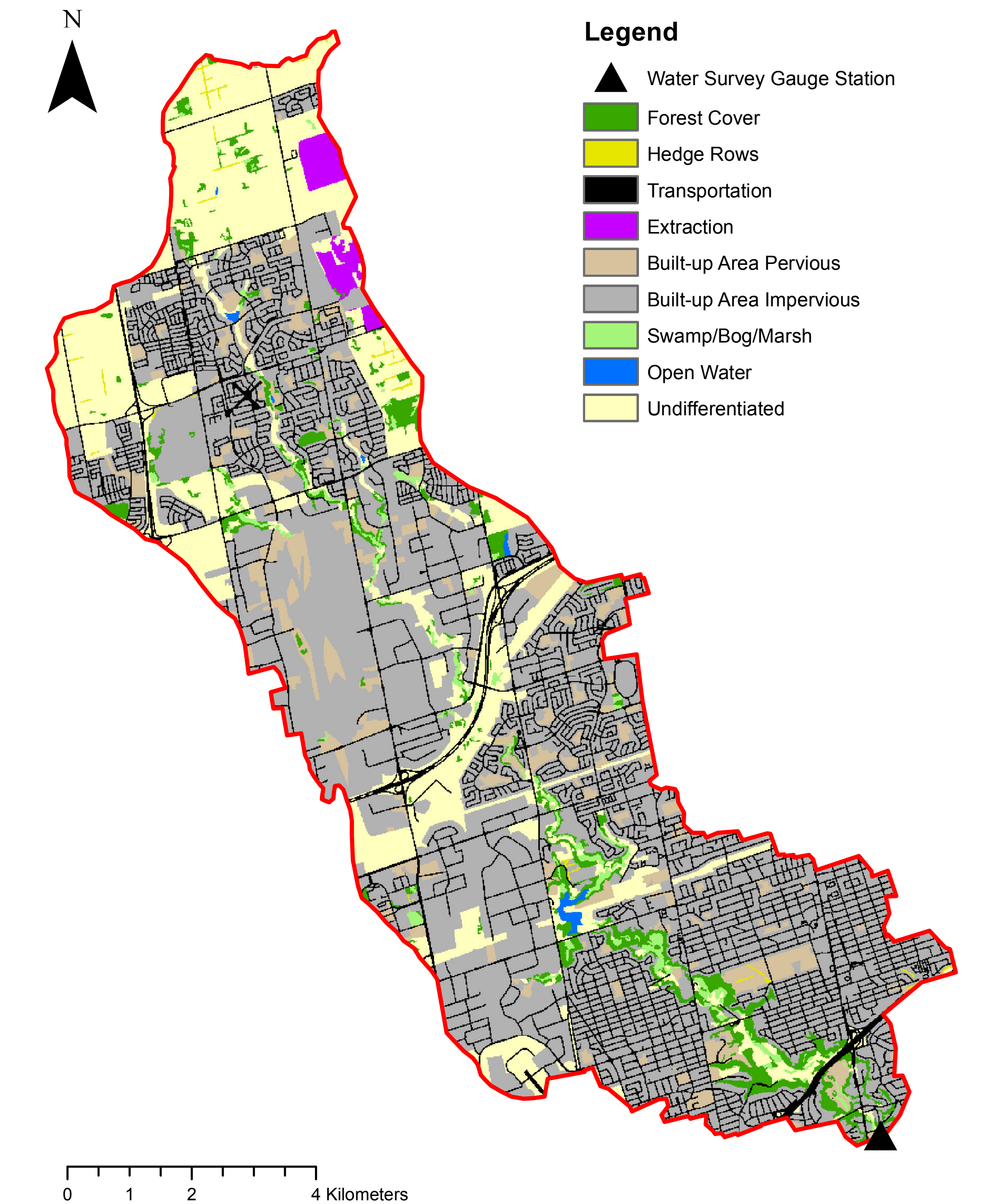
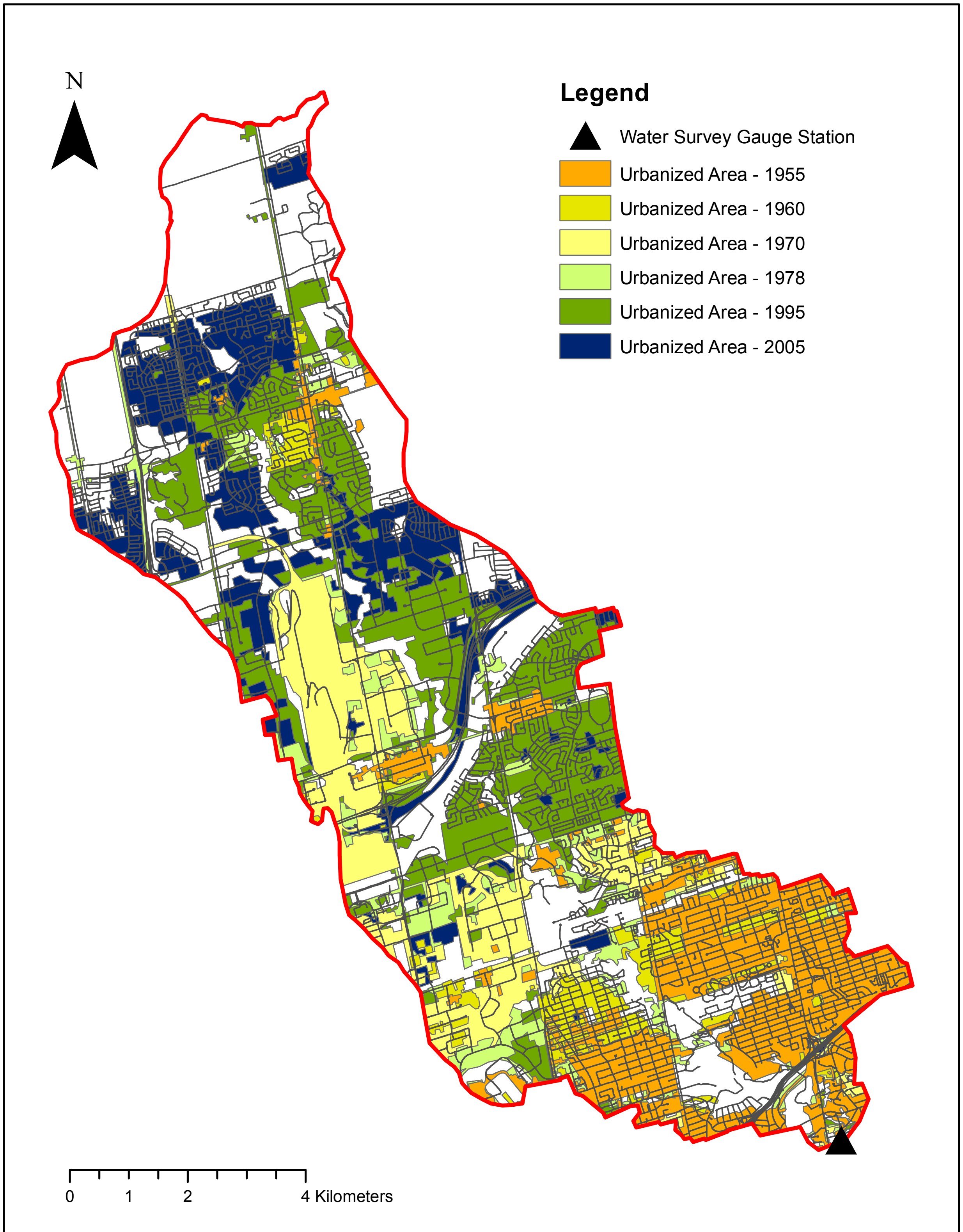


Figure C.6: Observed temporal change in urban area (red) and road density (blue)



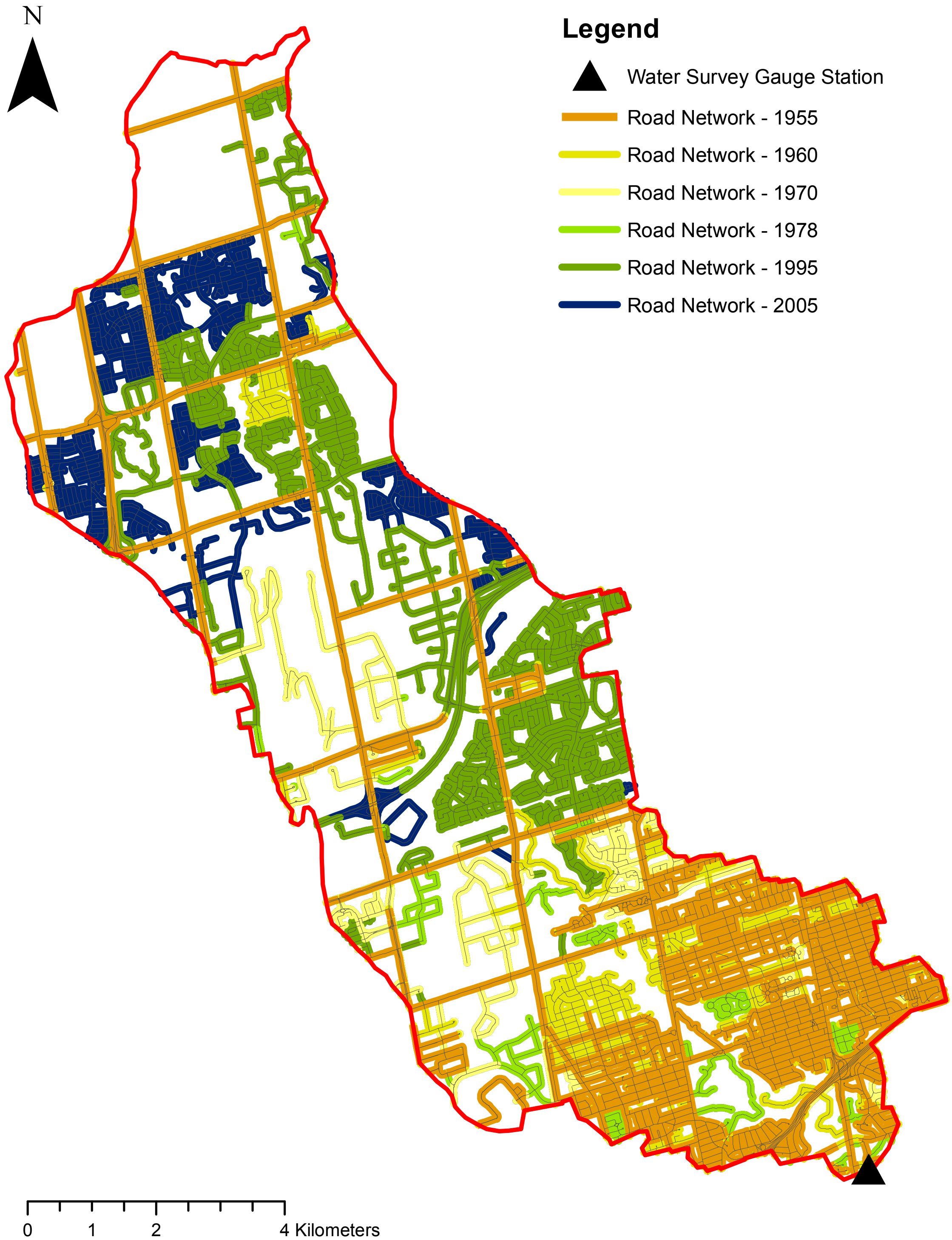
Don River at York Mills
02HC005

Land Classification
SOLRIS ver. 1.2 (MNR)



Don River at York Mills
02HC005

Urbanization



Don River at York Mills
02HC005

Road Network

02HC005 - Don River at York Mills

Topographic Catchment Area: 96.7 km^2
Effective Catchment Area: 95.5 km^2

Table C.7: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1954	14.5	15.1	283	3	181.2	12.5
1960	18.5	19.4	351	3.7	243.5	13.1
1970	29.9	31.3	420	4.4	320.2	10.7
1978	35.3	36.9	454	4.8	373.6	10.6
1995	53.5	56	669	7	593.3	11.1
2005	65.8	68.9	804	8.4	729.1	11.1

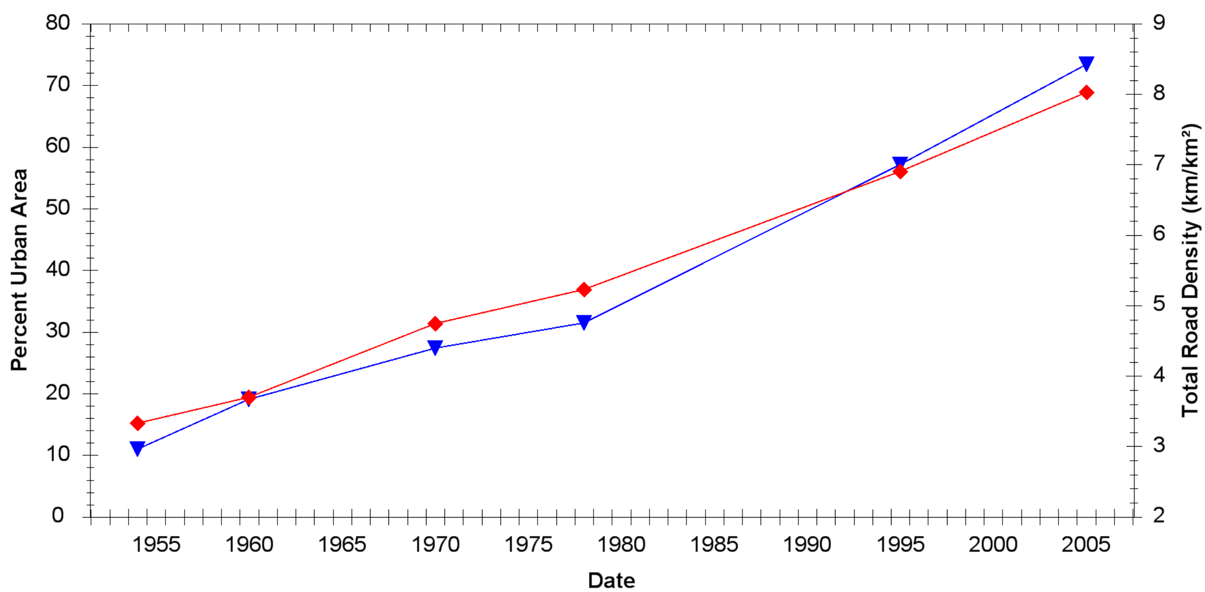
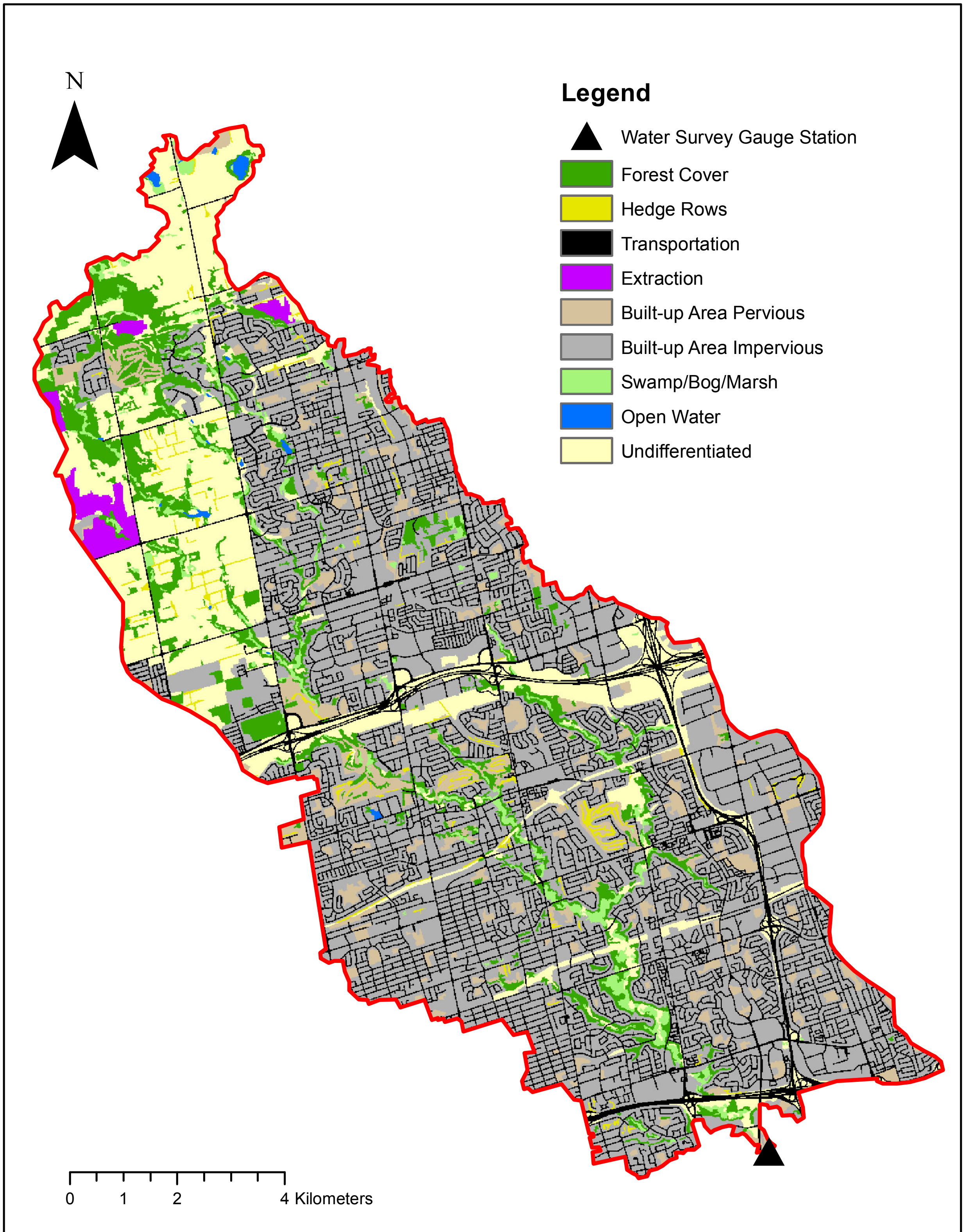
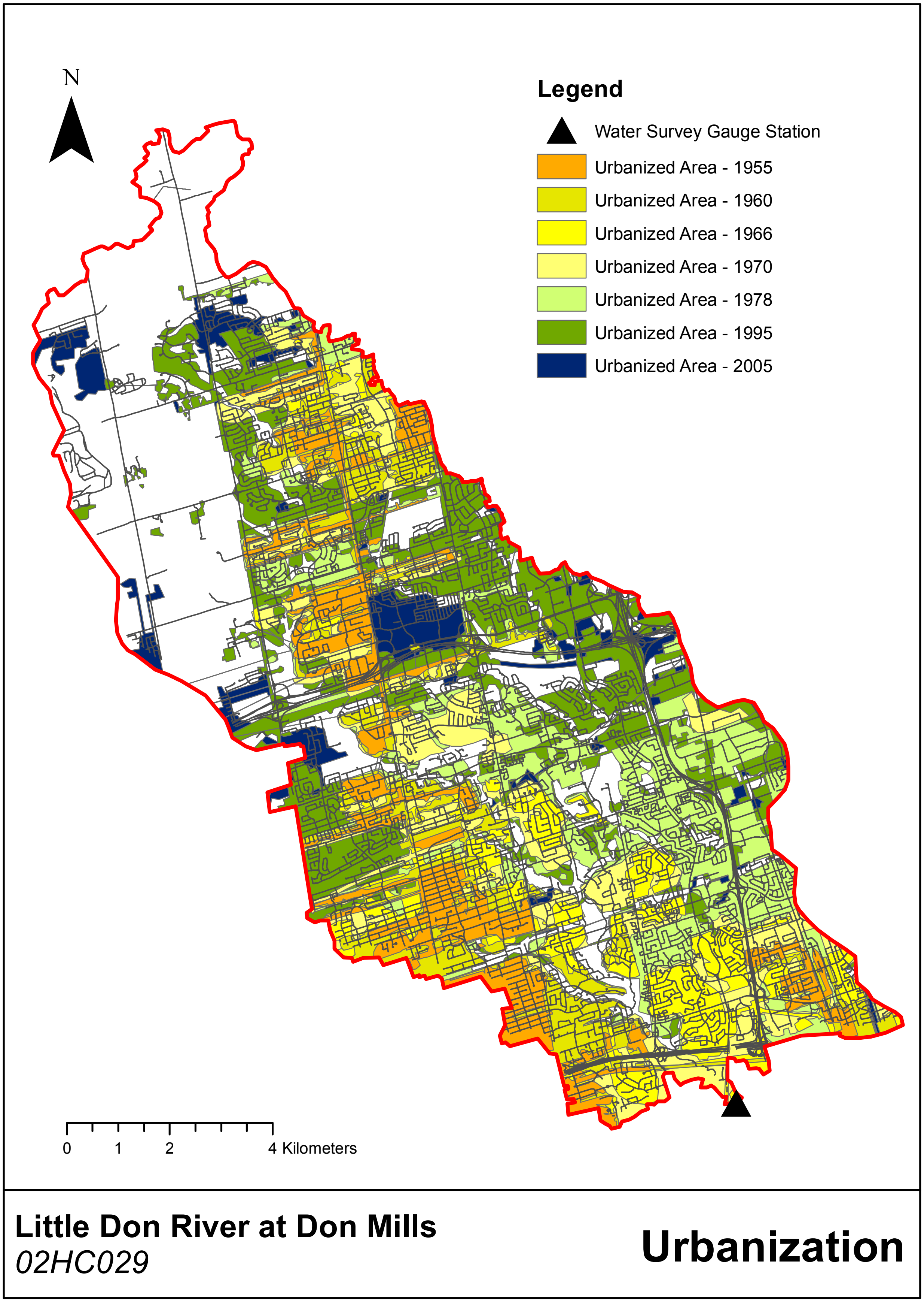


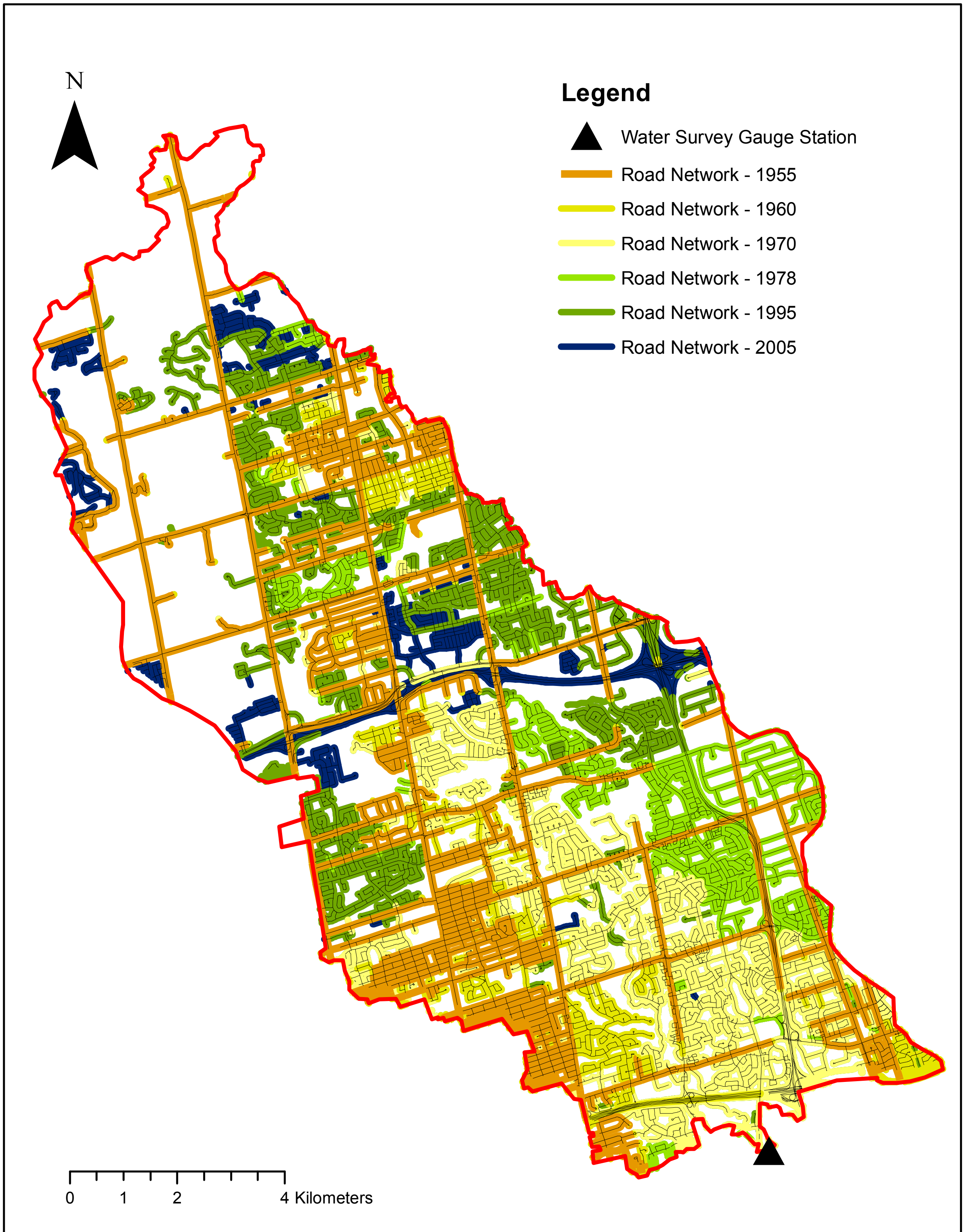
Figure C.7: Observed temporal change in urban area (red) and road density (blue)



Little Don River at Don Mills
02HC029

Land Classification
SOLRIS ver. 1.2 (MNR)


N
Legend
Water Survey Gauge Station
Urbanized Area - 1955
Urbanized Area - 1960
Urbanized Area - 1966
Urbanized Area - 1970
Urbanized Area - 1978
Urbanized Area - 1995
Urbanized Area - 2005
0 1 2 4 Kilometers
Little Don River at Don Mills
02HC029
Urbanization



Little Don River at Don Mills
02HC029

Road Network

02HC029 - Little Don River at Don Mills

Topographic Catchment Area: 137.8 km^2
Effective Catchment Area: 135.1 km^2

Table C.8: Observed Urban Coverage and Roadway Length

Year	**Urbanized Area (km^2)**	**Percent Urban Area**	**Total Roadway Length (km)**	**Total Roadway Density (km/km^2)**	**Urban Roadway Length (km)**	**Urban Roadway Density (km/km^2)**
1954	12.6	9.4	312	2.3	158.1	12.5
1960	21.2	15.7	390	2.9	242.3	11.4
1966	29.2	21.6	510	3.8	364.2	12.5
1970	43.6	32.3	688	5.1	489.6	11.2
1978	59	43.7	831	6.2	702.5	11.9
1995	84.8	62.8	1062	7.9	976.7	11.5
2005	92.3	68.4	1132	8.4	1096.6	11.9

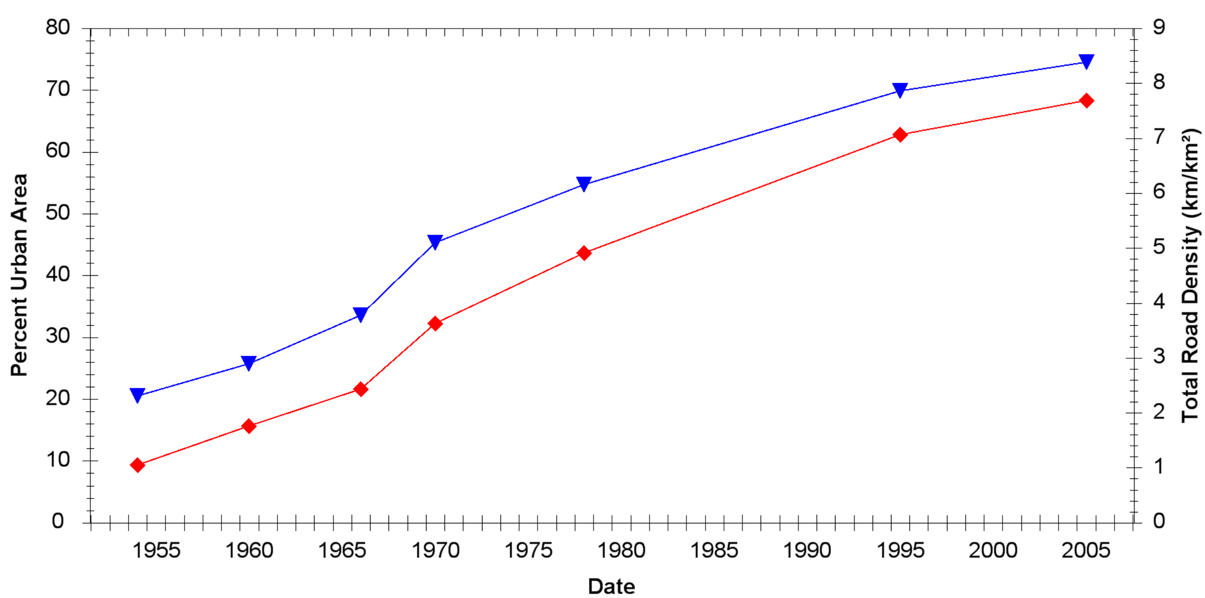
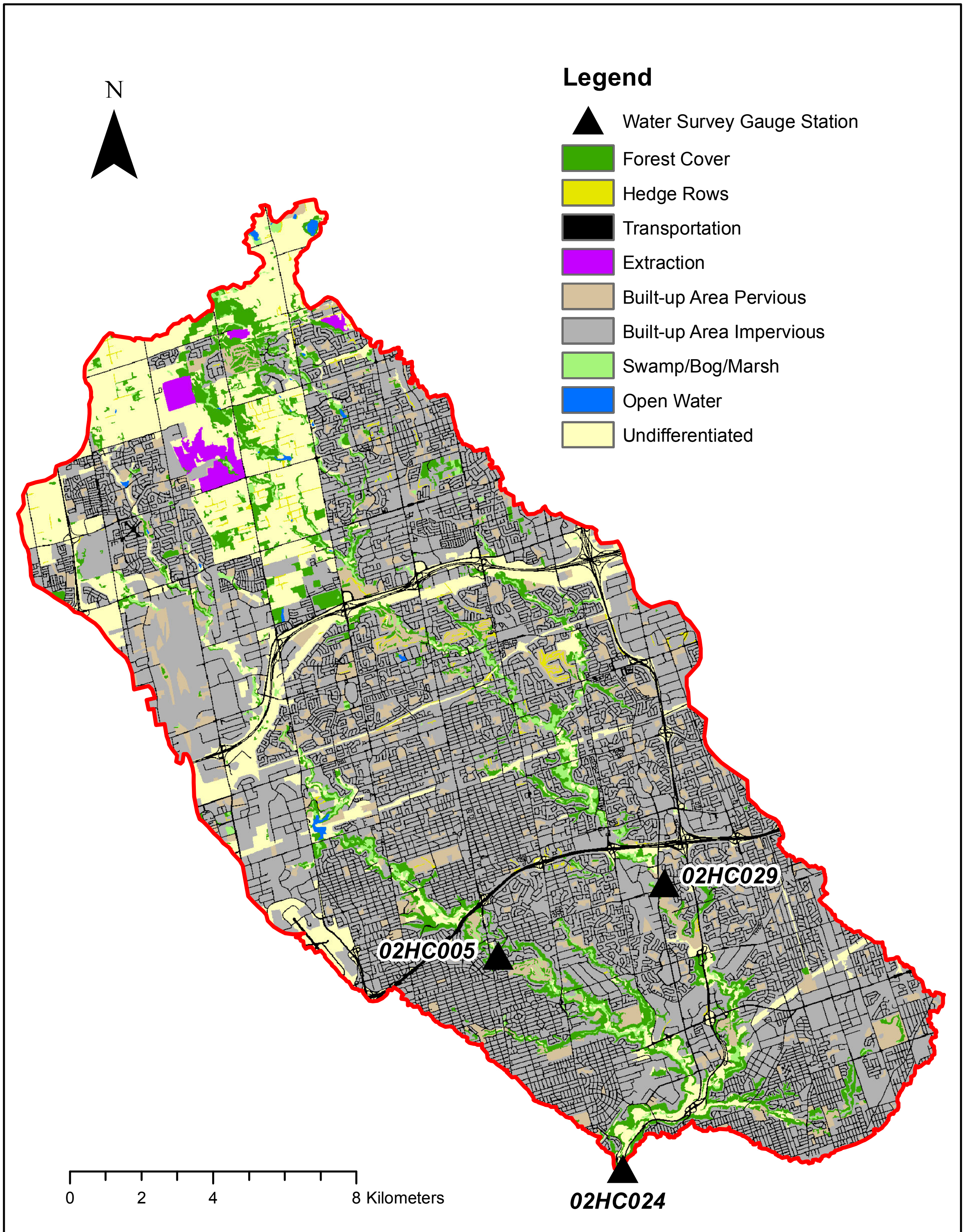
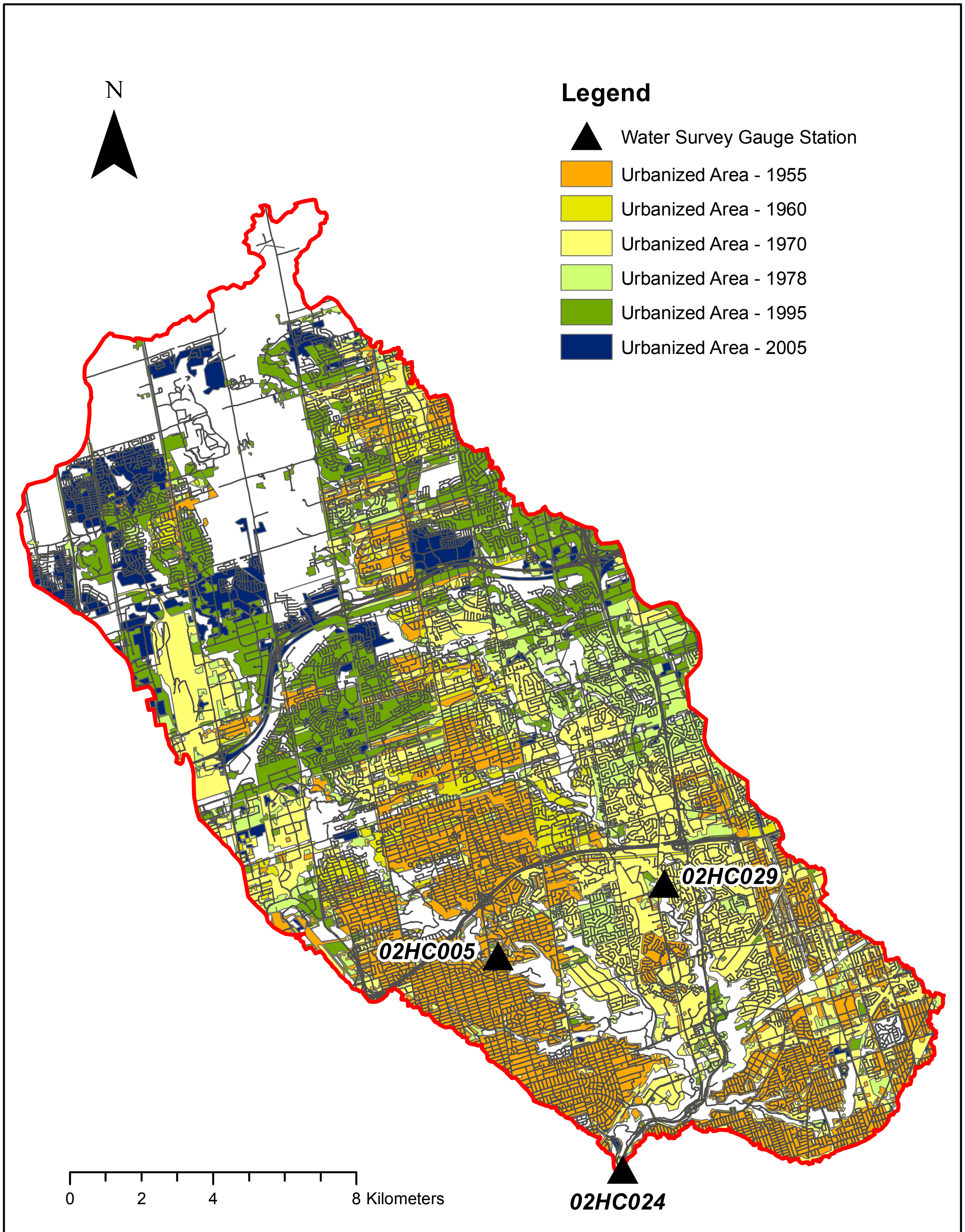


Figure C.8: Observed temporal change in urban area (red) and road density (blue)



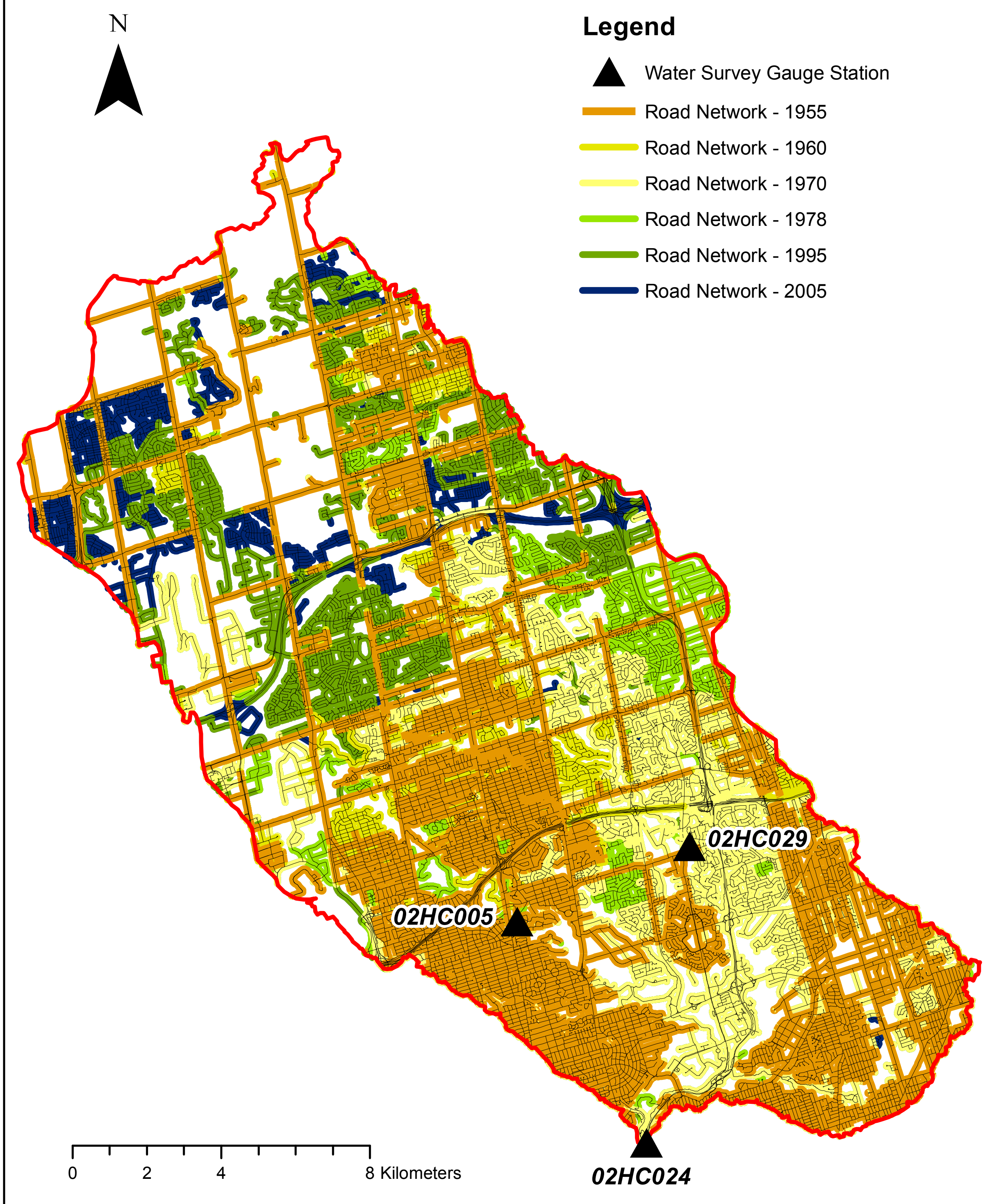
Don River at Todmorden
02HC024

Land Classification
SOLRIS ver. 1.2 (MNR)



Don River at Todmorden
02HC024

Urbanization



Don River at Todmorden
02HC024

Road Network

02HC024 - Don River at Todmorden

Topographic Catchment Area: 320.6 km^2
Effective Catchment Area: 322.2 km^2

Table C.9: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1955	64.7	20.1	1207	3.7	948.6	14.7
1970	142.4	44.2	2063	6.4	1718.2	12.1
1978	168.1	52.2	2268	7	2023	12
1995	213.9	66.4	2720	8.4	2527.4	11.8
2005	234.2	72.7	2927	9.1	2786.6	11.9

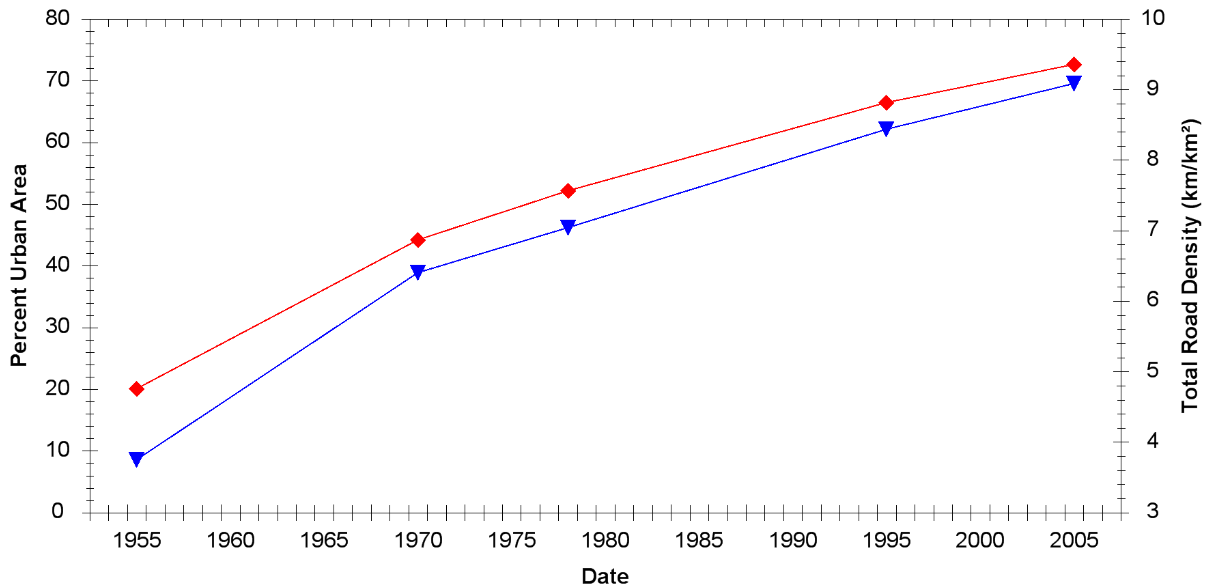
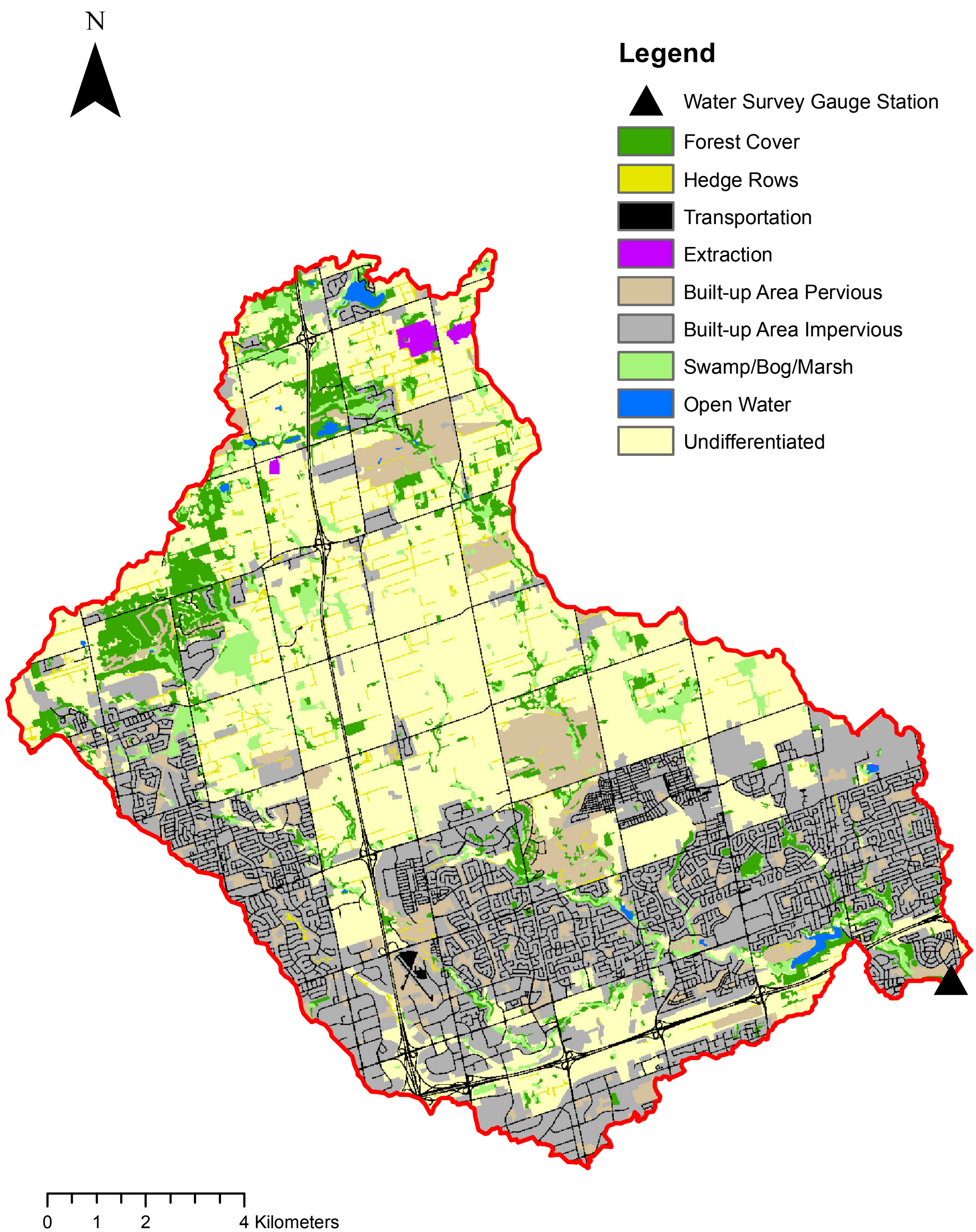
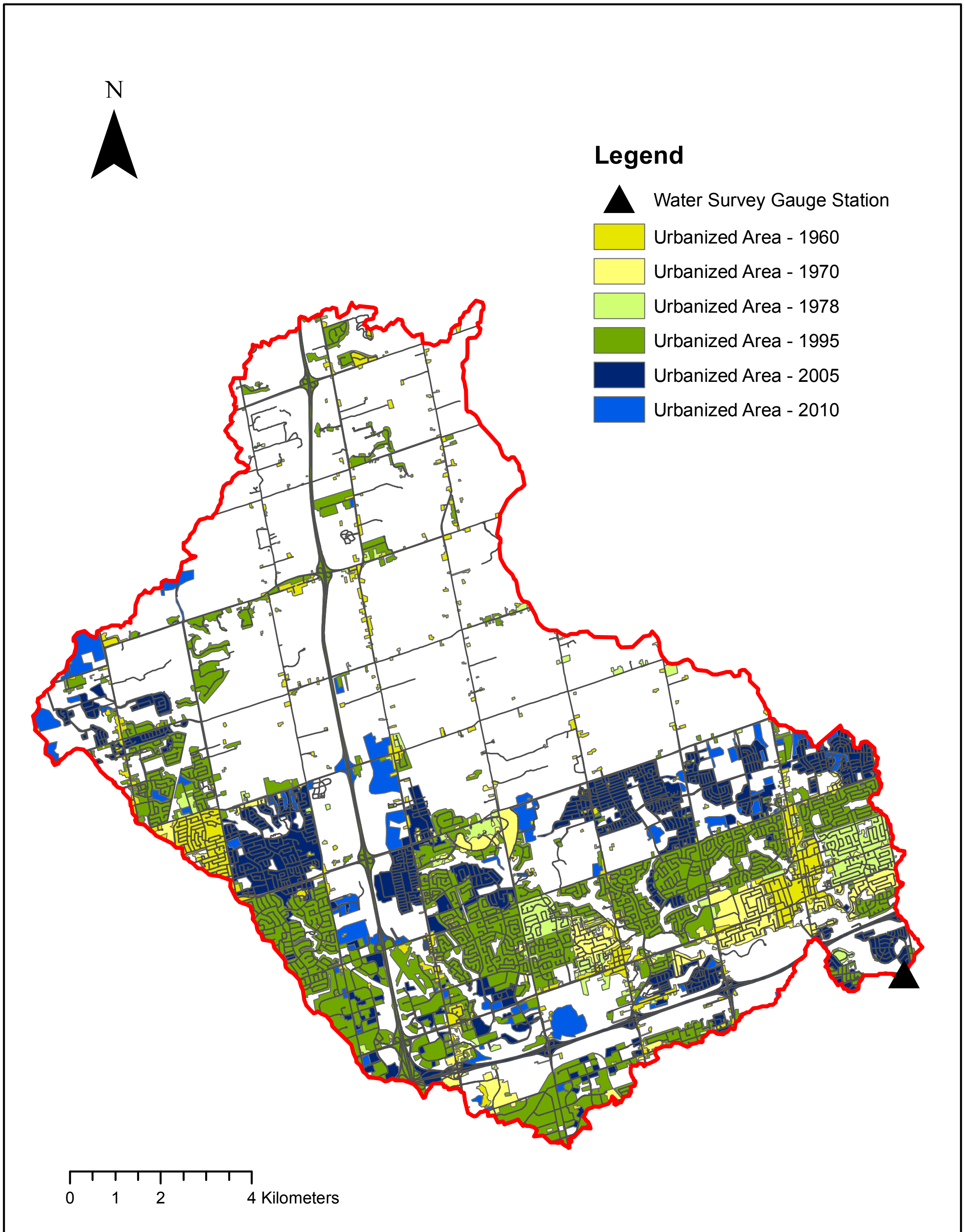


Figure C.9: Observed temporal change in urban area (red) and road density (blue)



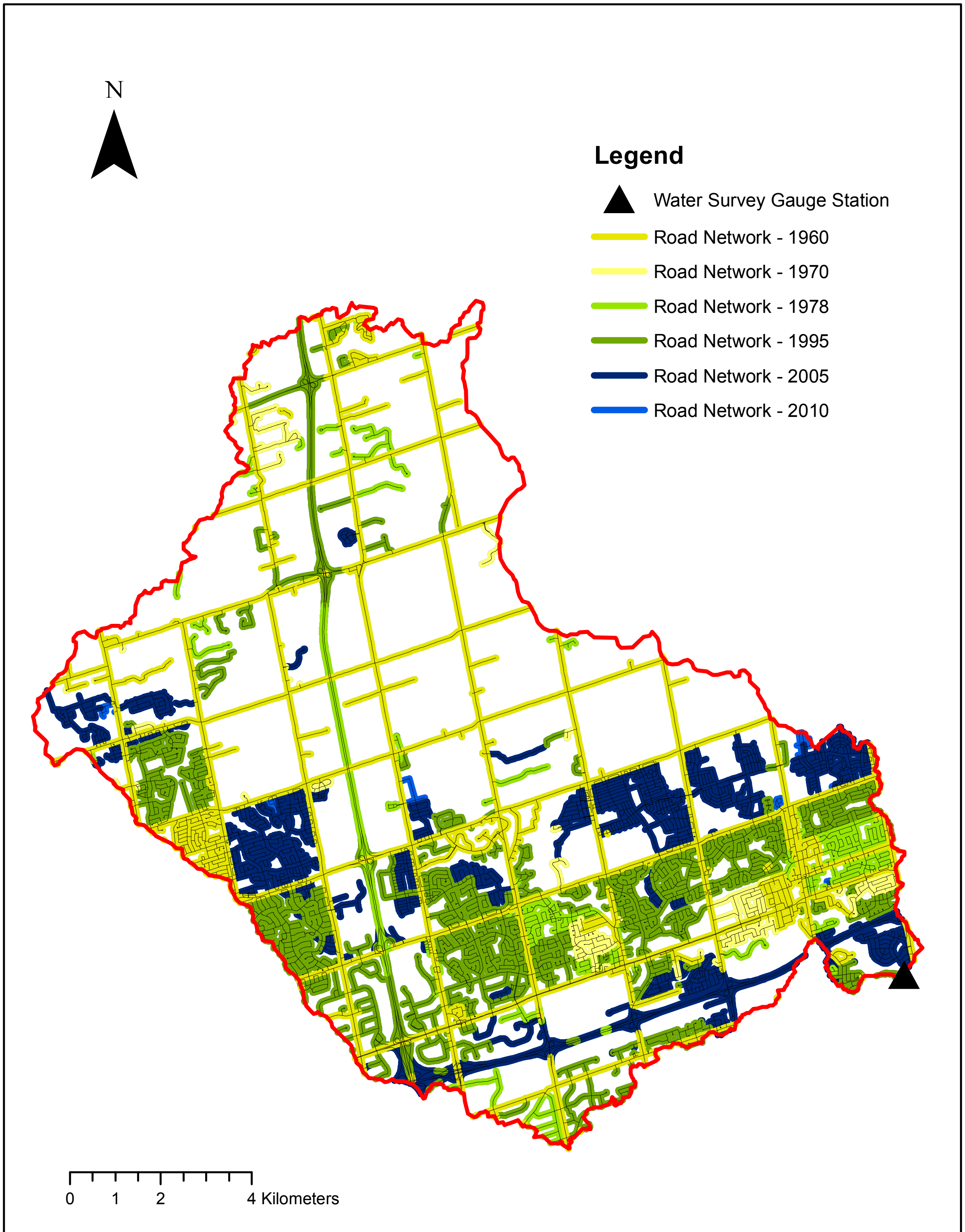
Rouge River near Markham
02HC022

Land Classification
SOLRIS ver. 1.2 (MNR)



Rouge River near Markham
02HC022

Urbanization



Rouge River near Markham
02HC022

Road Network

02HC022 - Rouge River near Markham

Topographic Catchment Area: 181.3 km^2

Table C.10: Observed Urban Coverage and Roadway Length

Year	**Urbanized Area (km^2)**	**Percent Urban Area**	**Total Roadway Length (km)**	**Total Roadway Density (km/km^2)**	**Urban Roadway Length (km)**	**Urban Roadway Density (km/km^2)**
2005	51.3	77.8	705	10.7	634.3	12.4
1960	8.4	4.6	187	1	162.8	19.4
1970	14.1	7.8	242	1.3	241	17.1
1978	18.6	10.2	302	1.7	293.4	15.8
1995	50.1	27.6	691	3.8	596.5	11.9
2005	66.9	36.9	991	5.5	964.1	14.4
2010	72.2	39.9	1003	5.5	1008.9	14

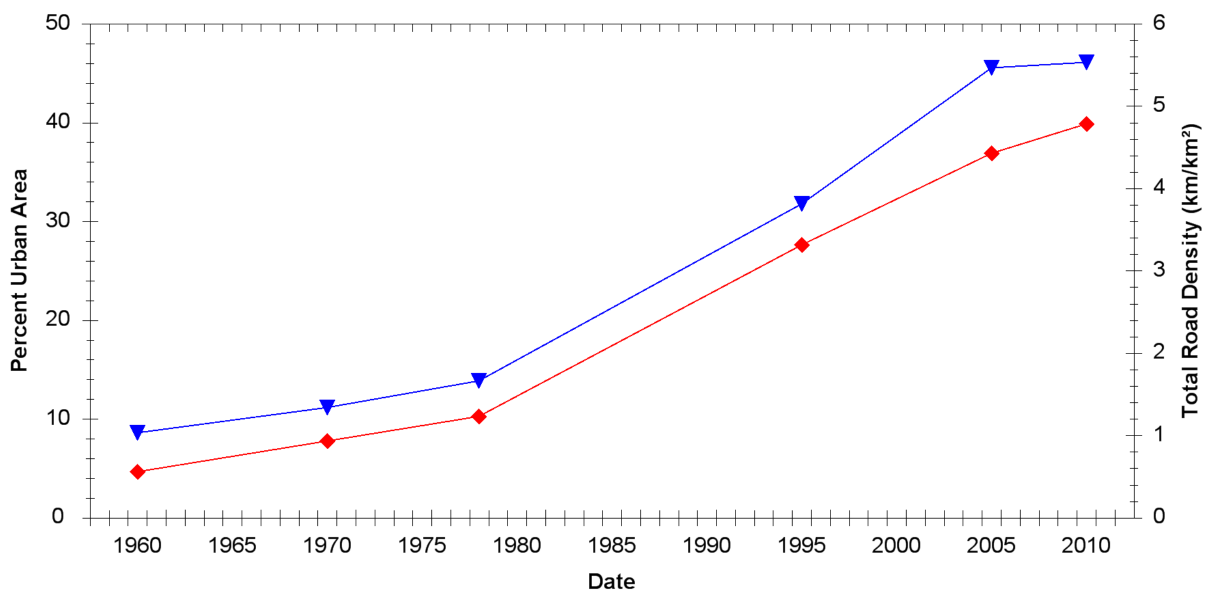
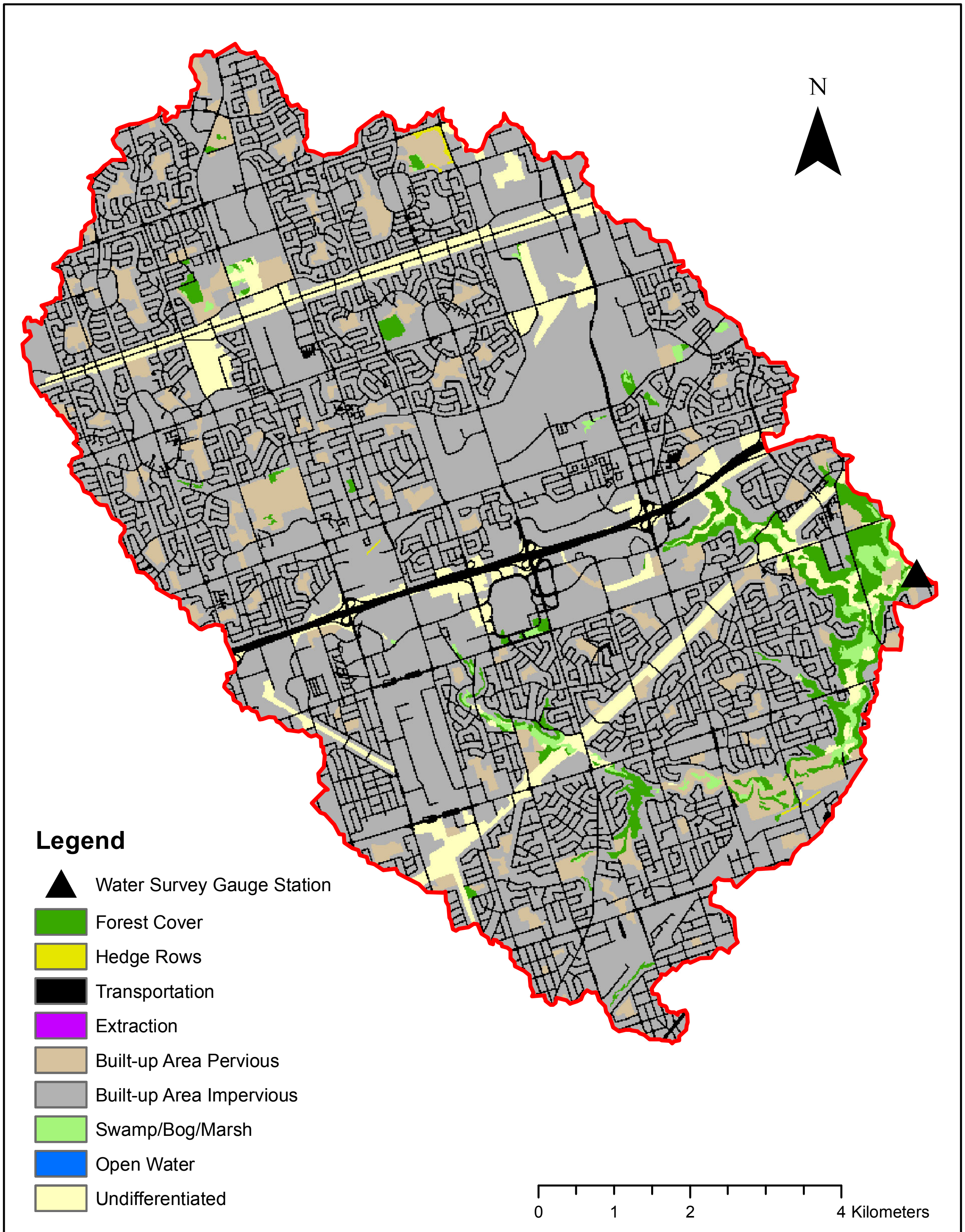
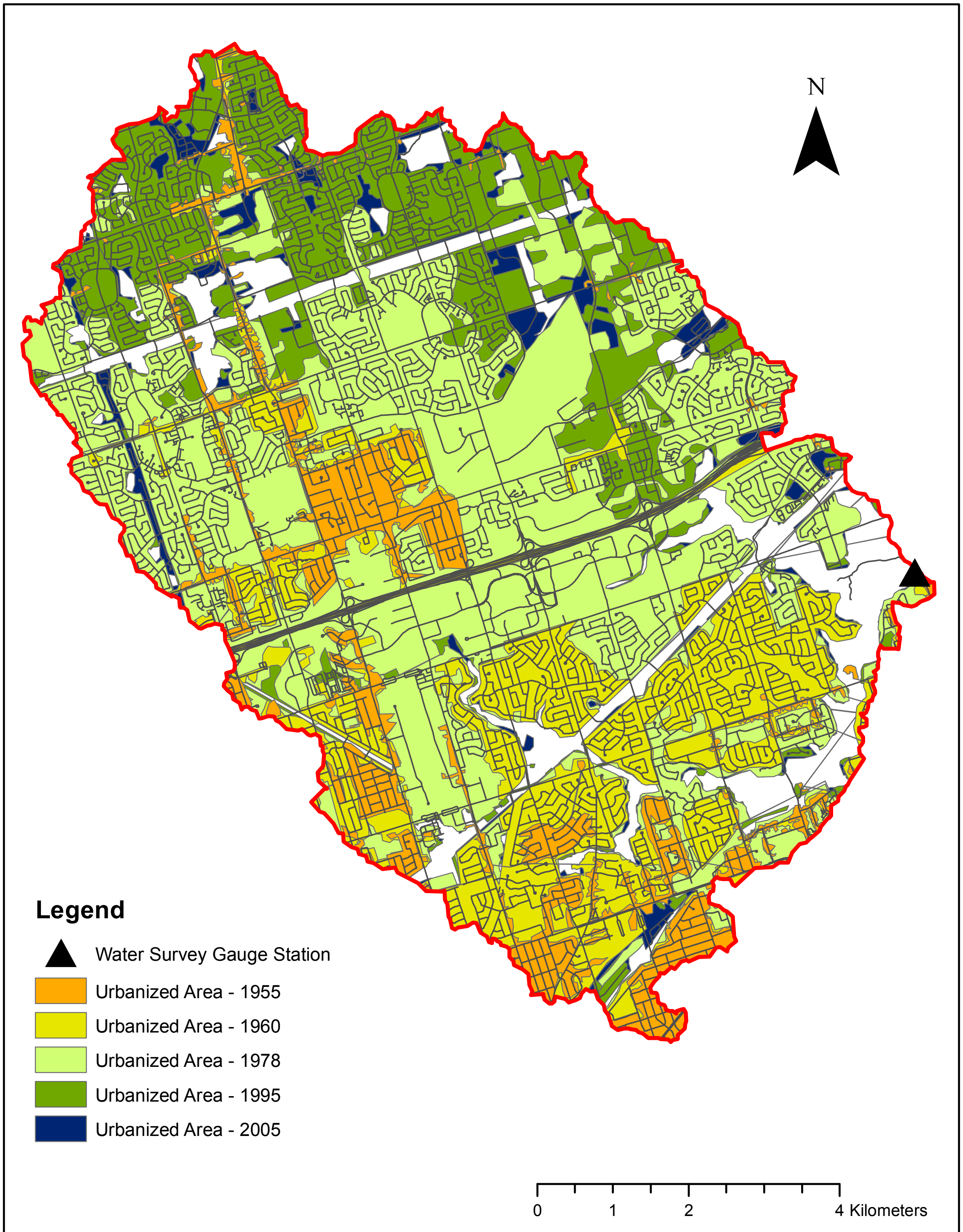


Figure C.10: Observed temporal change in urban area (red) and road density (blue)



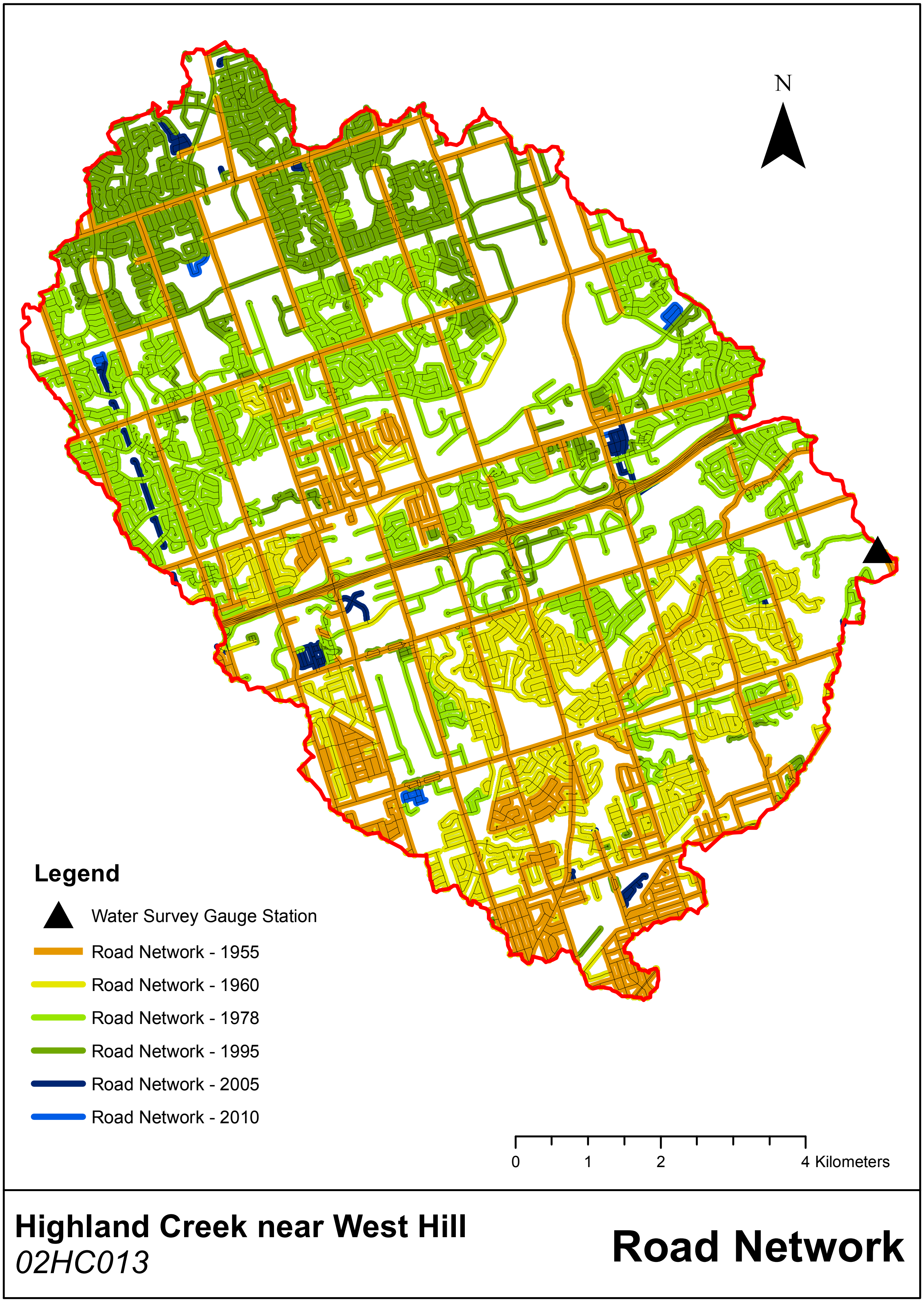
Highland Creek near West Hill
02HC013

Land Classification
SOLRIS ver. 1.2 (MNR)



Highland Creek near West Hill
02HC013

Urbanization


N
Legend
Water Survey Gauge Station
Road Network - 1955
Road Network - 1960
Road Network - 1978
Road Network - 1995
Road Network - 2005
Road Network - 2010
0
1
2
4 Kilometers
Highland Creek near West Hill
02HC013
Road Network

02HC013 - Highland Creek near West Hill

Topographic Catchment Area: 89.0 km^2

Table C.11: Observed Urban Coverage and Roadway Length

Year	Urbanized Area (km^2)	Percent Urban Area	Total Roadway Length (km)	Total Roadway Density (km/km^2)	Urban Roadway Length (km)	Urban Roadway Density (km/km^2)
1955	8.9	10	248	2.8	128.5	14.5
1960	23.4	26.3	397	4.5	323.2	13.8
1978	60.5	67.9	693	7.8	659.8	10.9
1995	75.3	84.6	858	9.6	851.9	11.3
2004	76.1	85.4	872	9.8	863.8	11.4
2010	76.5	85.9	876	9.8	869.6	11.4

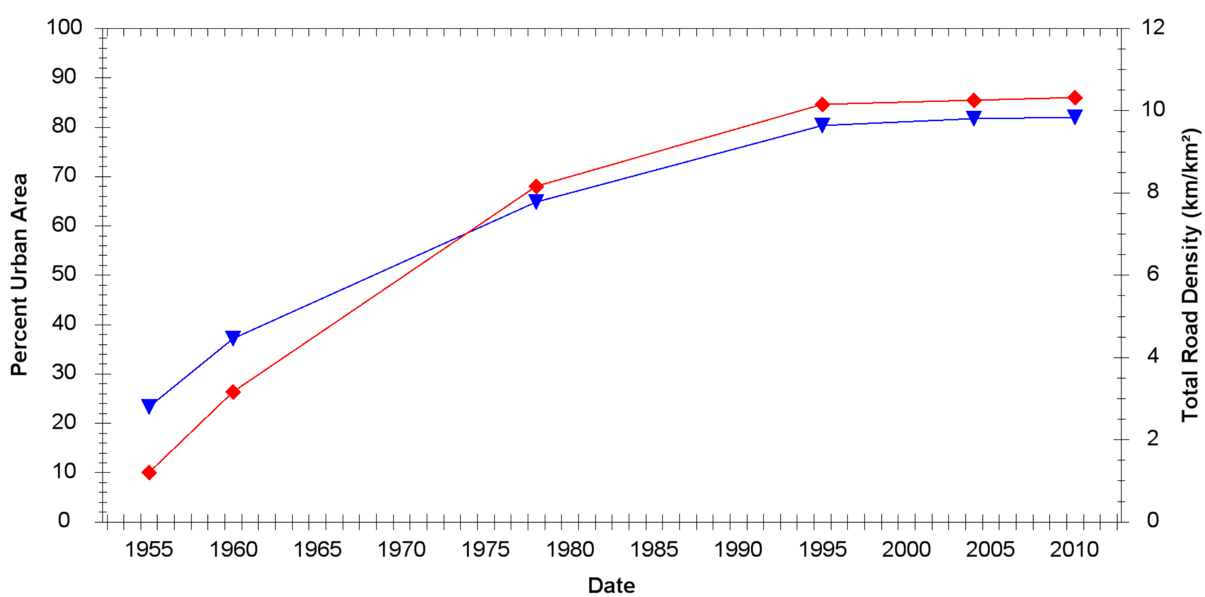
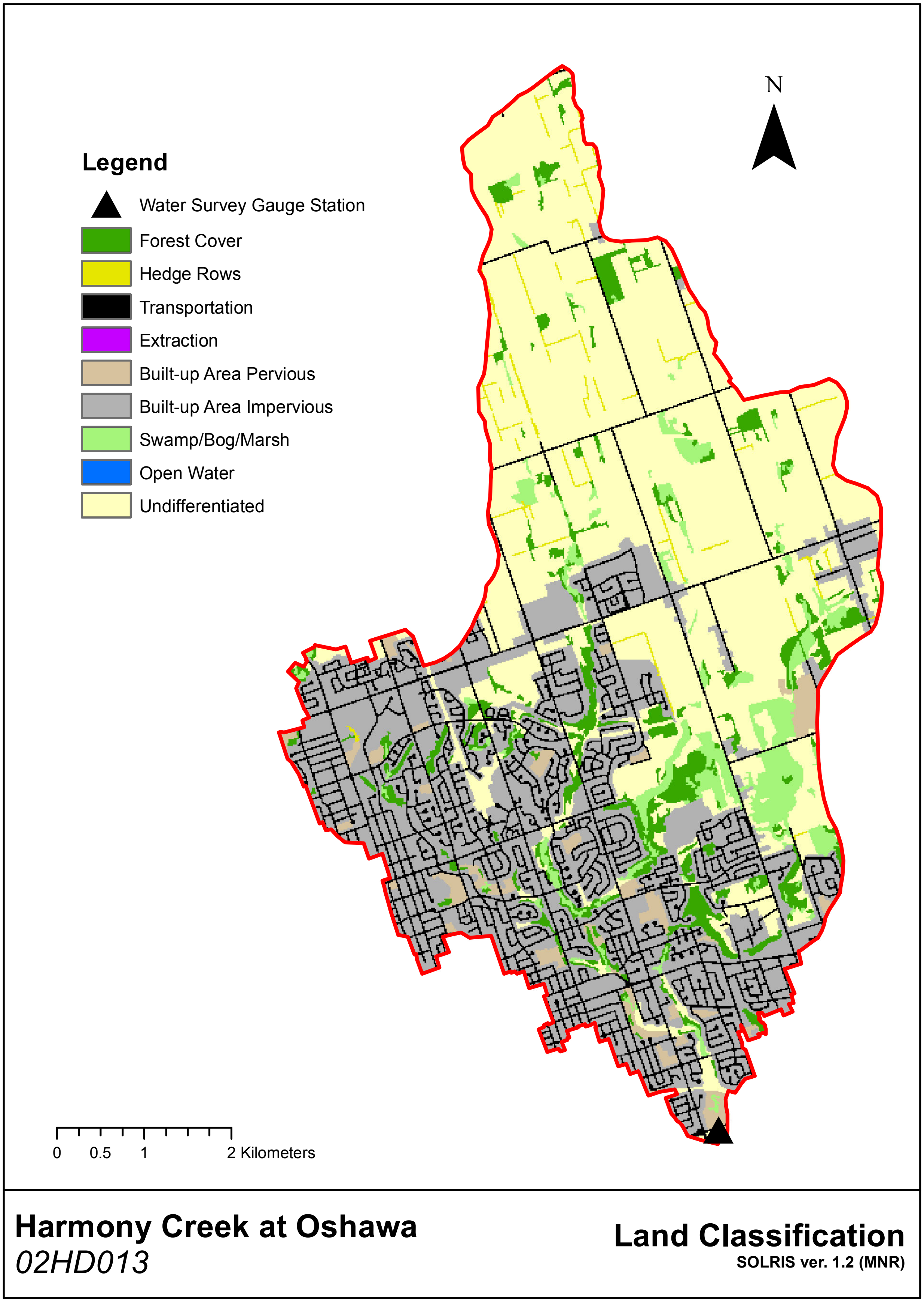
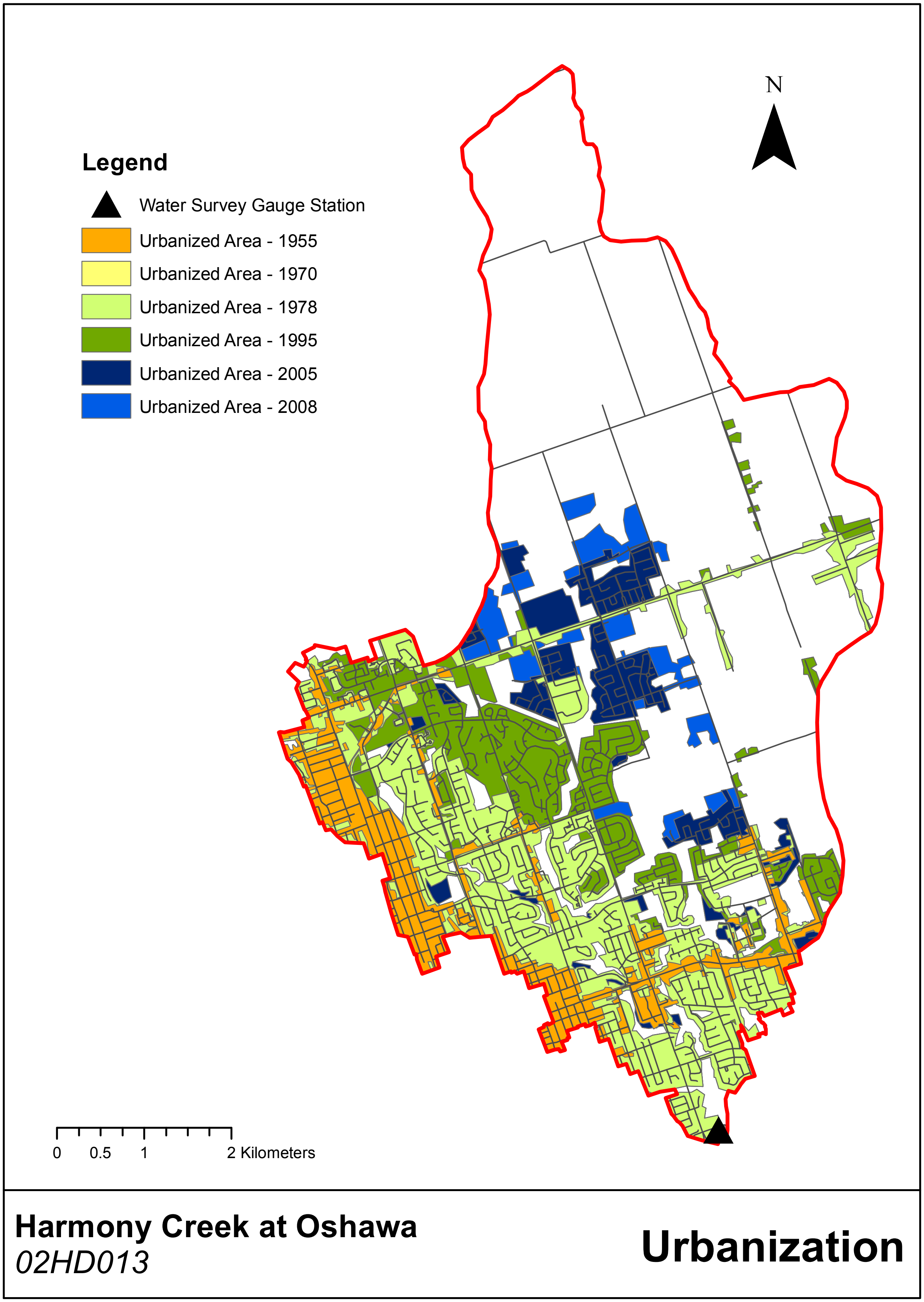
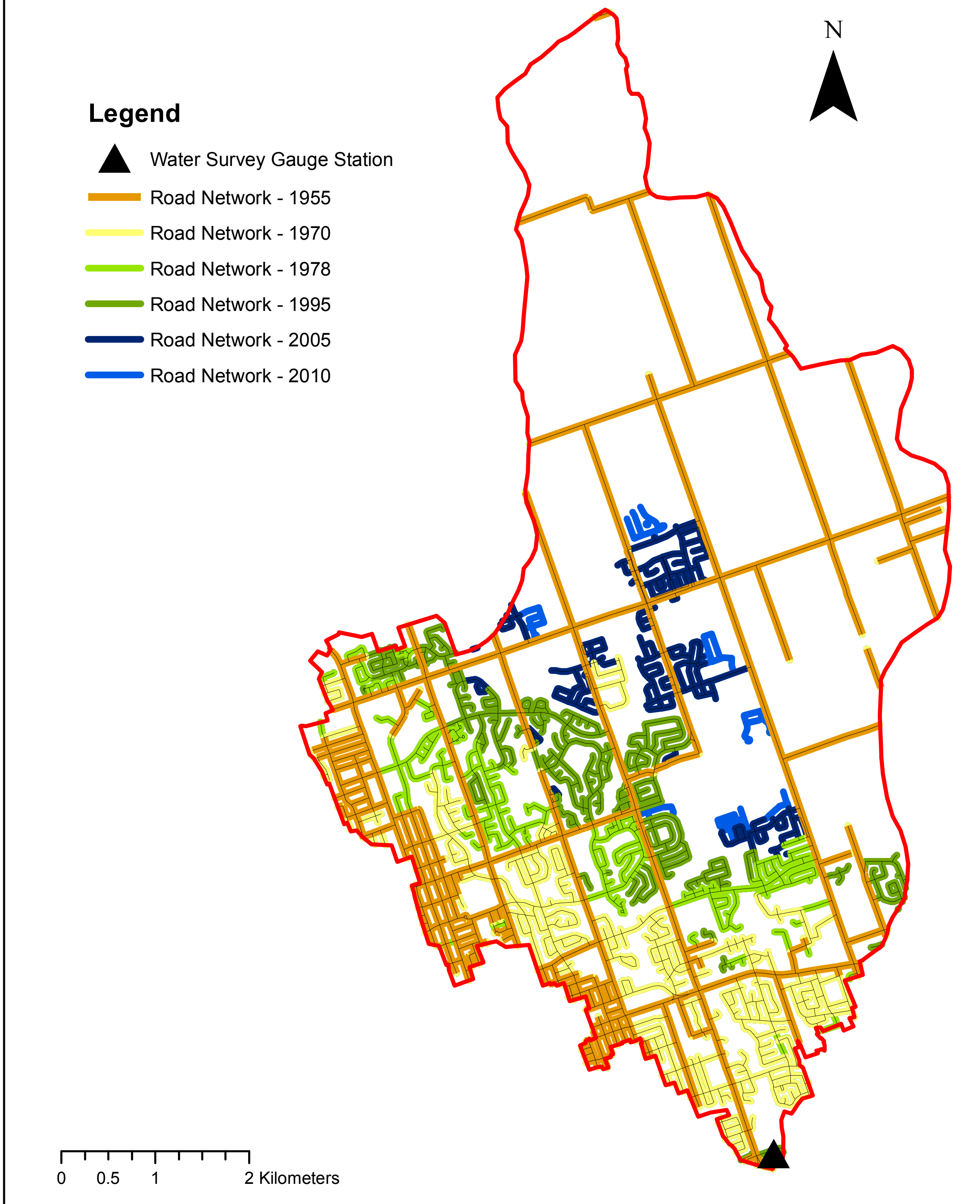


Figure C.11: Observed temporal change in urban area (red) and road density (blue)


N
Legend
Water Survey Gauge Station
Forest Cover
Hedge Rows
Transportation
Extraction
Built-up Area Pervious
Built-up Area Impervious
Swamp/Bog/Marsh
Open Water
Undifferentiated
0
0.5
1
2 Kilometers
Harmony Creek at Oshawa
02HD013
Land Classification
SOLRIS ver. 1.2 (MNR)


Legend
Water Survey Gauge Station
Urbanized Area - 1955
Urbanized Area - 1970
Urbanized Area - 1978
Urbanized Area - 1995
Urbanized Area - 2005
Urbanized Area - 2008
N
0 0.5 1 2 Kilometers
Harmony Creek at Oshawa
02HD013
Urbanization



Harmony Creek at Oshawa
02HD013

Road Network

02HD013 - Harmony Creek at Oshawa

Topographic Catchment Area: 42.1 km^2
Effective Catchment Area: 43.0 km^2

Table C.12: Observed Urban Coverage and Roadway Length

Year	**Urbanized Area (km^2)**	**Percent Urban Area**	**Total Roadway Length (km)**	**Total Roadway Density (km/km^2)**	**Urban Roadway Length (km)**	**Urban Roadway Density (km/km^2)**
1954	3.6	8.3	102	2.4	50.9	14.3
1972	9.4	21.9	155	3.6	131.9	14
1978	11.7	27.1	184	4.3	164	14.1
1995	15.8	36.7	222	5.2	207.5	13.2
2005	18.2	42.3	247	5.7	234.7	12.9
2008	19.5	45.3	247	5.7	234.8	12

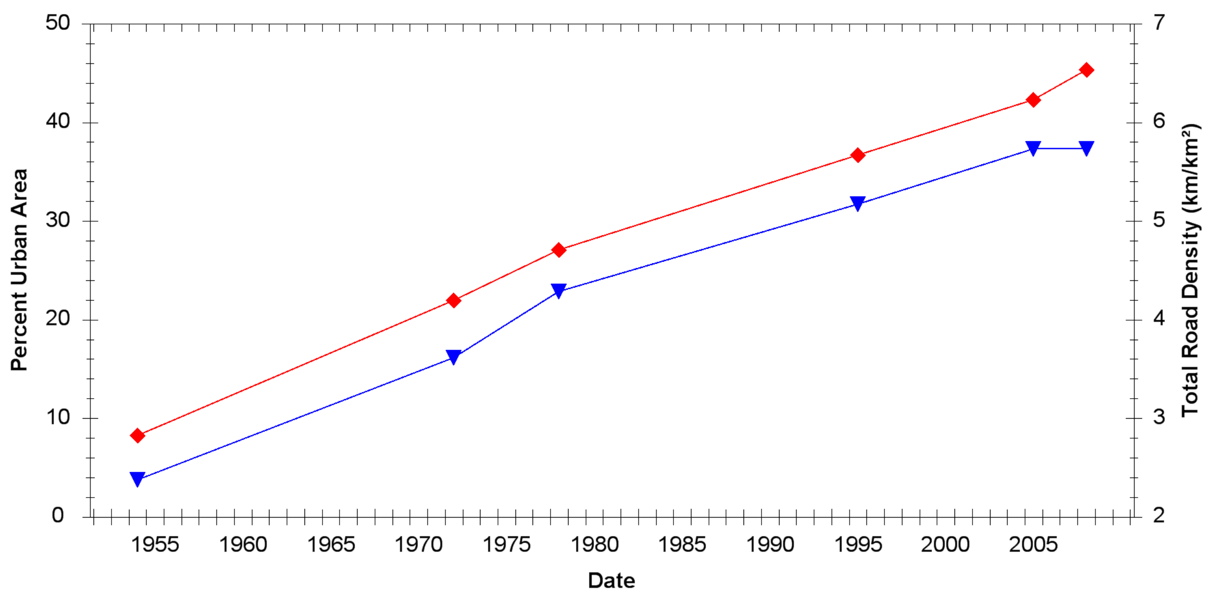


Figure C.12: Observed temporal change in urban area (red) and road density (blue)

Appendix D

Flow Duration and Peak Exceedance Curves

02HC019 - Duffins Creek above Pickering

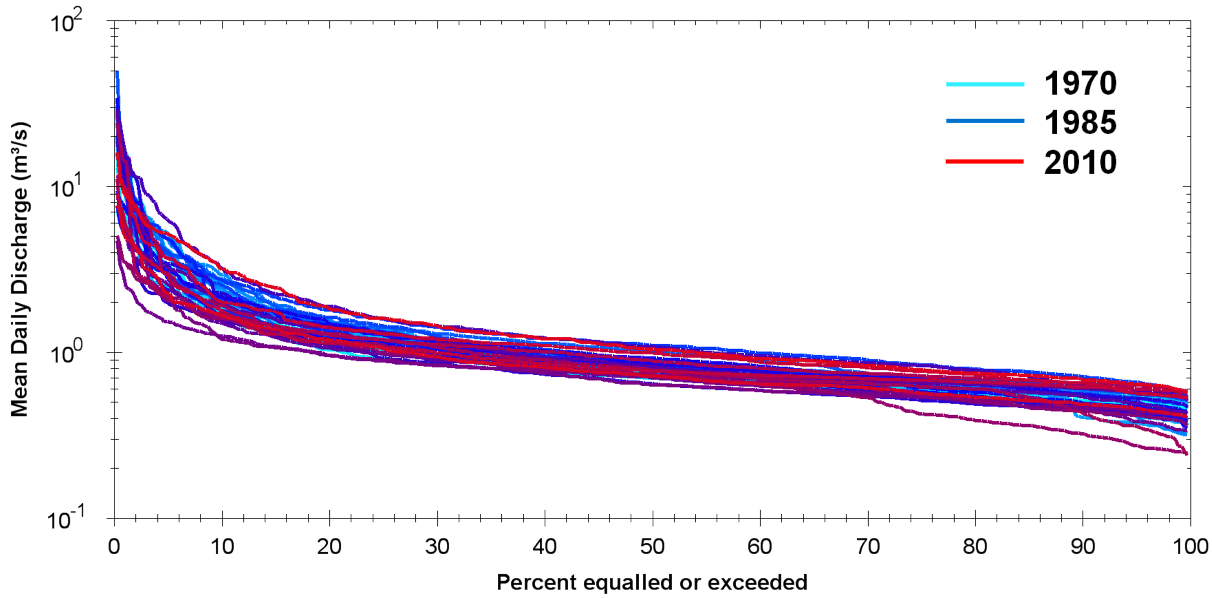


Figure D.1: Mean Daily Flow Duration Curve (by Year)

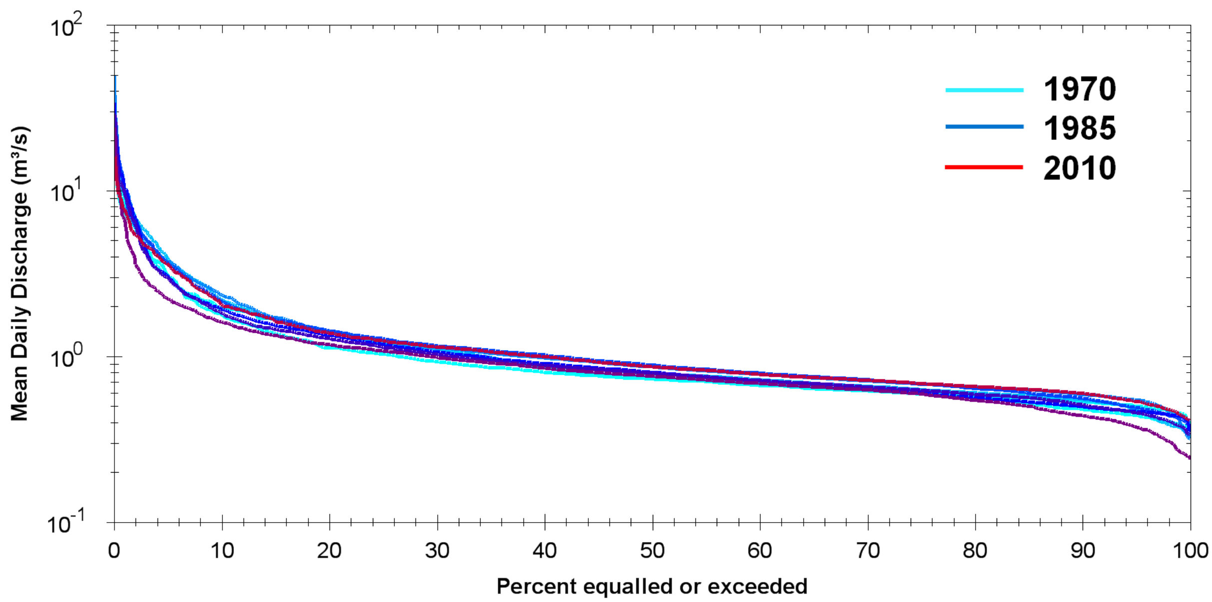


Figure D.2: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC019 - Duffins Creek above Pickering

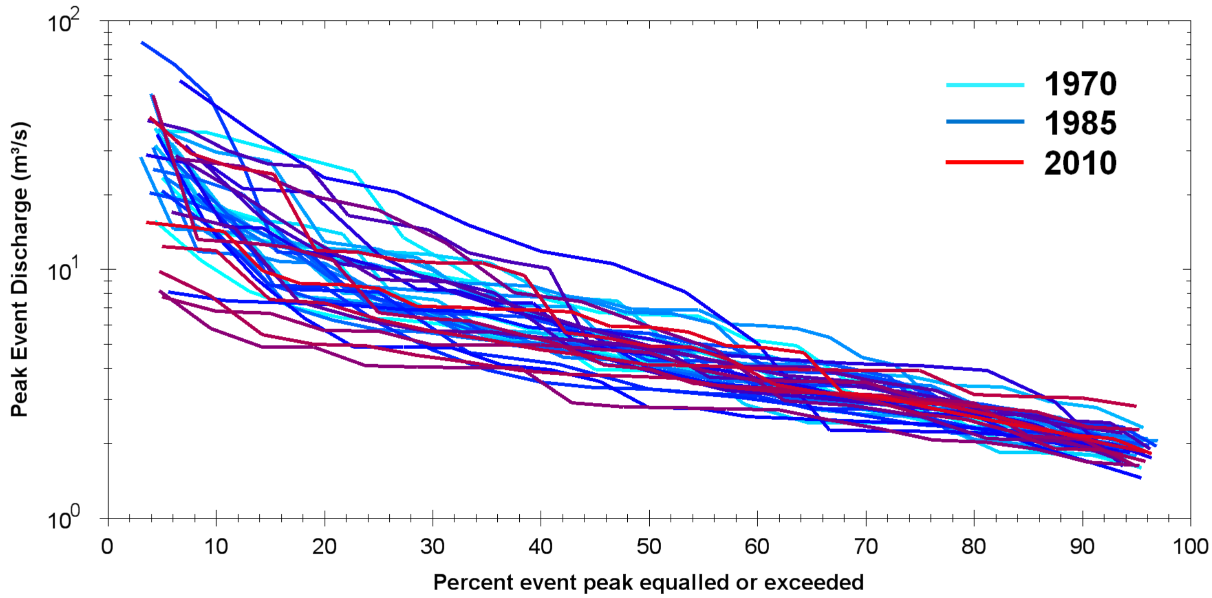


Figure D.3: Peak Exceedance Curve (by Year)

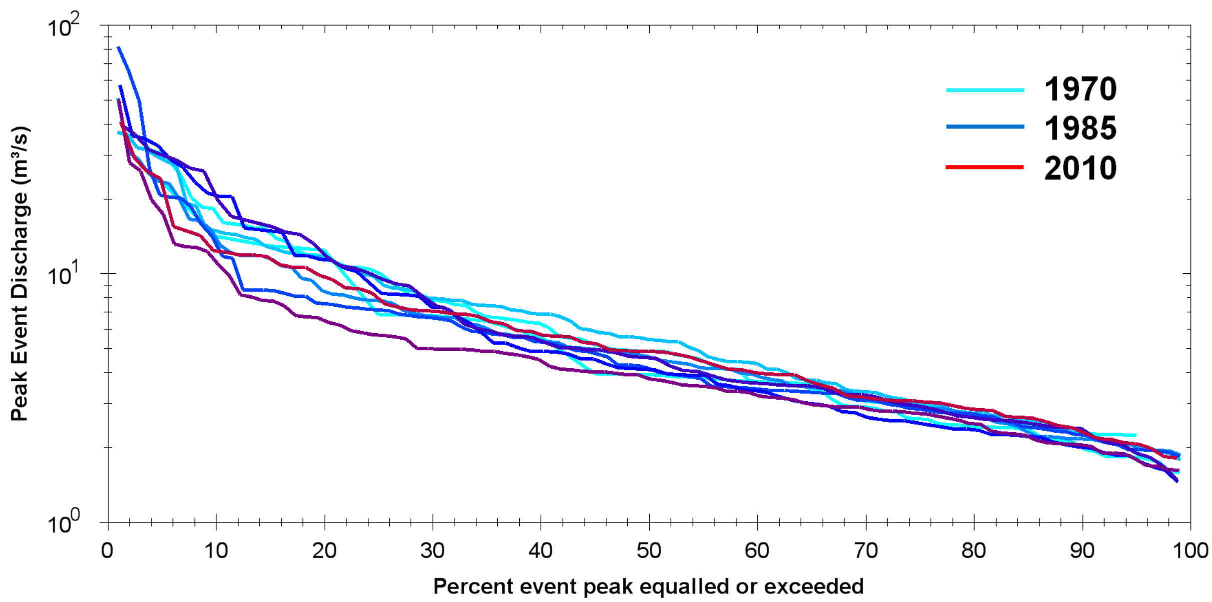


Figure D.4: Peak Exceedance Curve (5 Year Moving Average)

02HC009 - East Humber River near Pine Grove

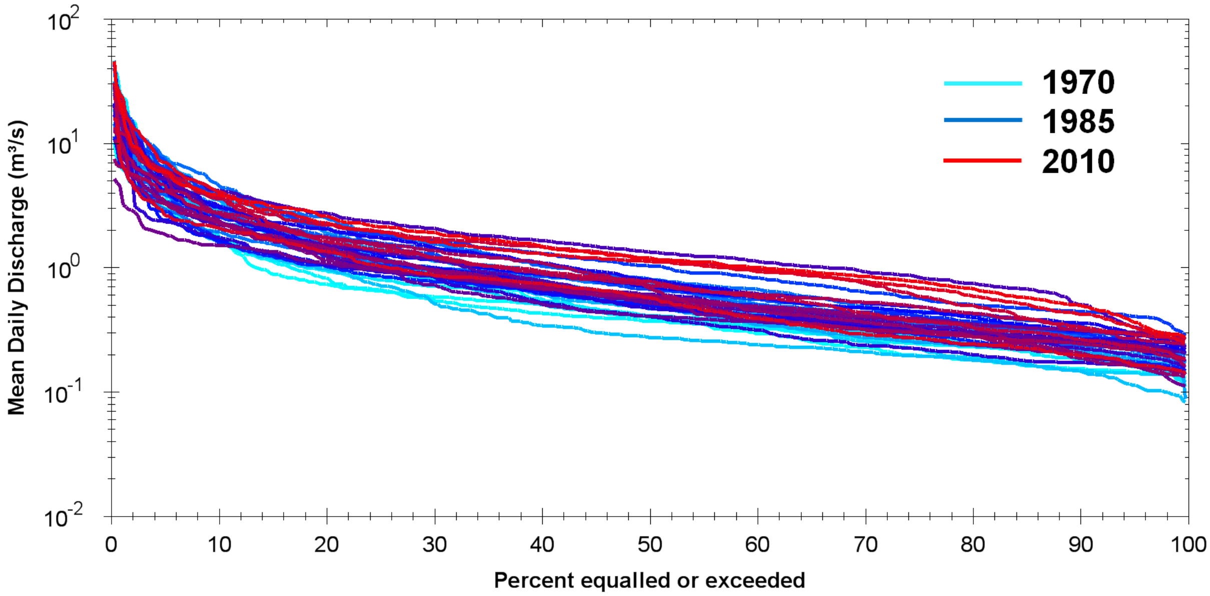


Figure D.5: Mean Daily Flow Duration Curve (by Year)

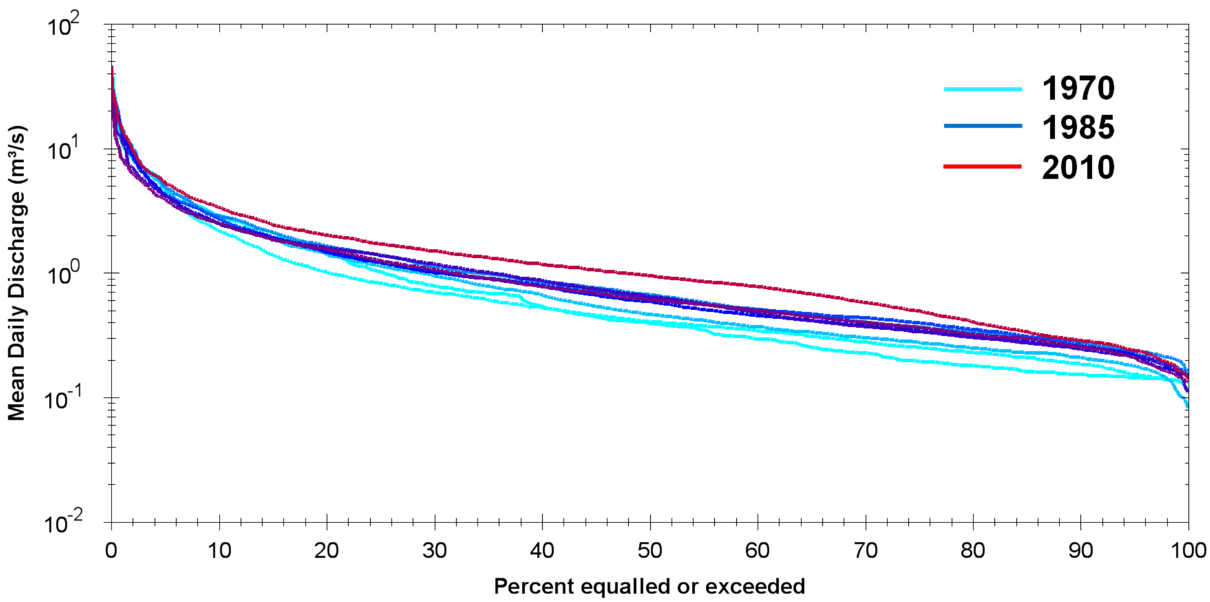


Figure D.6: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC009 - East Humber River near Pine Grove

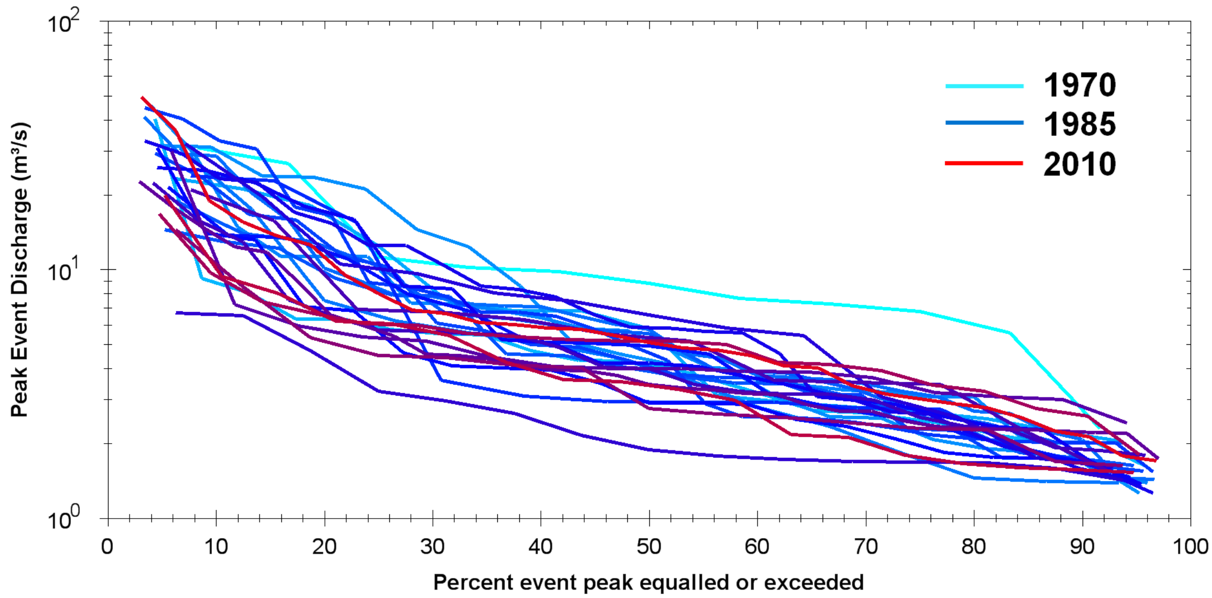


Figure D.7: Peak Exceedance Curve (by Year)

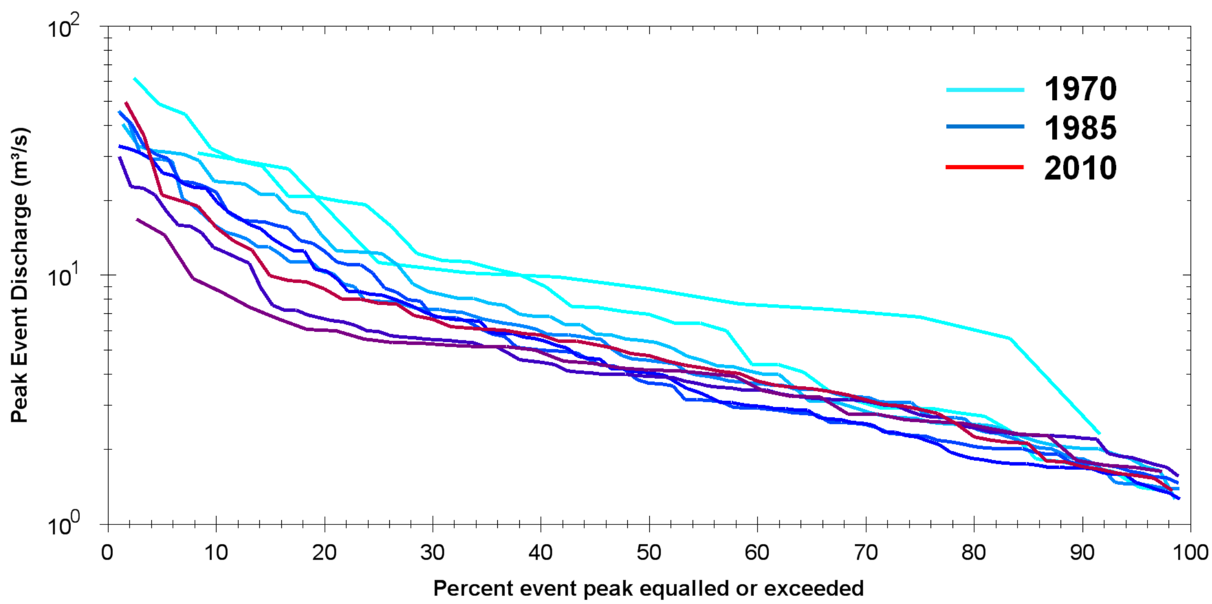


Figure D.8: Peak Exceedance Curve (5 Year Moving Average)

02HB004 - East Oakville Creek near Omagh

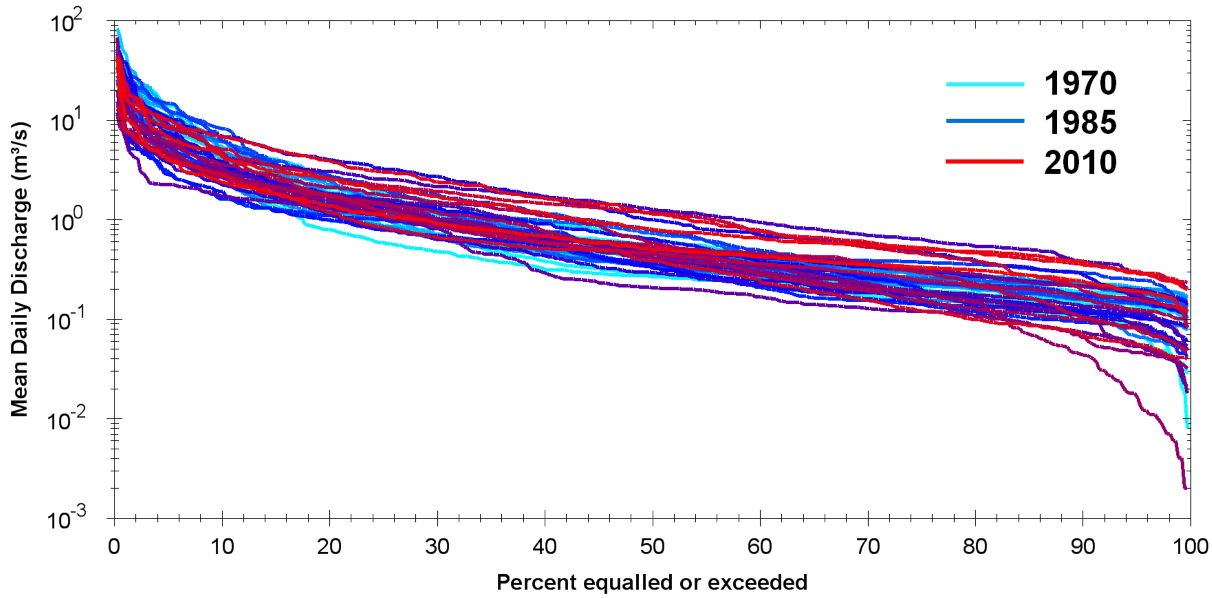


Figure D.9: Mean Daily Flow Duration Curve (by Year)

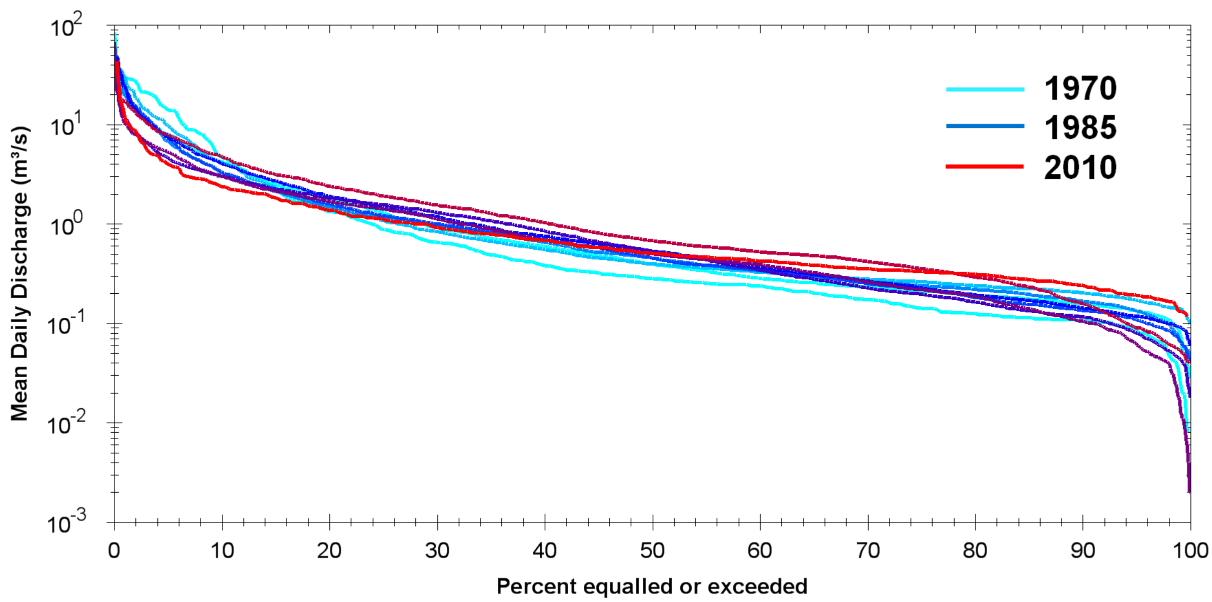


Figure D.10: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HB004 - East Oakville Creek near Omagh

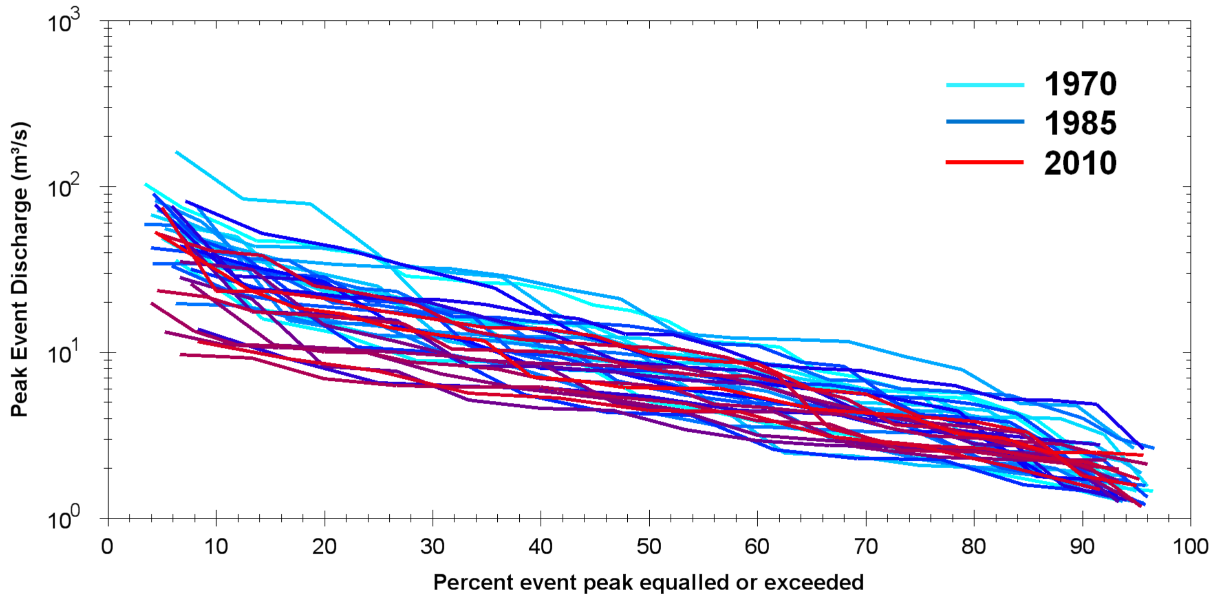


Figure D.11: Peak Exceedance Curve (by Year)

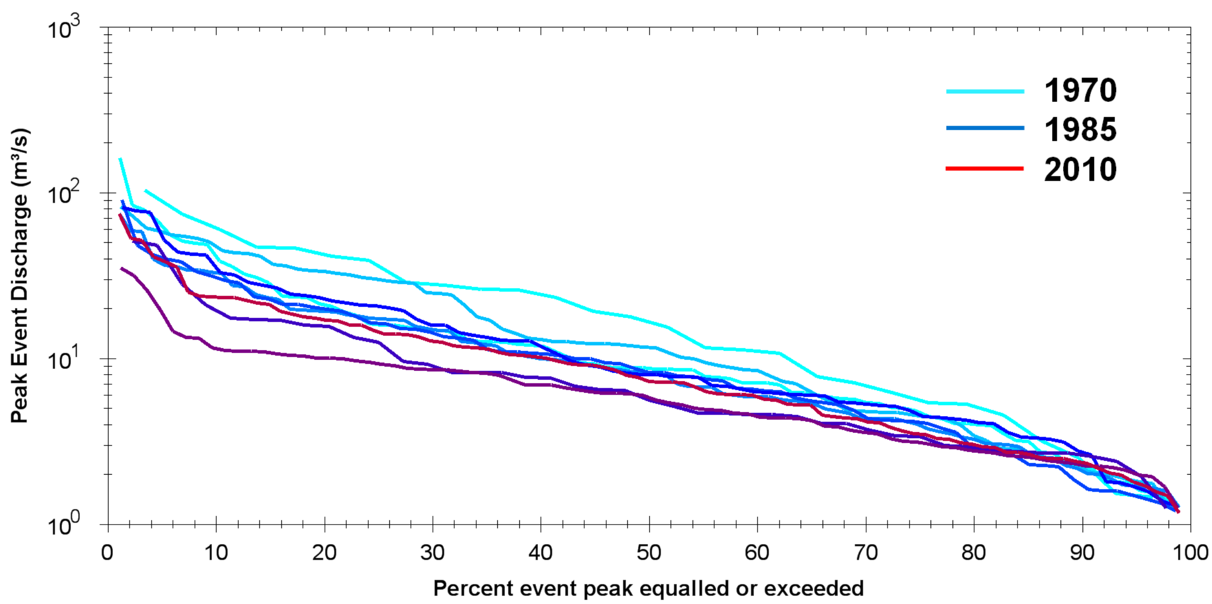


Figure D.12: Peak Exceedance Curve (5 Year Moving Average)

02HB005 - Oakville Creek at Milton

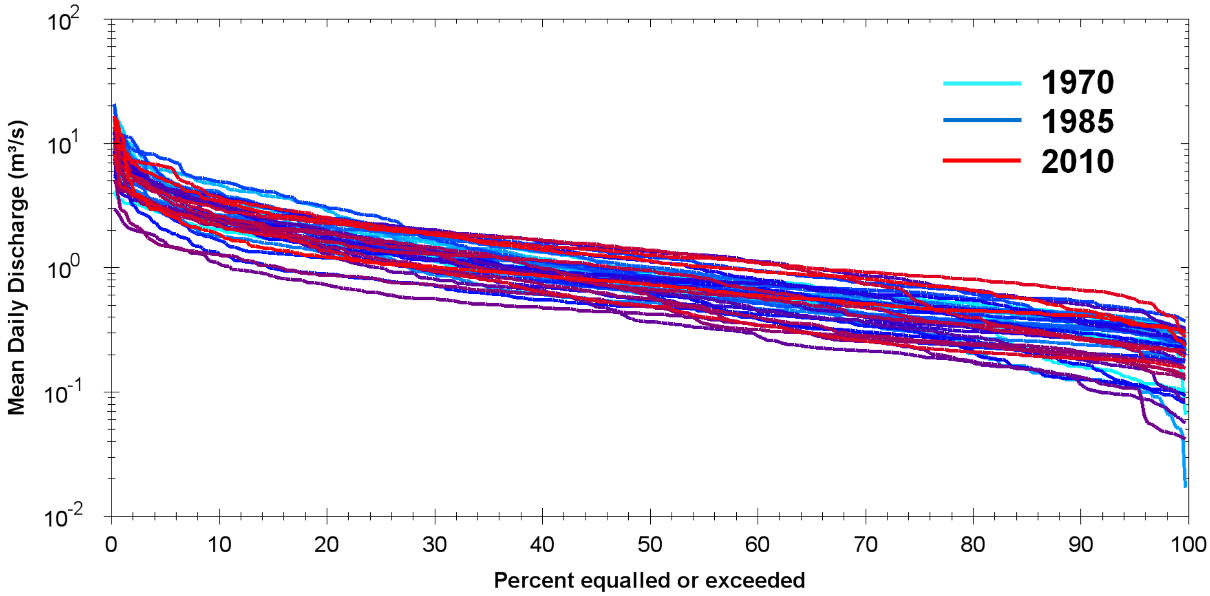


Figure D.13: Mean Daily Flow Duration Curve (by Year)

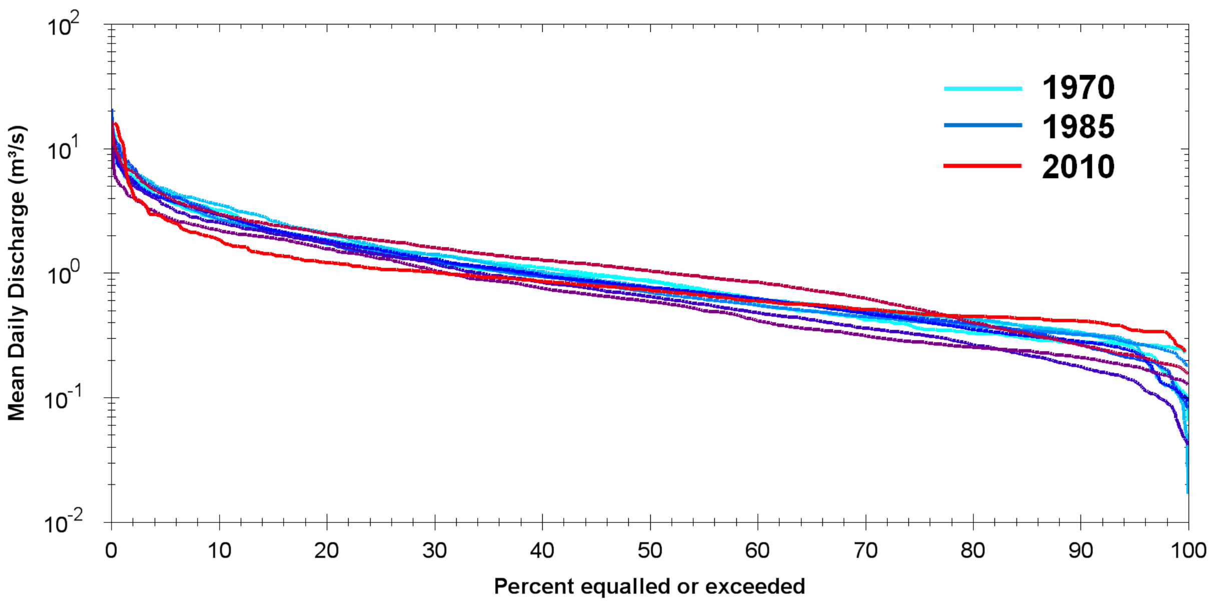


Figure D.14: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HB005 - Oakville Creek at Milton

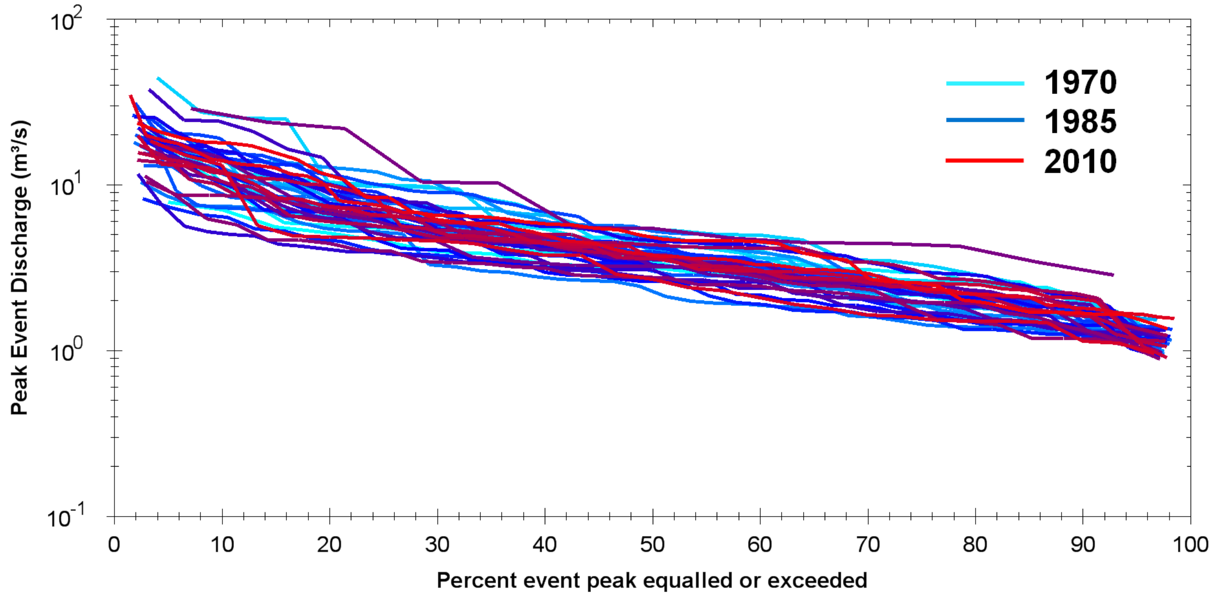


Figure D.15: Peak Exceedance Curve (by Year)

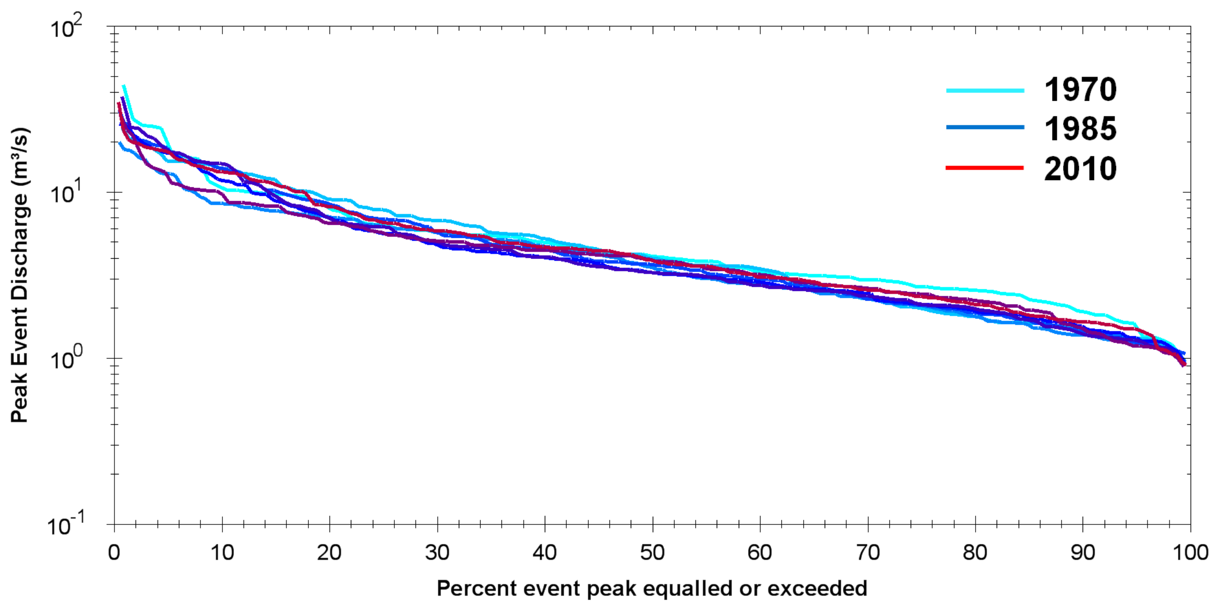


Figure D.16: Peak Exceedance Curve (5 Year Moving Average)

02HB013 - Credit River near Orangeville

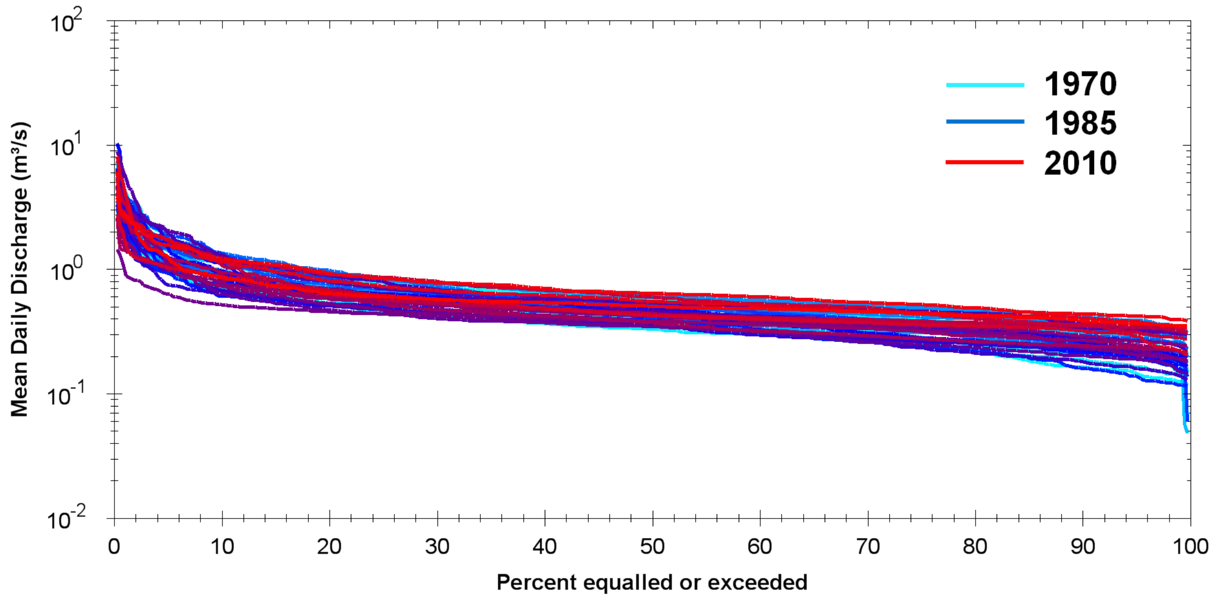


Figure D.17: Mean Daily Flow Duration Curve (by Year)

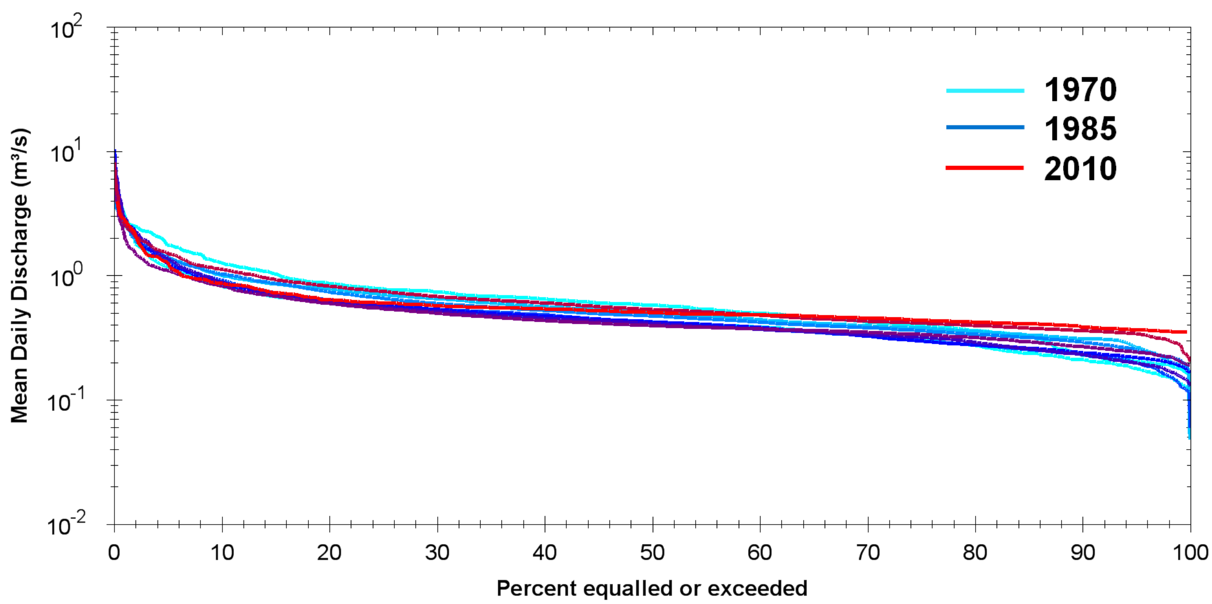


Figure D.18: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HB013 - Credit River near Orangeville

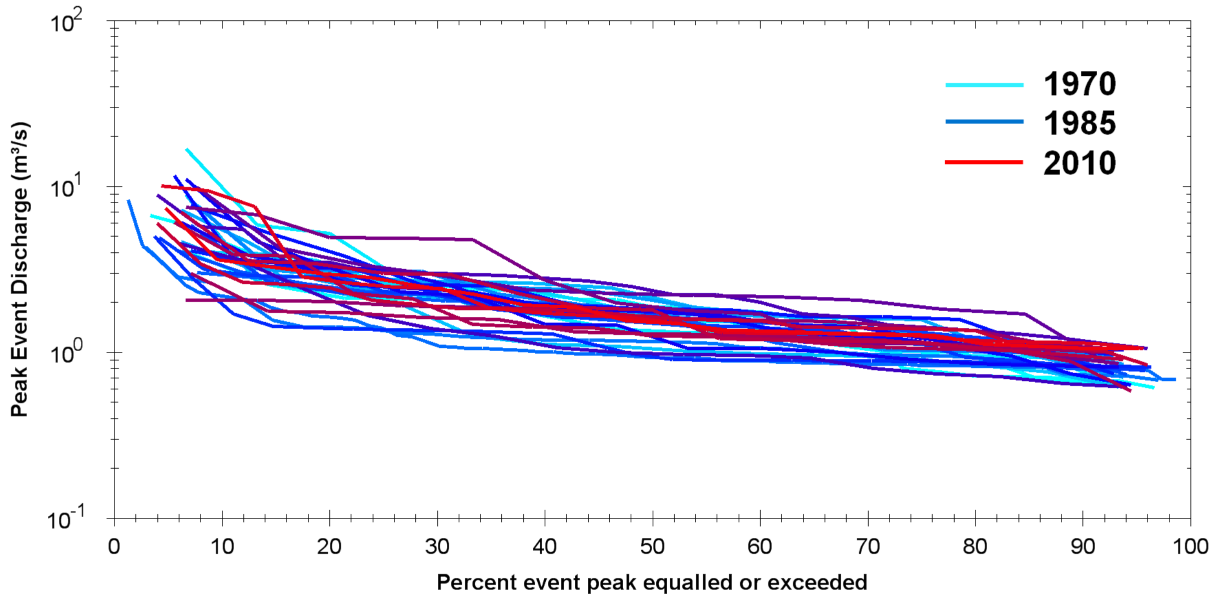


Figure D.19: Peak Exceedance Curve (by Year)

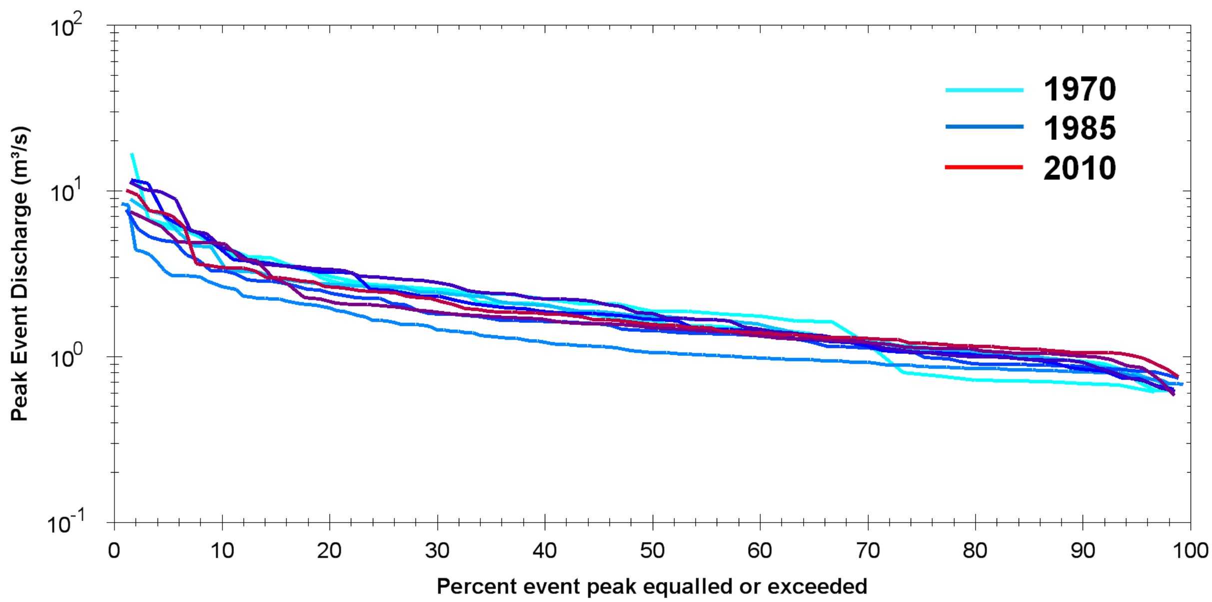


Figure D.20: Peak Exceedance Curve (5 Year Moving Average)

02GA024 - Laurel Creek at Waterloo

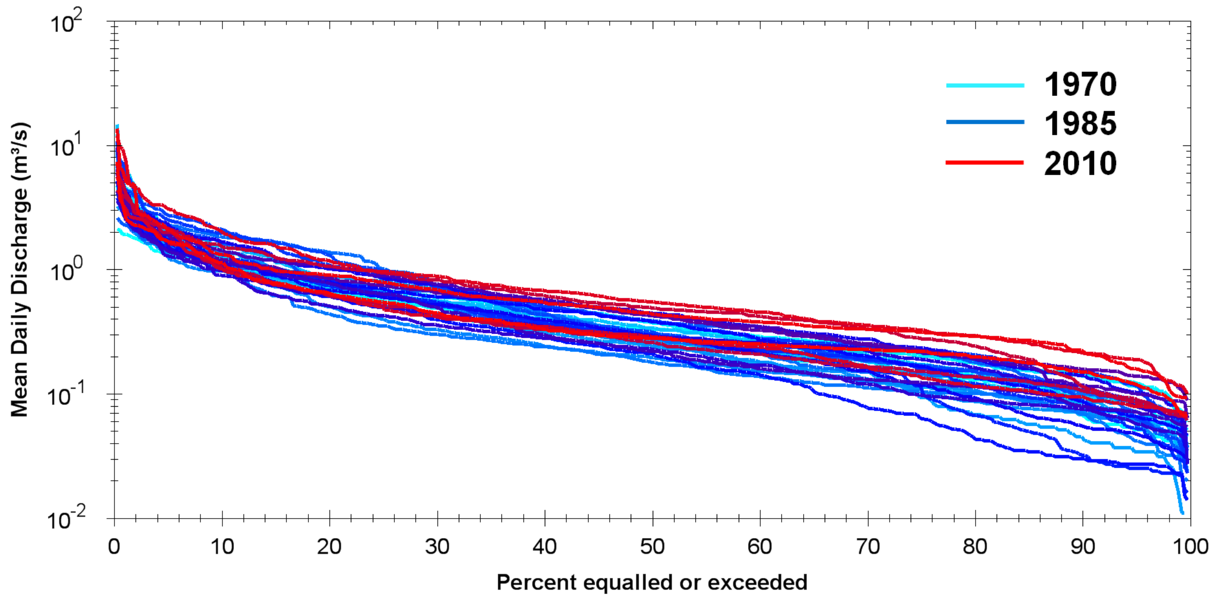


Figure D.21: Mean Daily Flow Duration Curve (by Year)

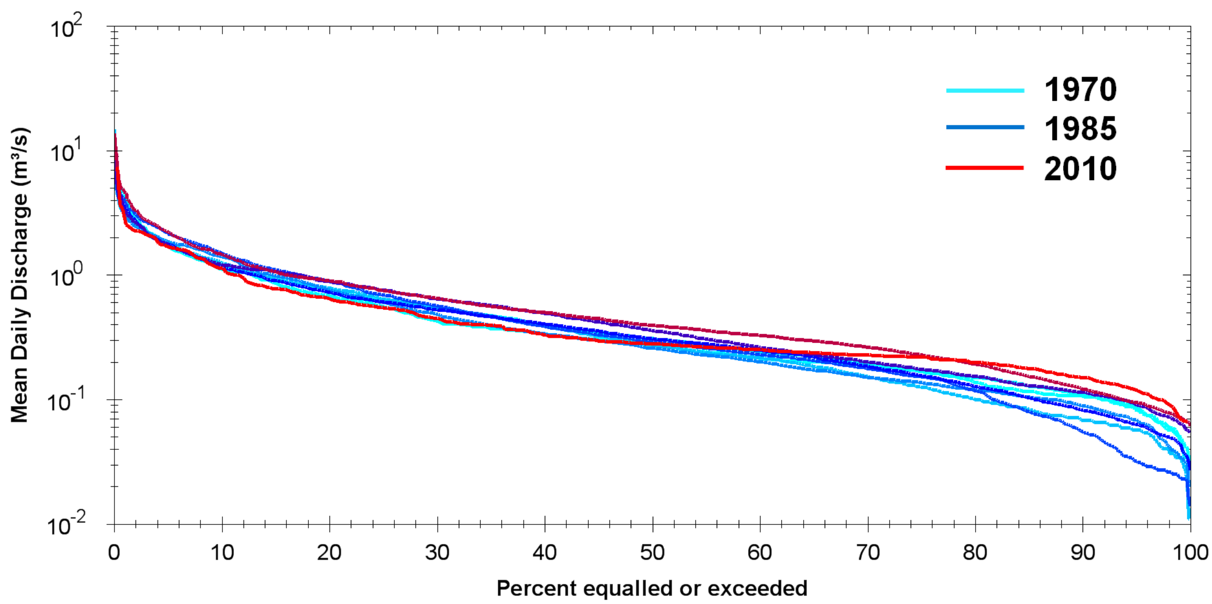


Figure D.22: Mean Daily Flow Duration Curve (5 Year Moving Average)

02GA024 - Laurel Creek at Waterloo

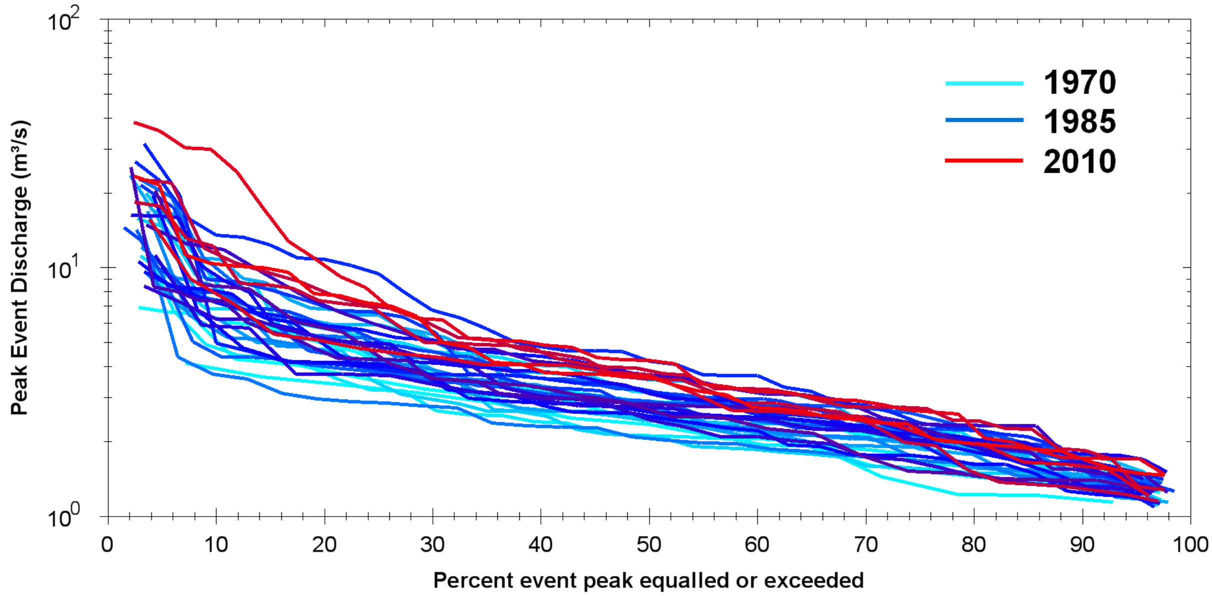


Figure D.23: Peak Exceedance Curve (by Year)

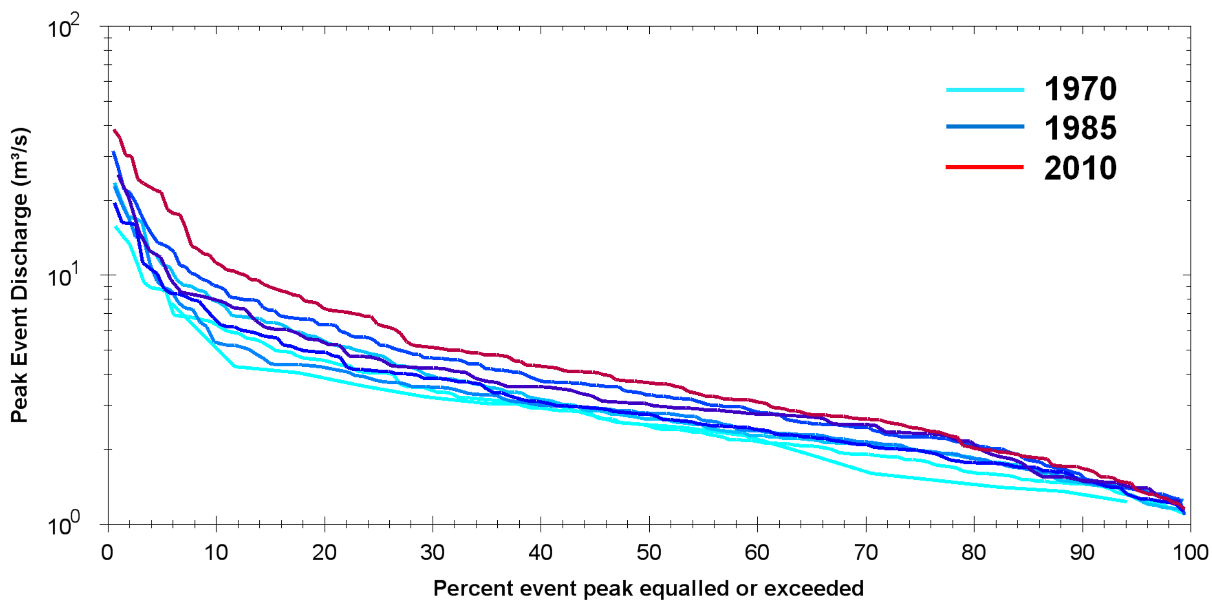


Figure D.24: Peak Exceedance Curve (5 Year Moving Average)

02HA014 - Red Hill Creek at Hamilton

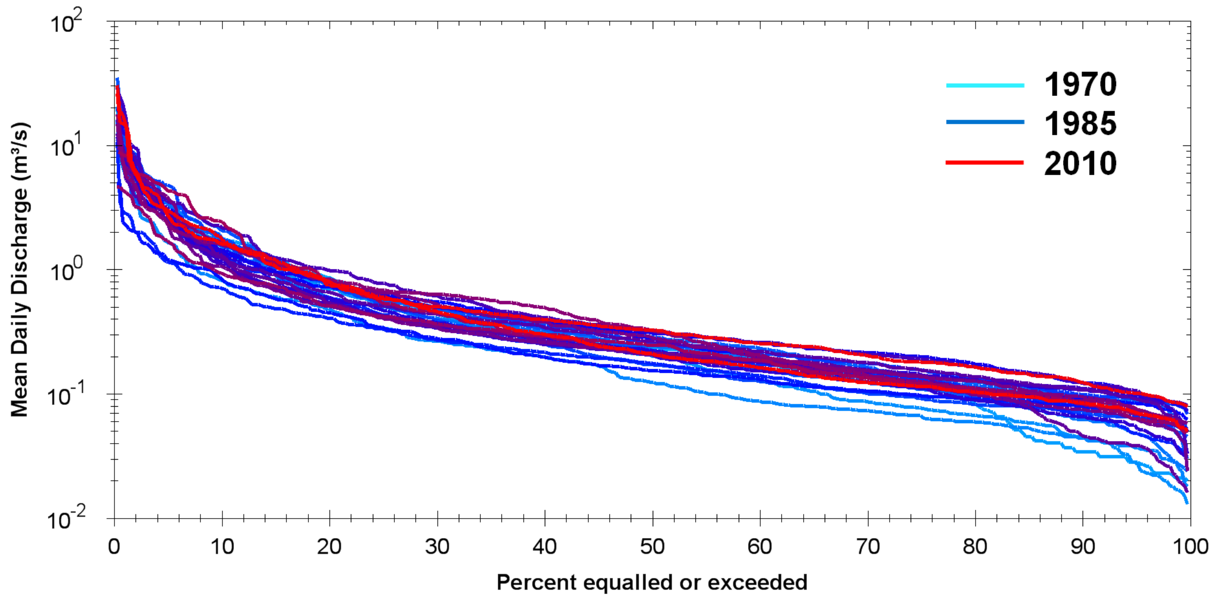


Figure D.25: Mean Daily Flow Duration Curve (by Year)

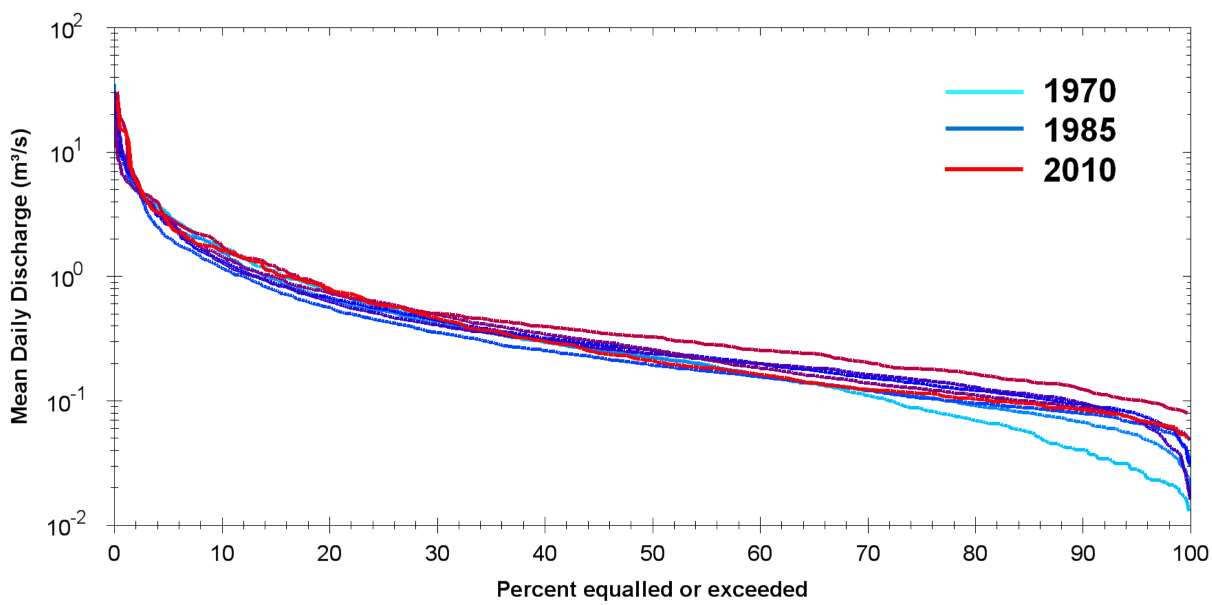


Figure D.26: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HA014 - Red Hill Creek at Hamilton

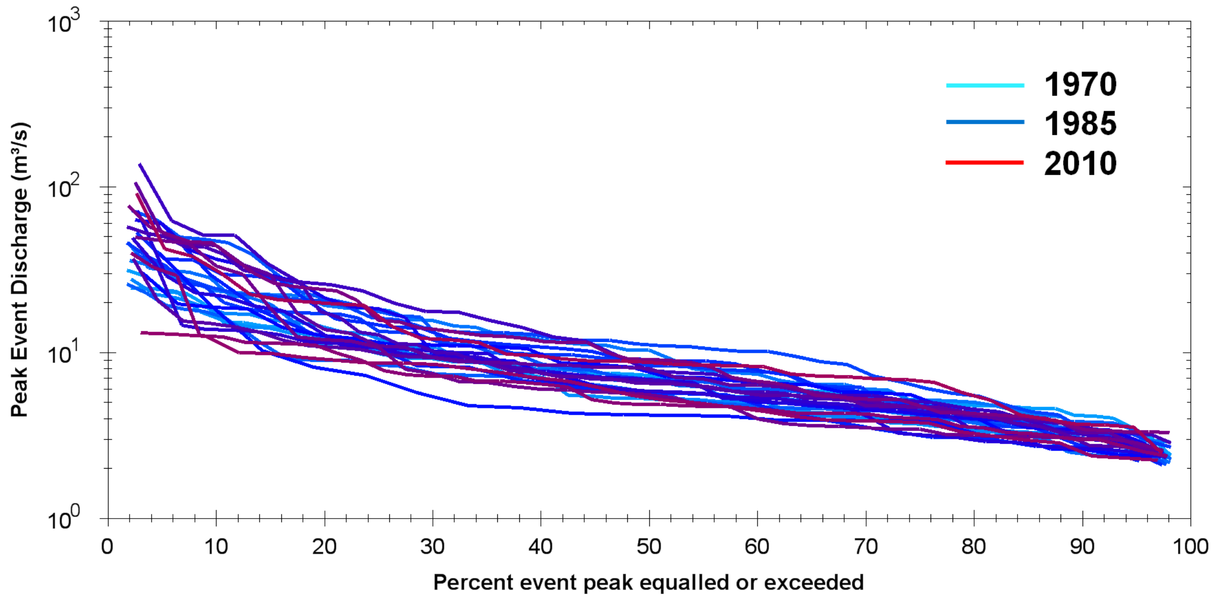


Figure D.27: Peak Exceedance Curve (by Year)

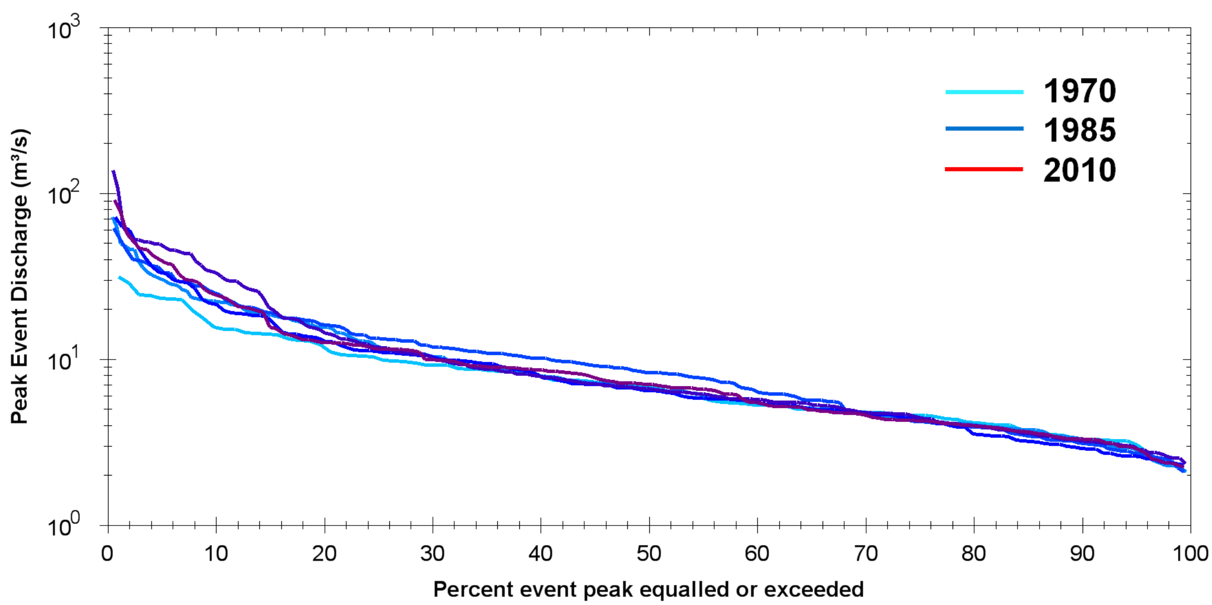


Figure D.28: Peak Exceedance Curve (5 Year Moving Average)

02HC027 - Black Creek near Weston

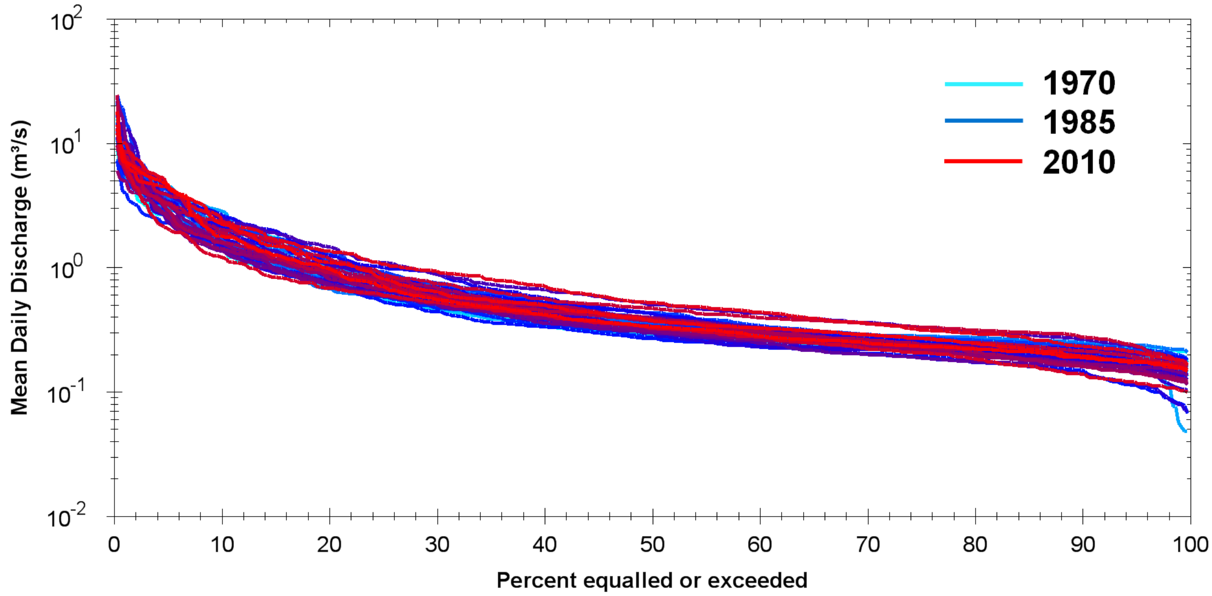


Figure D.29: Mean Daily Flow Duration Curve (by Year)

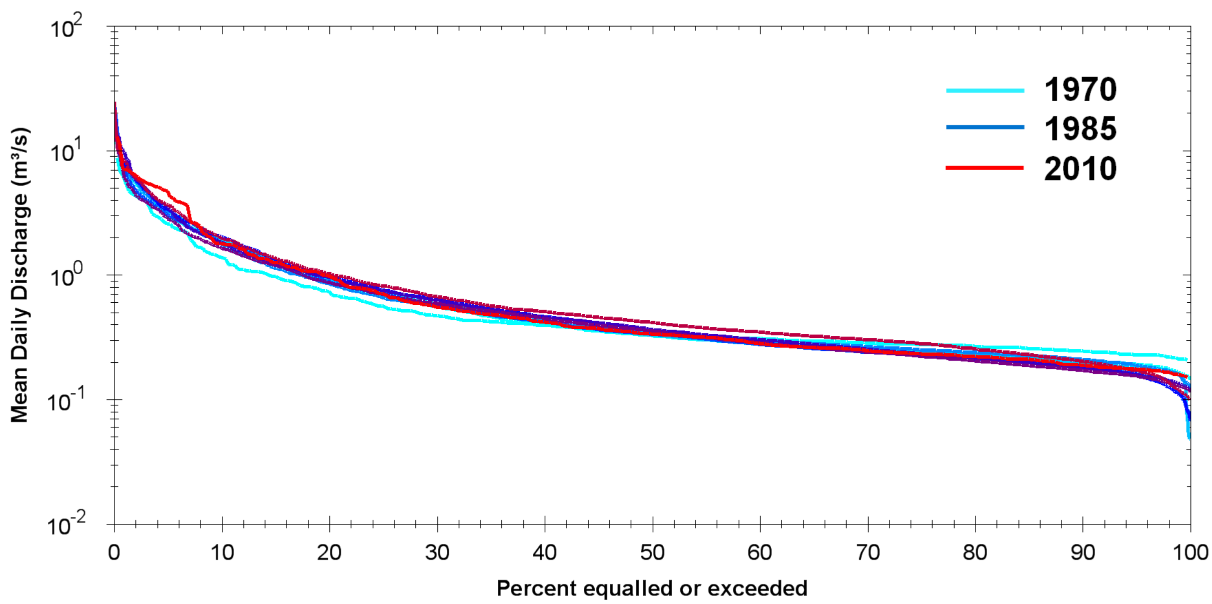


Figure D.30: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC027 - Black Creek near Weston

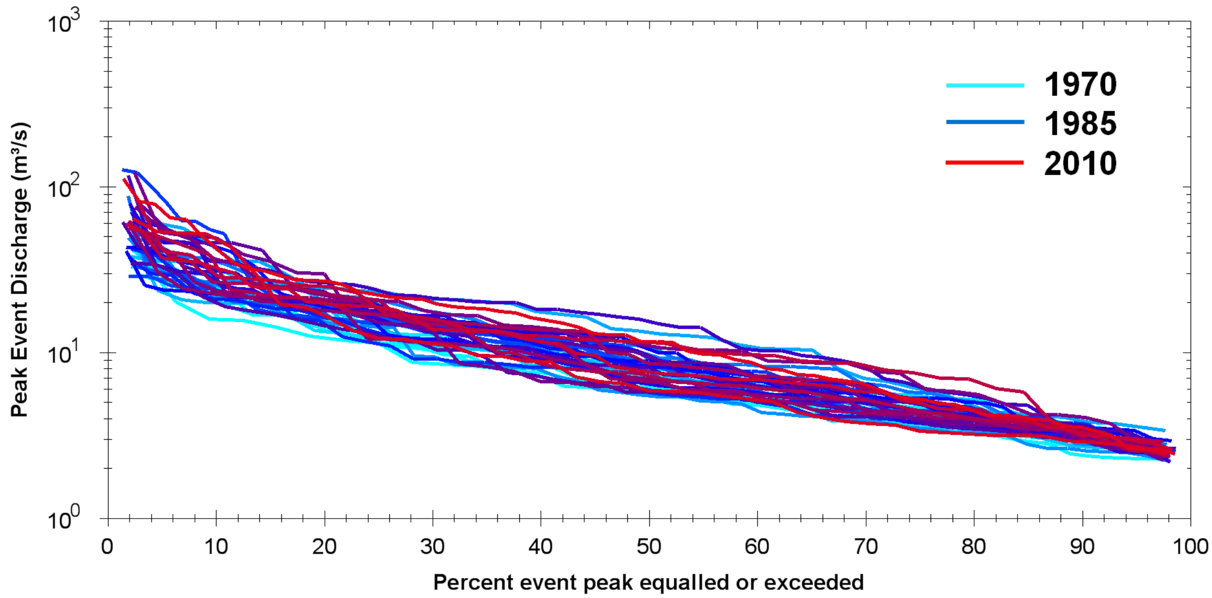


Figure D.31: Peak Exceedance Curve (by Year)

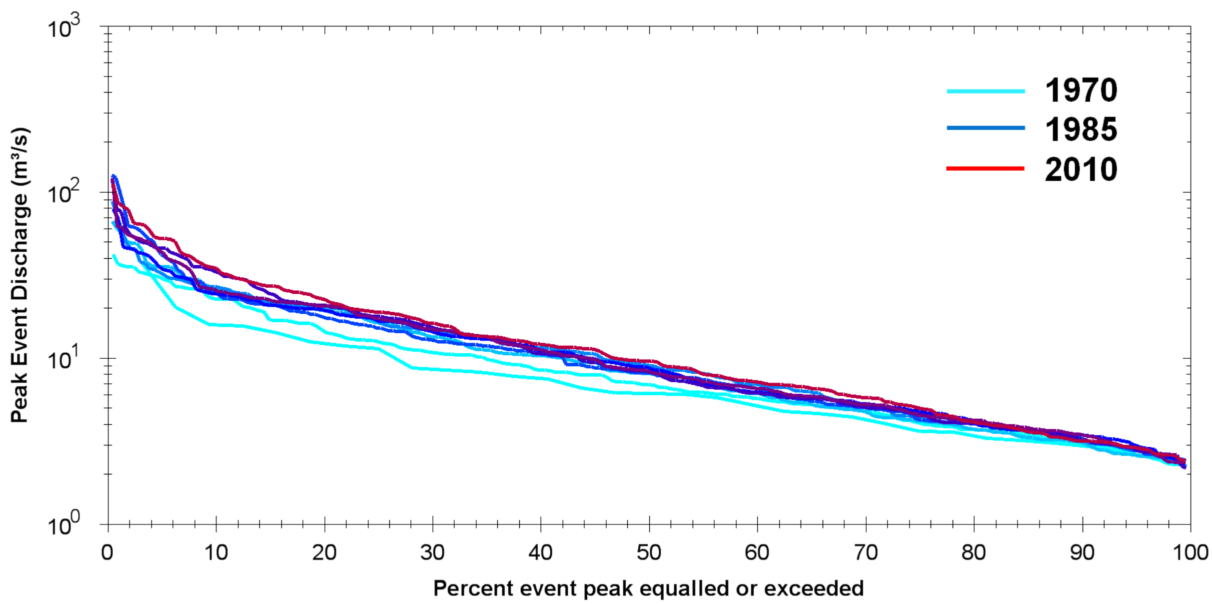


Figure D.32: Peak Exceedance Curve (5 Year Moving Average)

02HC017 - Etobicoke Creek at Brampton

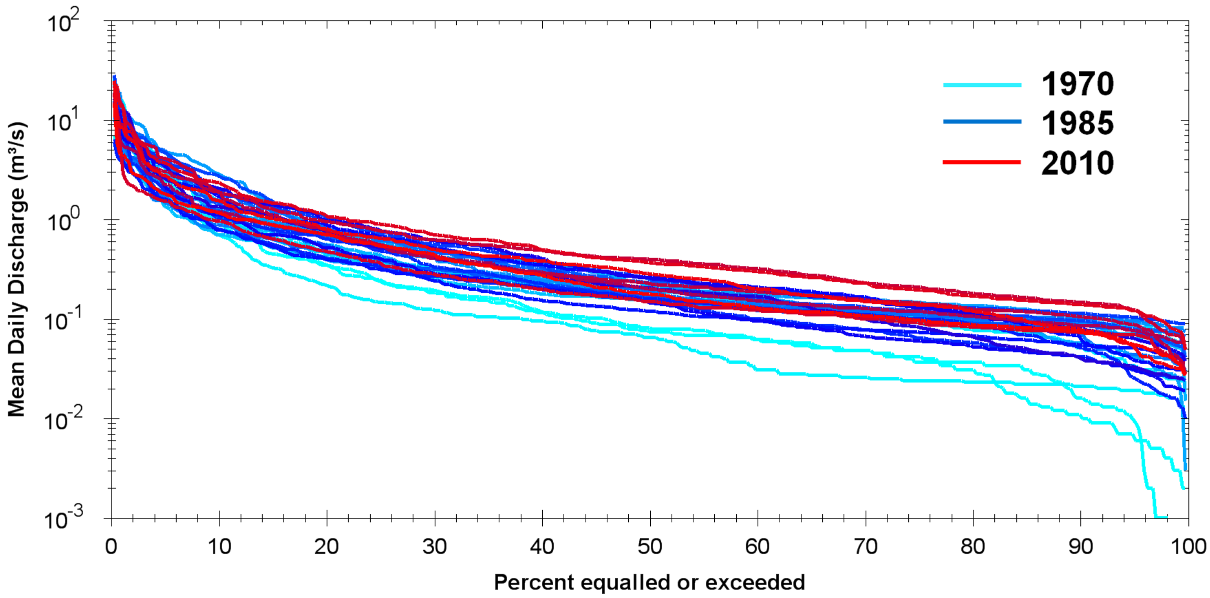


Figure D.33: Mean Daily Flow Duration Curve (by Year)

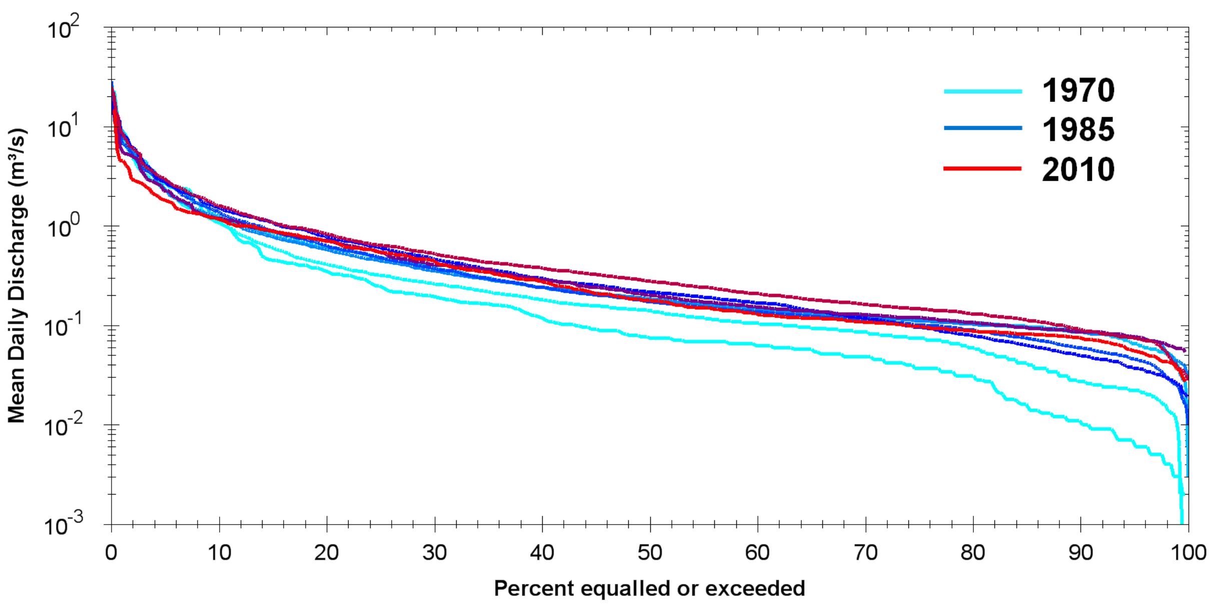


Figure D.34: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC017 - Etobicoke Creek at Brampton

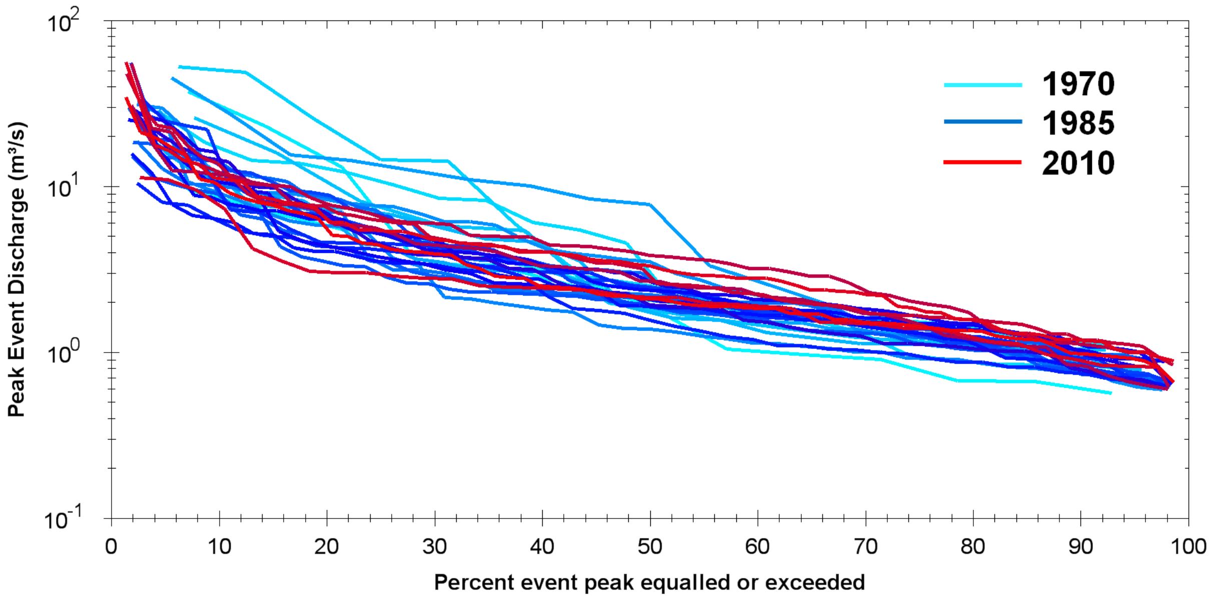


Figure D.35: Peak Exceedance Curve (by Year)

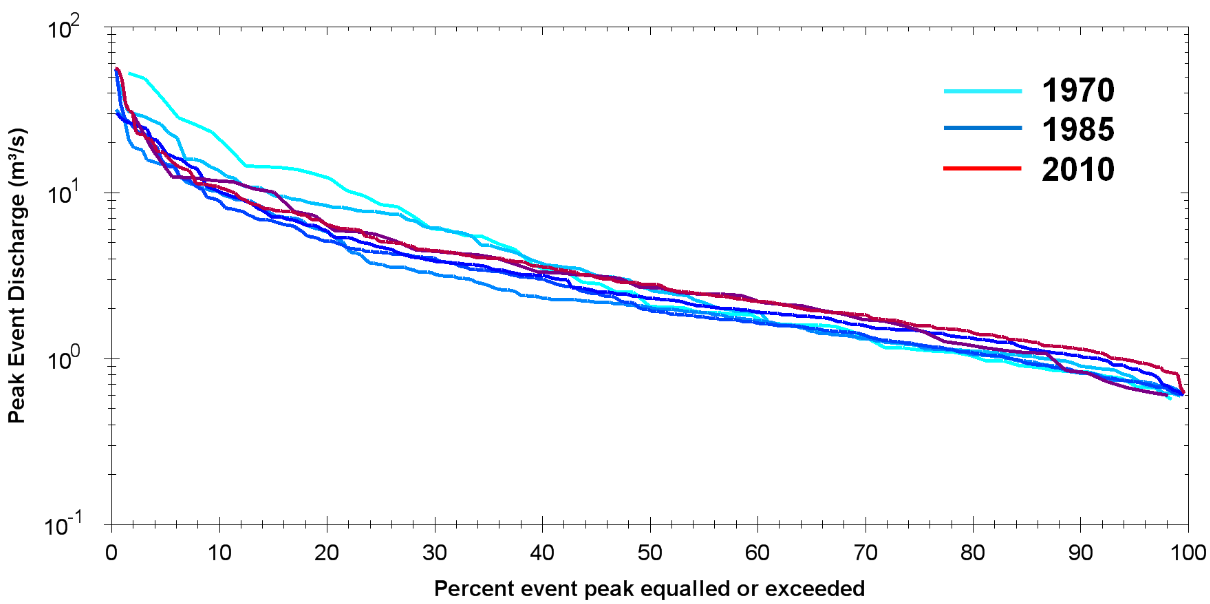


Figure D.36: Peak Exceedance Curve (5 Year Moving Average)

02HC030 - Etobicoke Creek below QEW

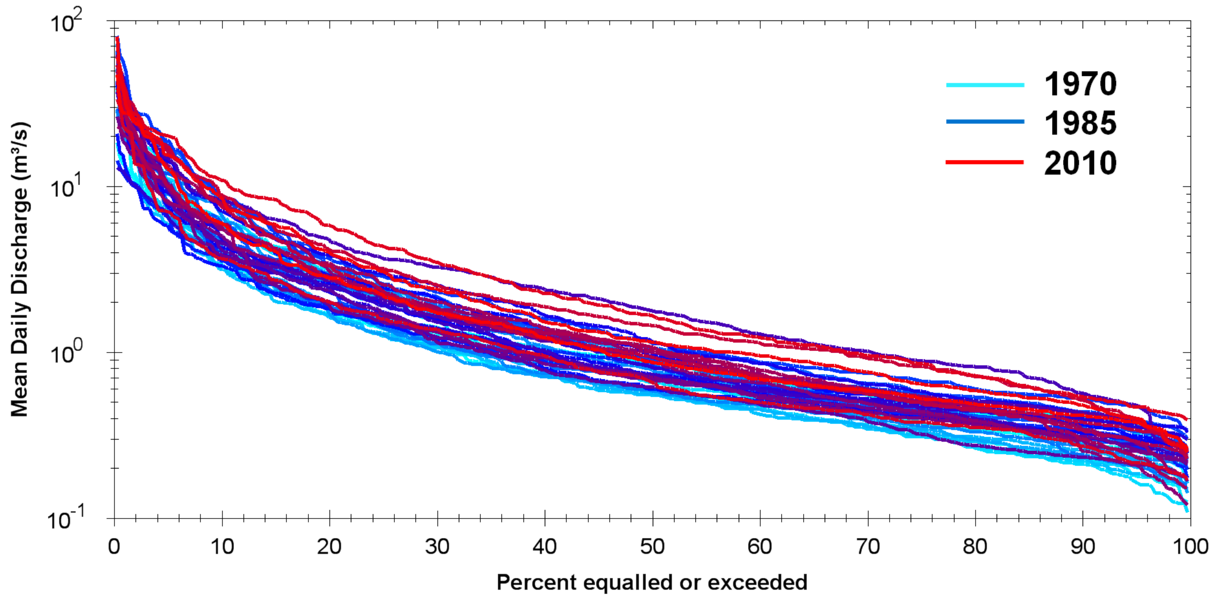


Figure D.37: Mean Daily Flow Duration Curve (by Year)

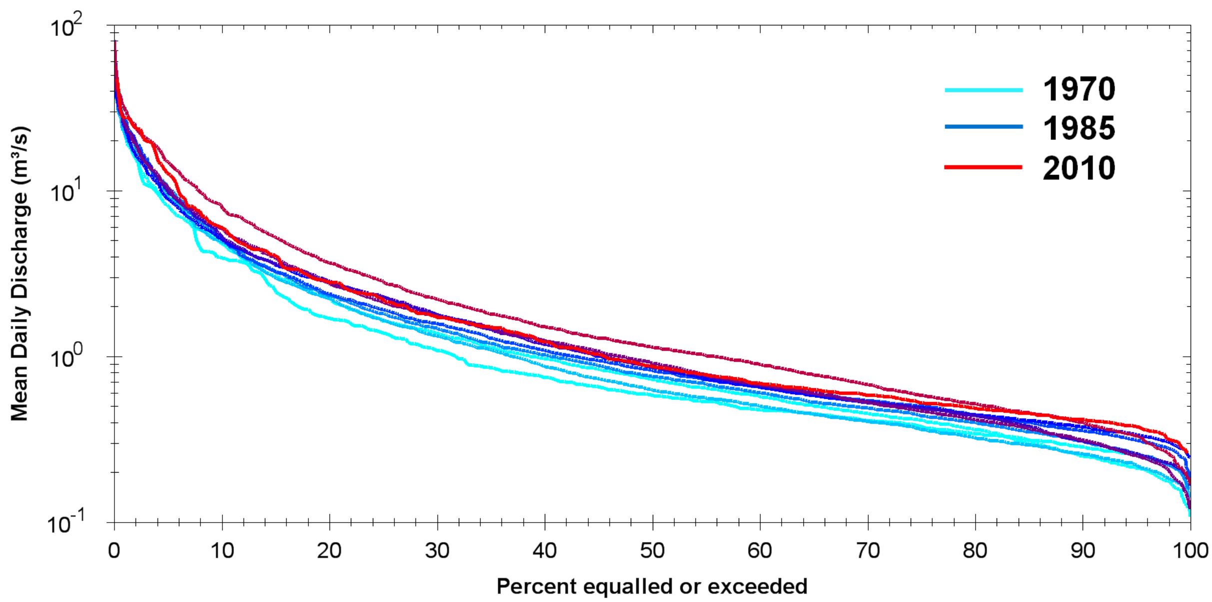


Figure D.38: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC030 - Etobicoke Creek below QEW

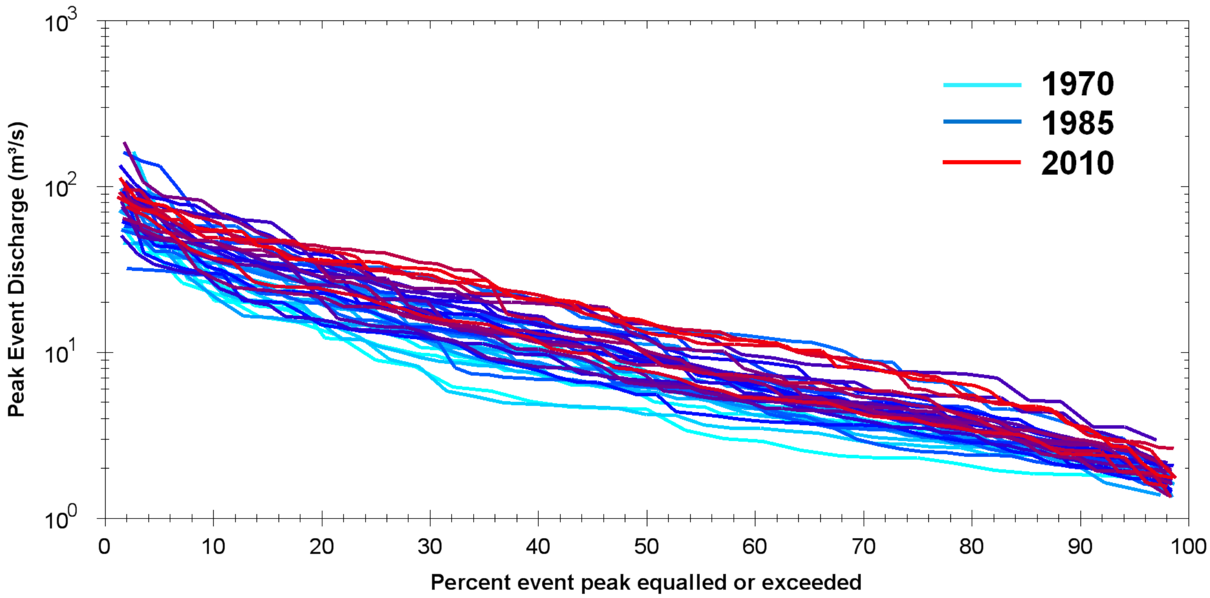


Figure D.39: Peak Exceedance Curve (by Year)

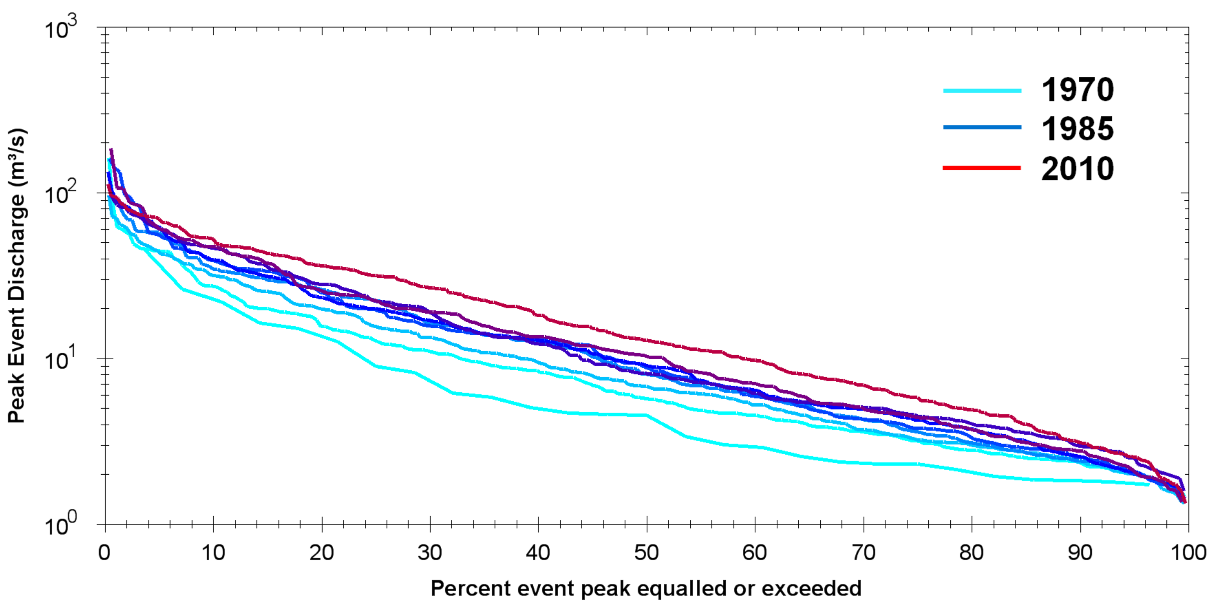


Figure D.40: Peak Exceedance Curve (5 Year Moving Average)

02HC033 - Mimico Creek at Islington

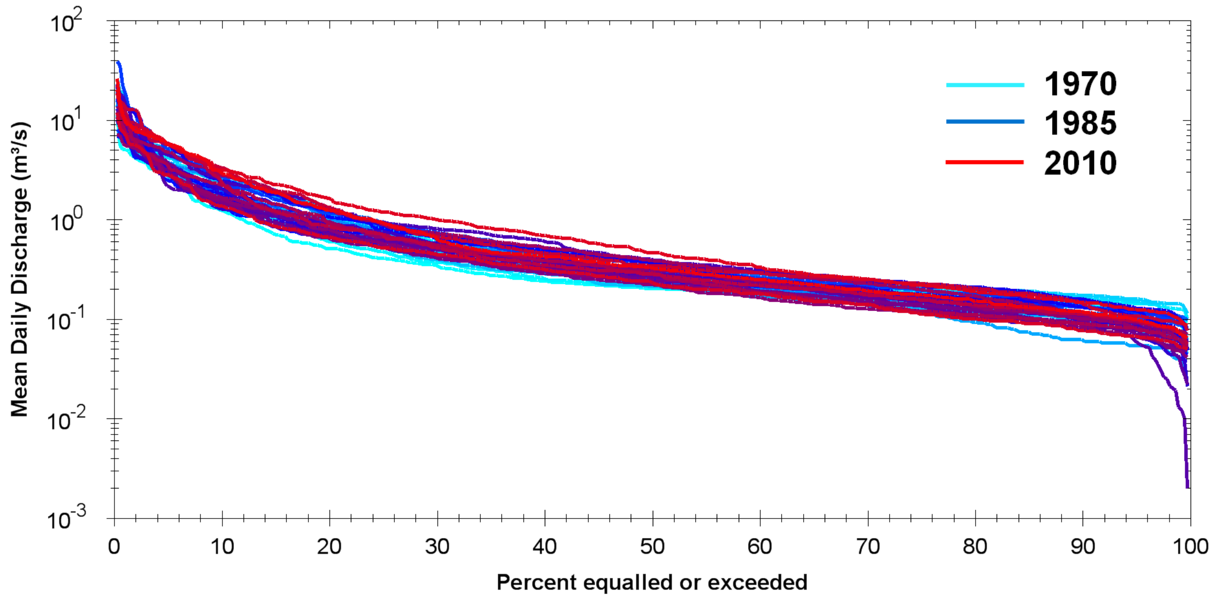


Figure D.41: Mean Daily Flow Duration Curve (by Year)

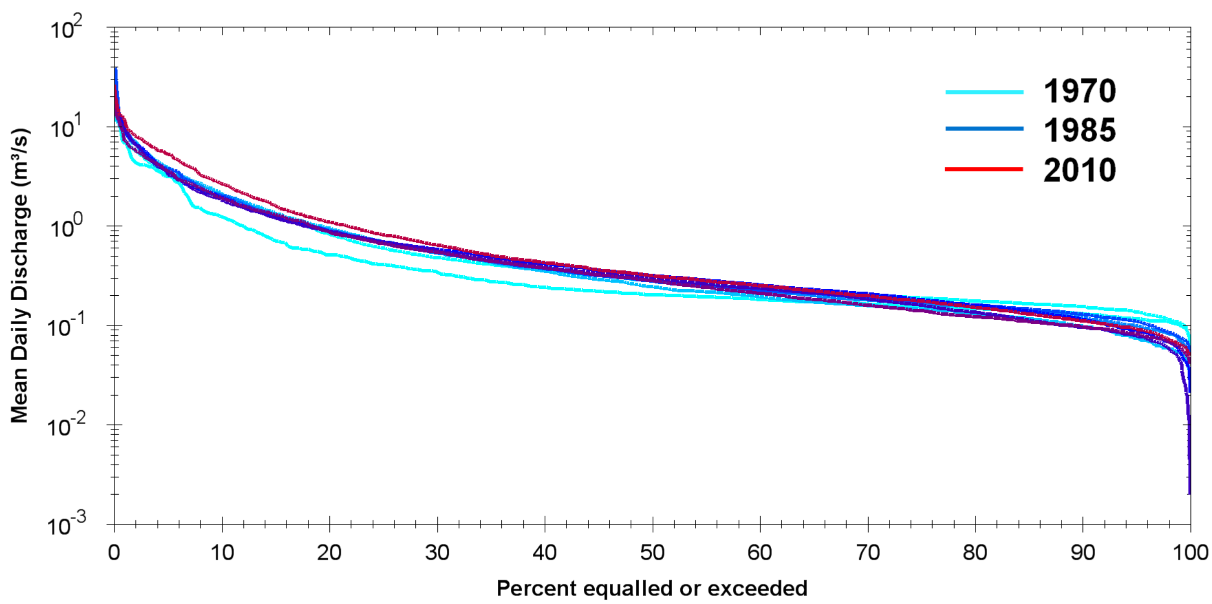


Figure D.42: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC033 - Mimico Creek at Islington

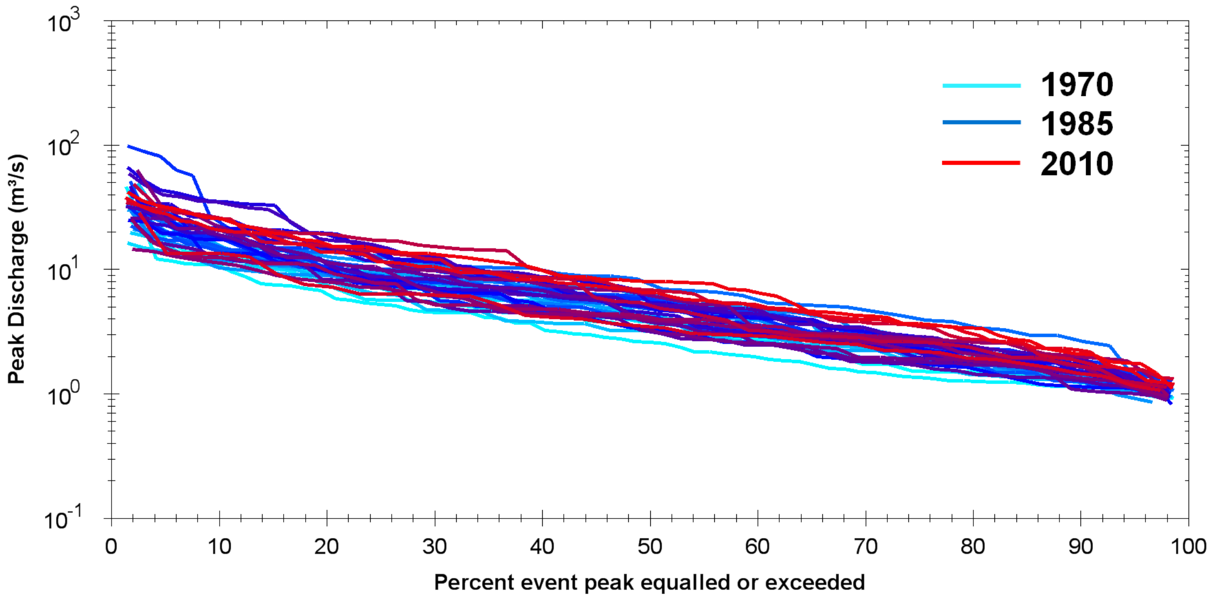


Figure D.43: Peak Exceedance Curve (by Year)

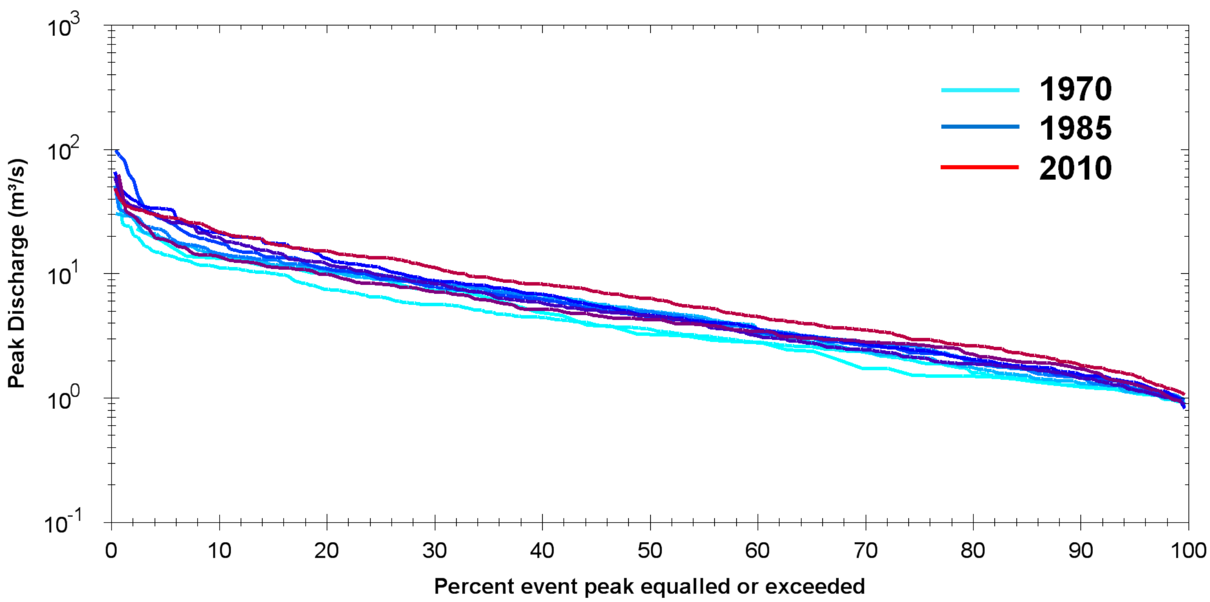


Figure D.44: Peak Exceedance Curve (5 Year Moving Average)

02HC005 - Don River at York Mills

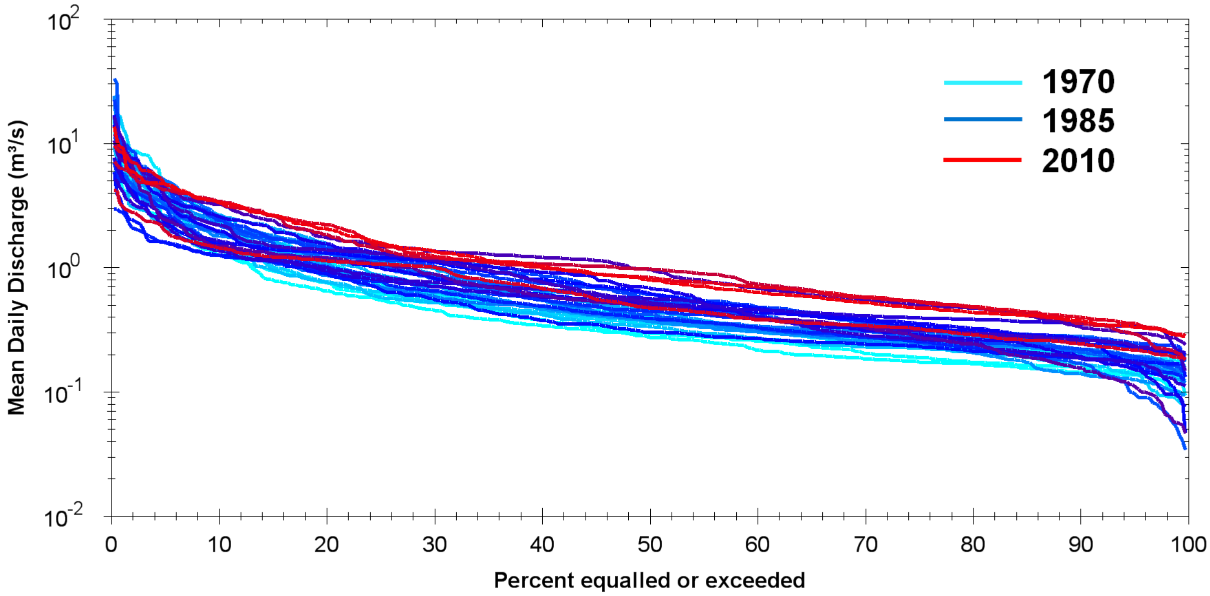


Figure D.45: Mean Daily Flow Duration Curve (by Year)

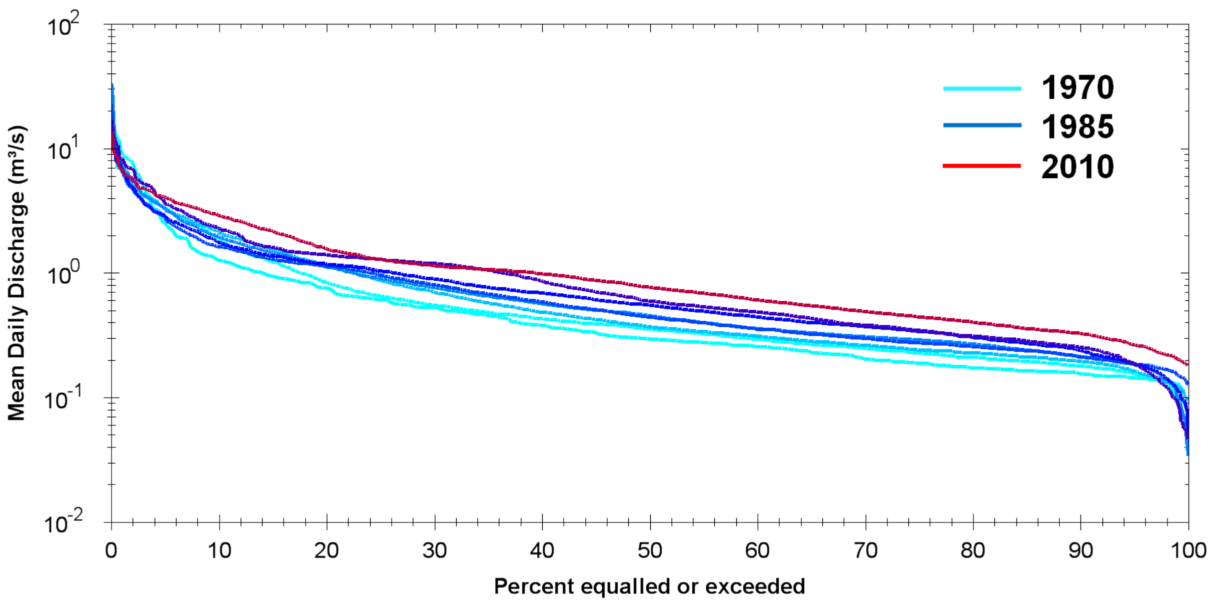


Figure D.46: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC005 - Don River at York Mills

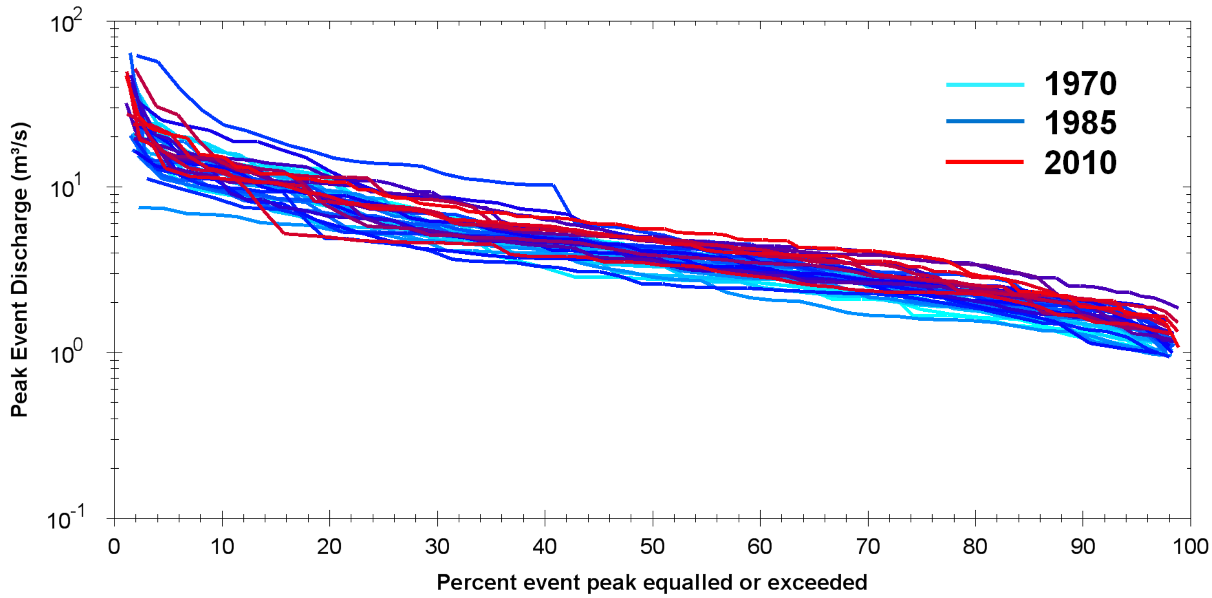


Figure D.47: Peak Exceedance Curve (by Year)

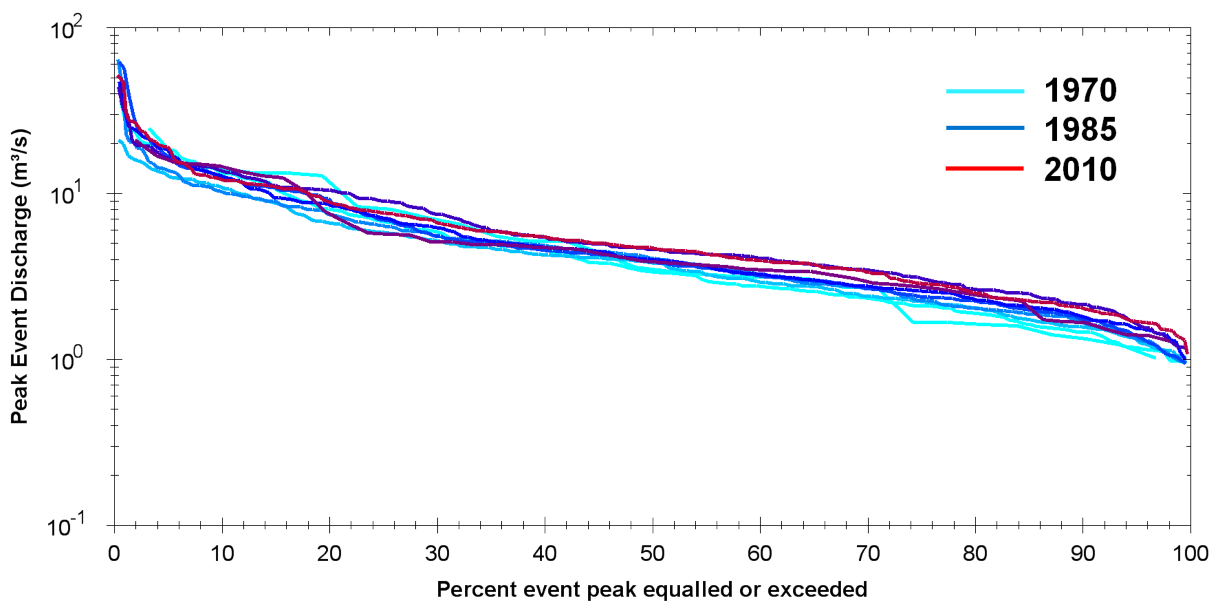


Figure D.48: Peak Exceedance Curve (5 Year Moving Average)

02HC029 - Little Don River at Don Mills

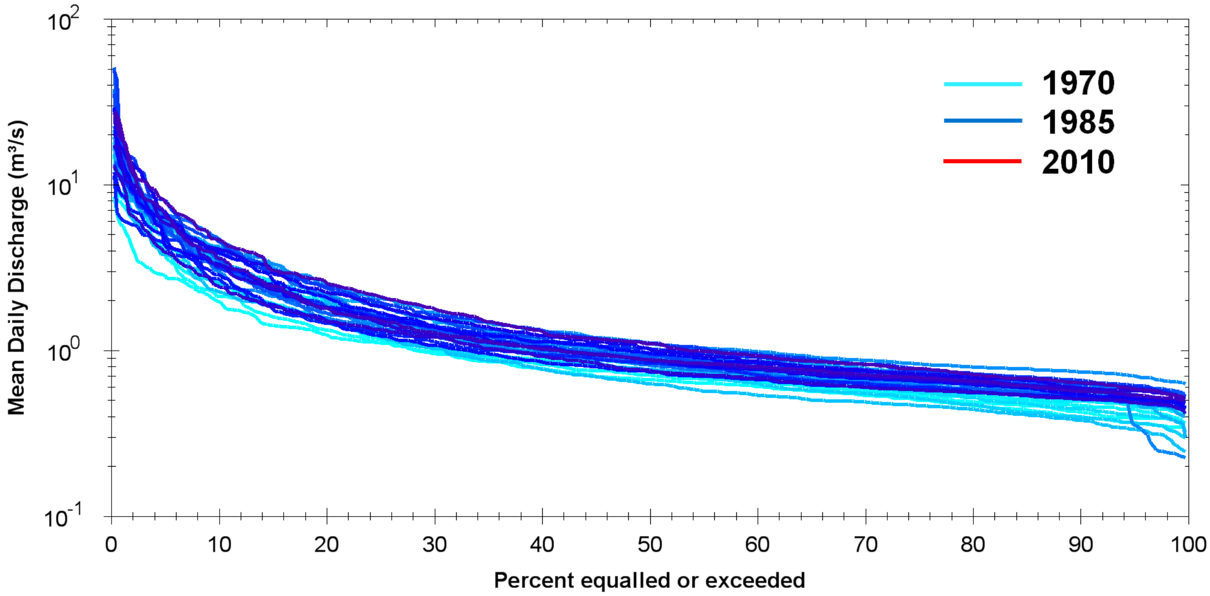


Figure D.49: Mean Daily Flow Duration Curve (by Year)

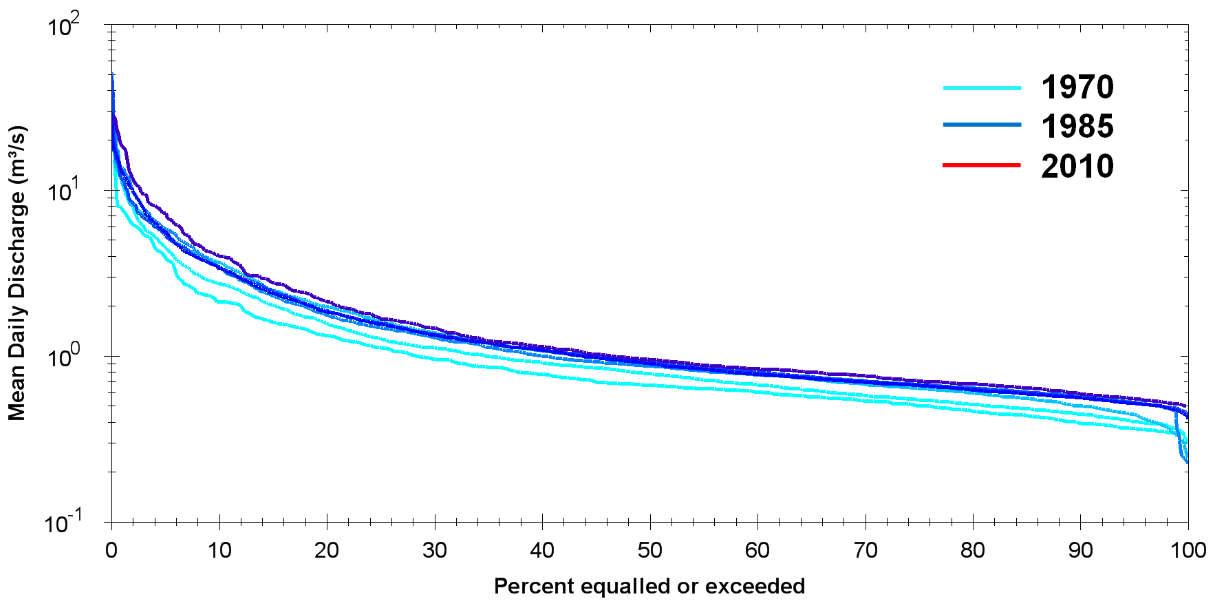


Figure D.50: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC029 - Little Don River at Don Mills

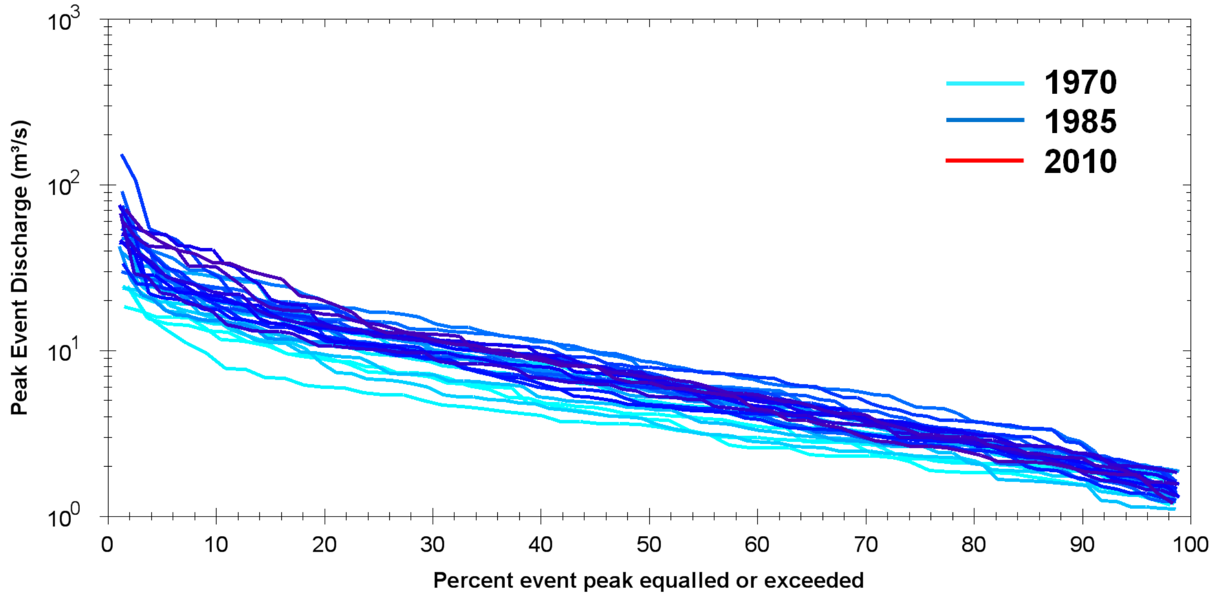


Figure D.51: Peak Exceedance Curve (by Year)

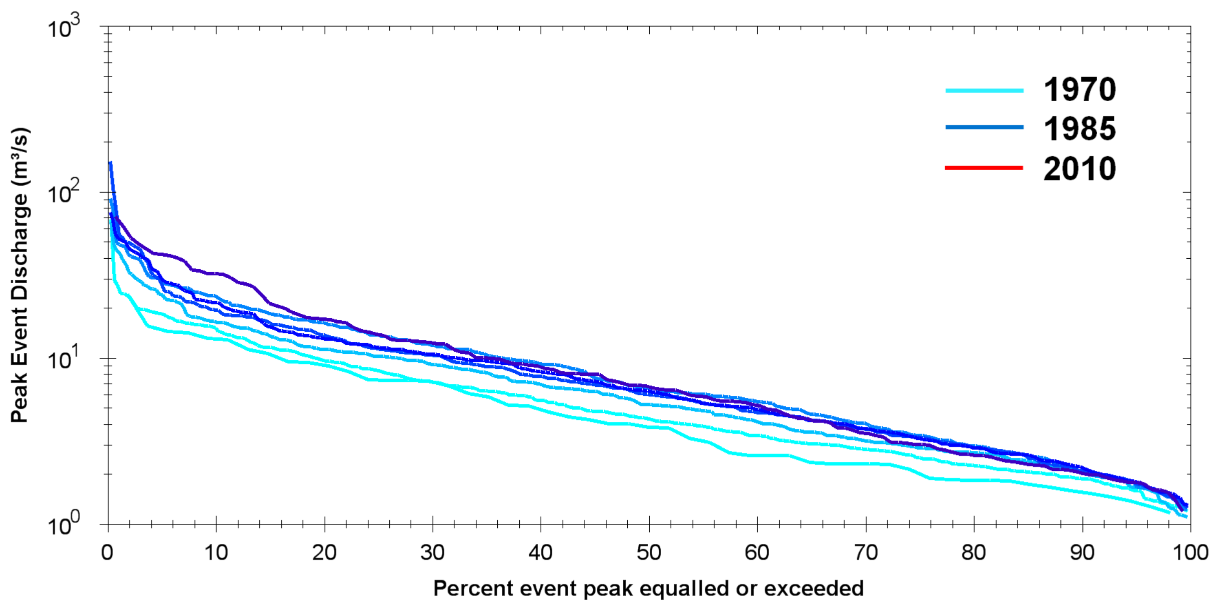


Figure D.52: Peak Exceedance Curve (5 Year Moving Average)

02HC024 - Don River at Todmorden

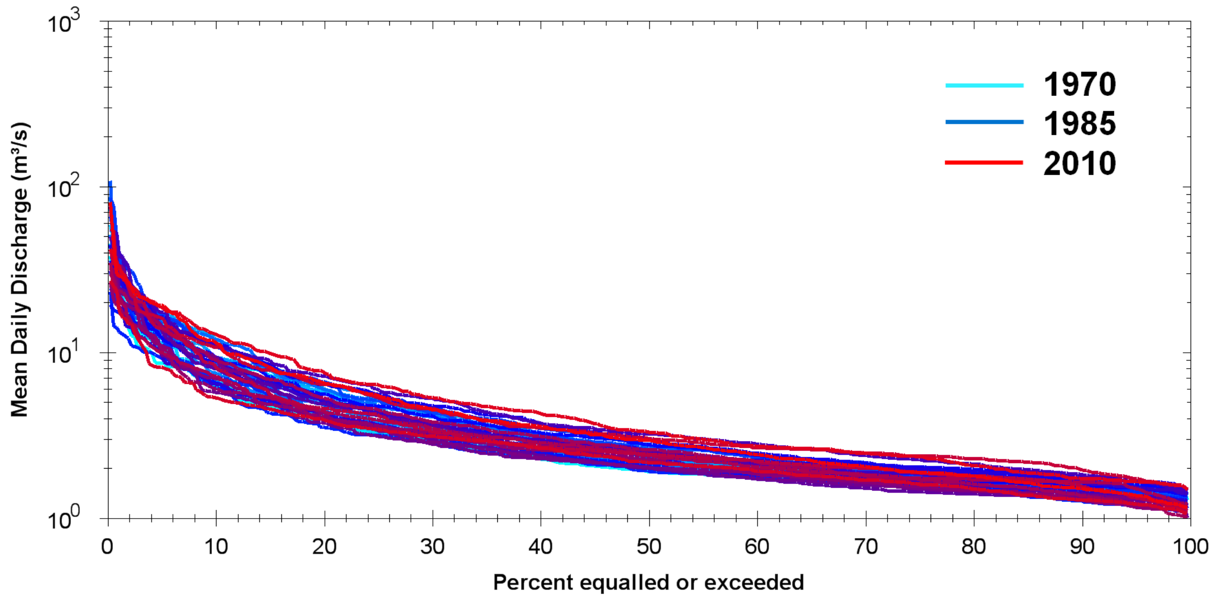


Figure D.53: Mean Daily Flow Duration Curve (by Year)

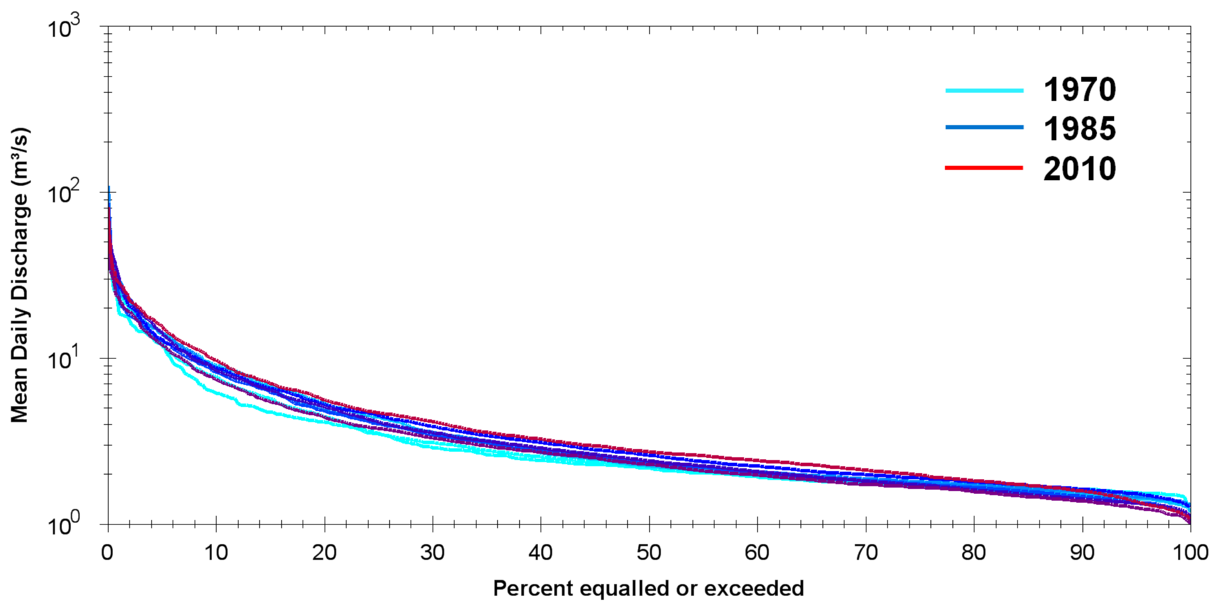


Figure D.54: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC024 - Don River at Todmorden

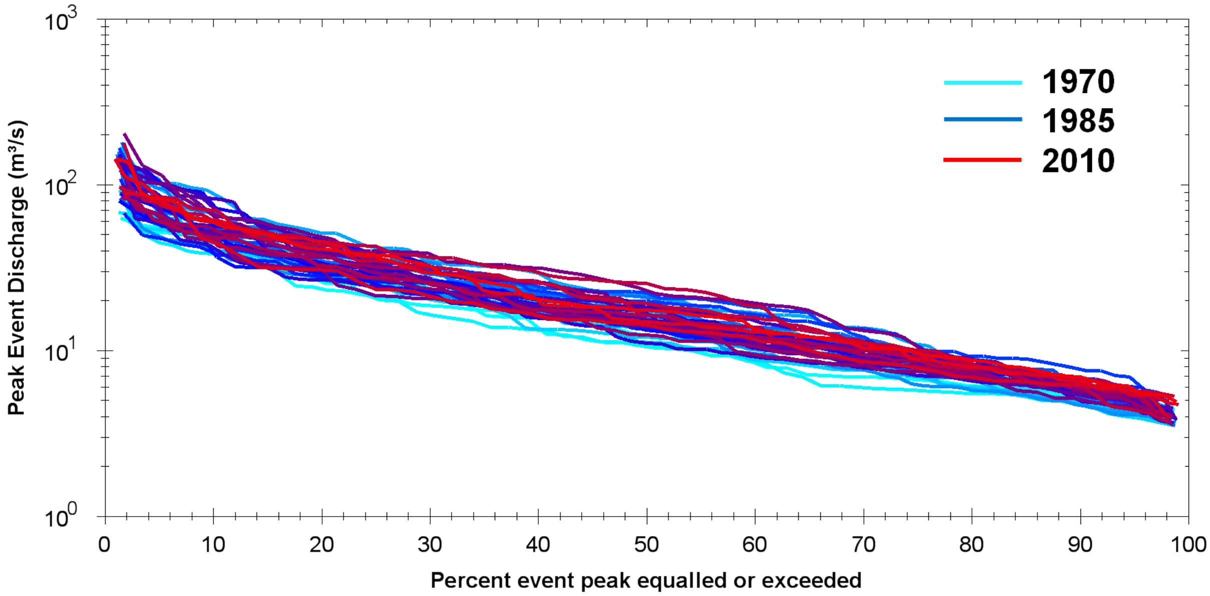


Figure D.55: Peak Exceedance Curve (by Year)

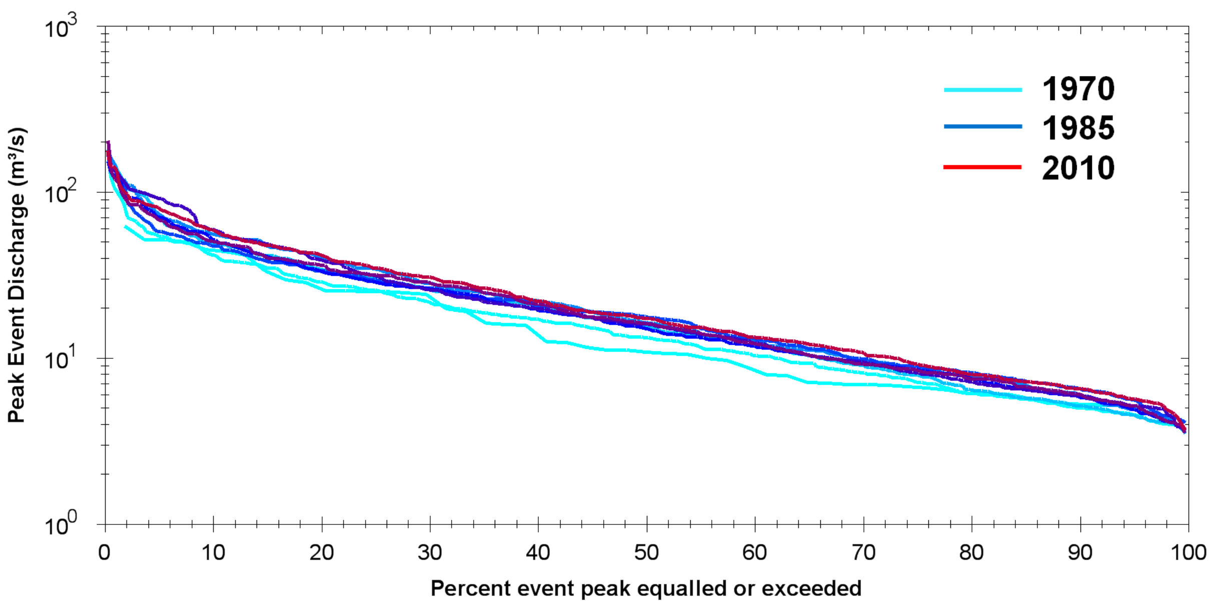


Figure D.56: Peak Exceedance Curve (5 Year Moving Average)

02HC022 - Rouge River near Markham

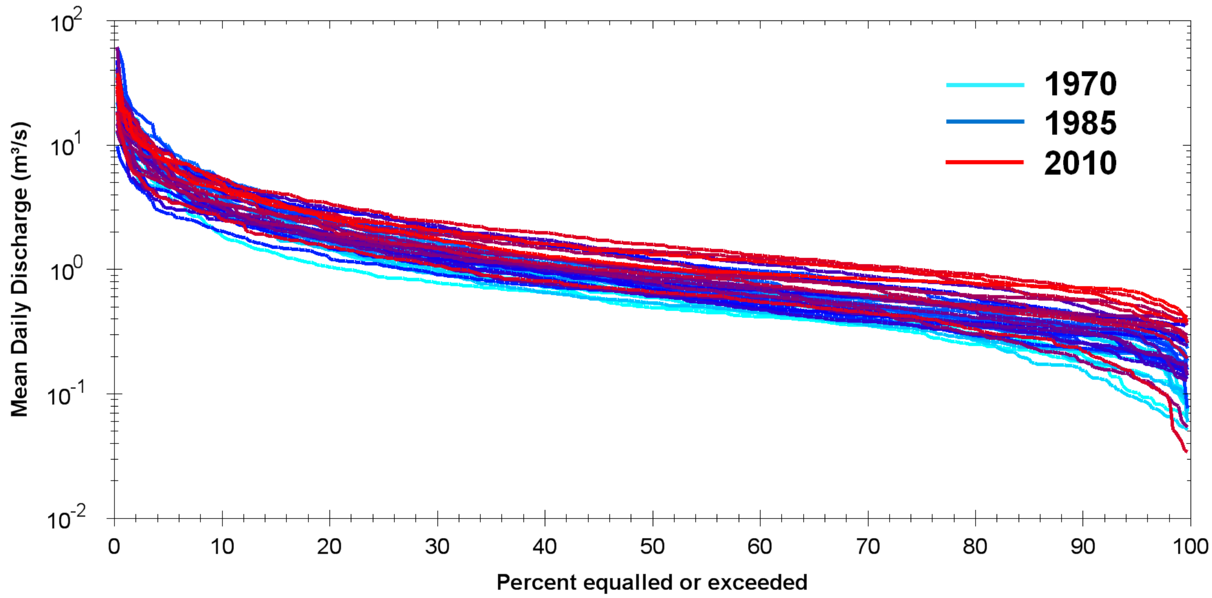


Figure D.57: Mean Daily Flow Duration Curve (by Year)

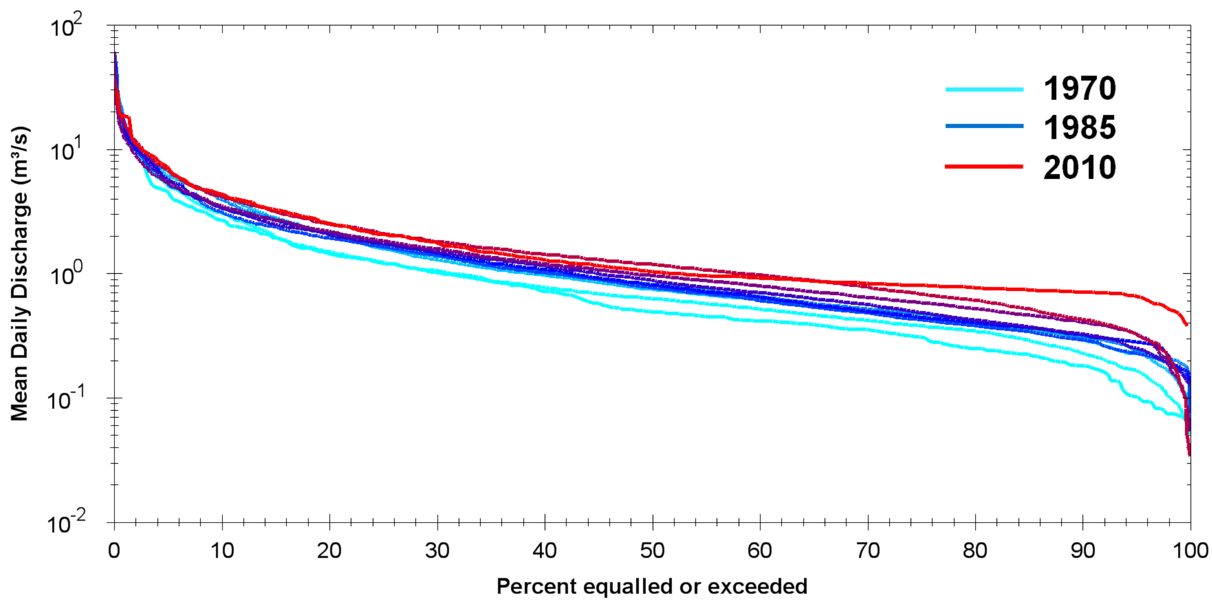


Figure D.58: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC022 - Rouge River near Markham

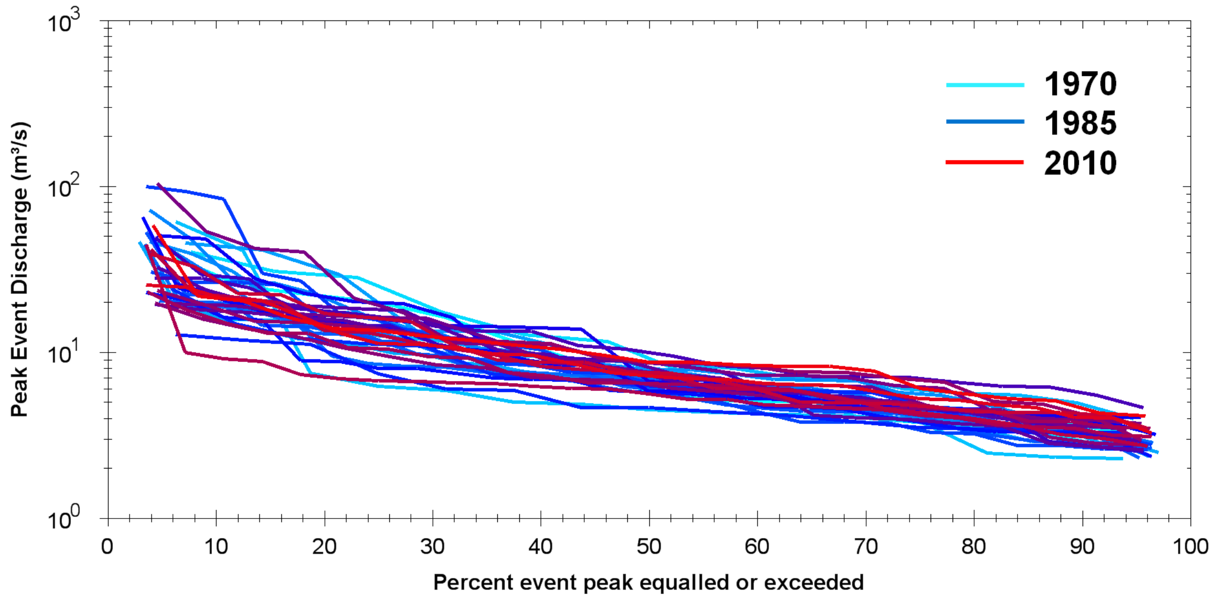


Figure D.59: Peak Exceedance Curve (by Year)

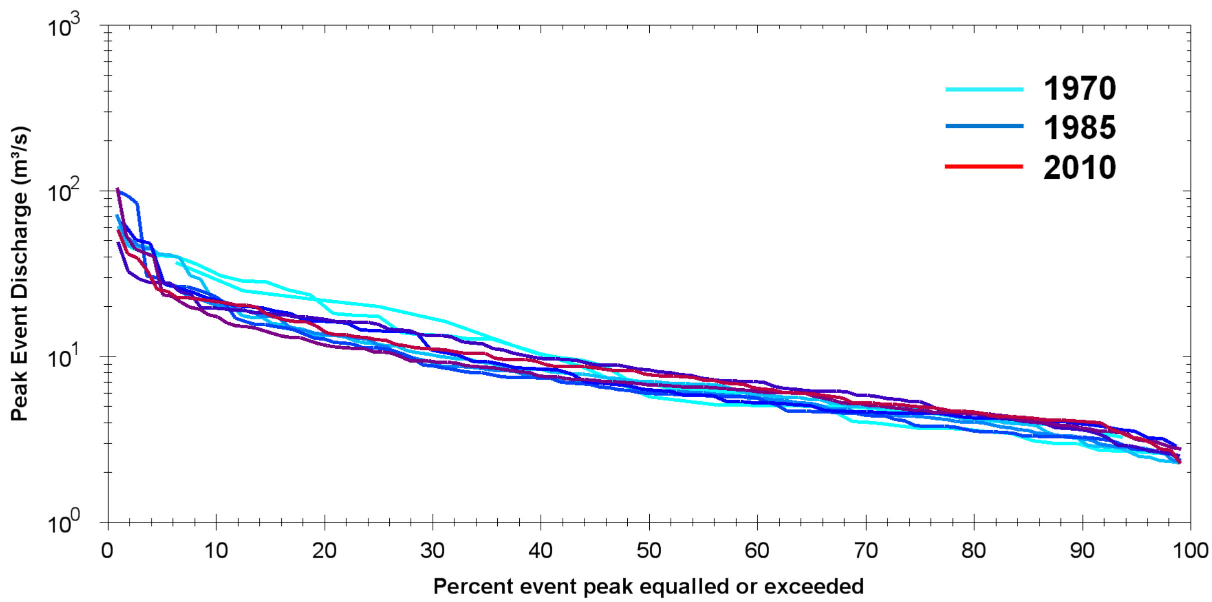


Figure D.60: Peak Exceedance Curve (5 Year Moving Average)

02HC013 - Highland Creek near West Hill

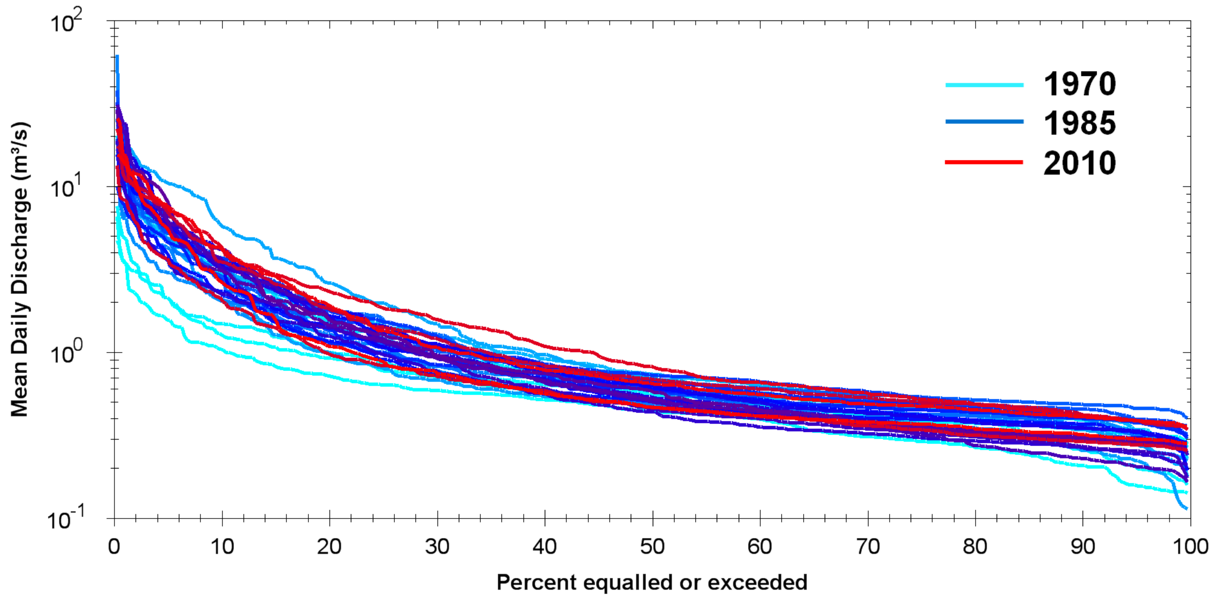


Figure D.61: Mean Daily Flow Duration Curve (by Year)

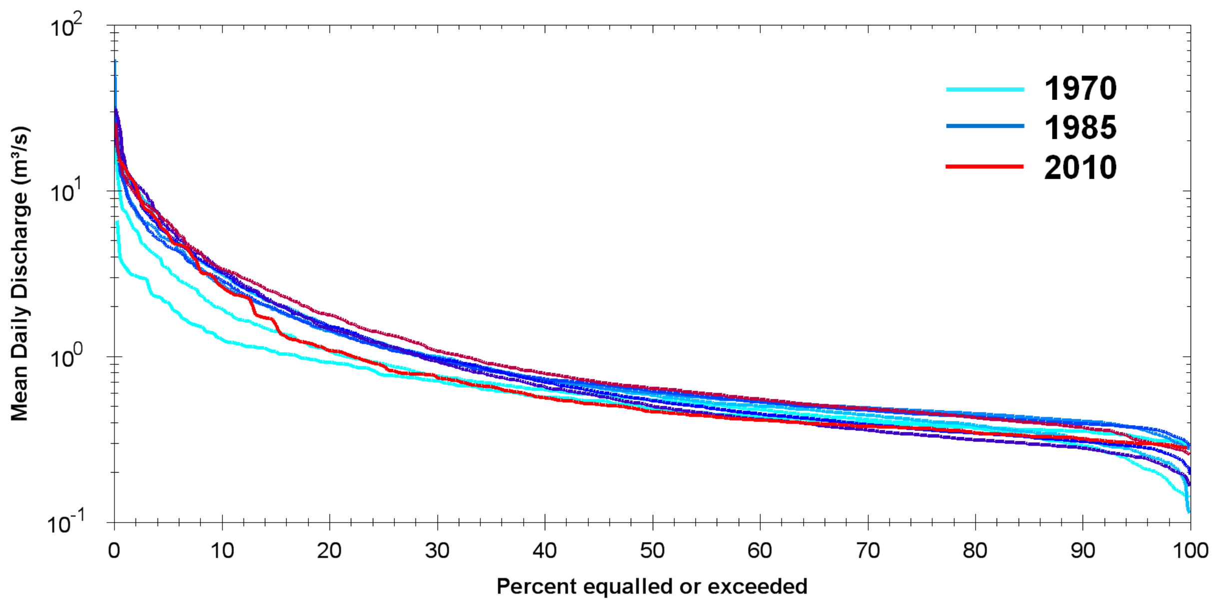


Figure D.62: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HC013 - Highland Creek near West Hill

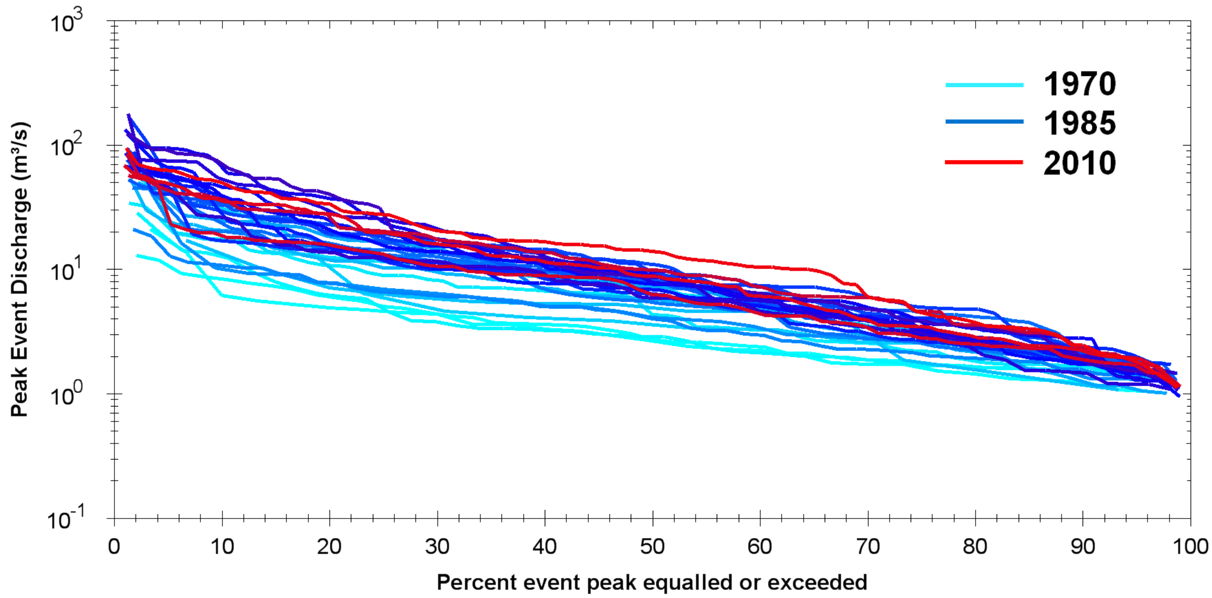


Figure D.63: Peak Exceedance Curve (by Year)

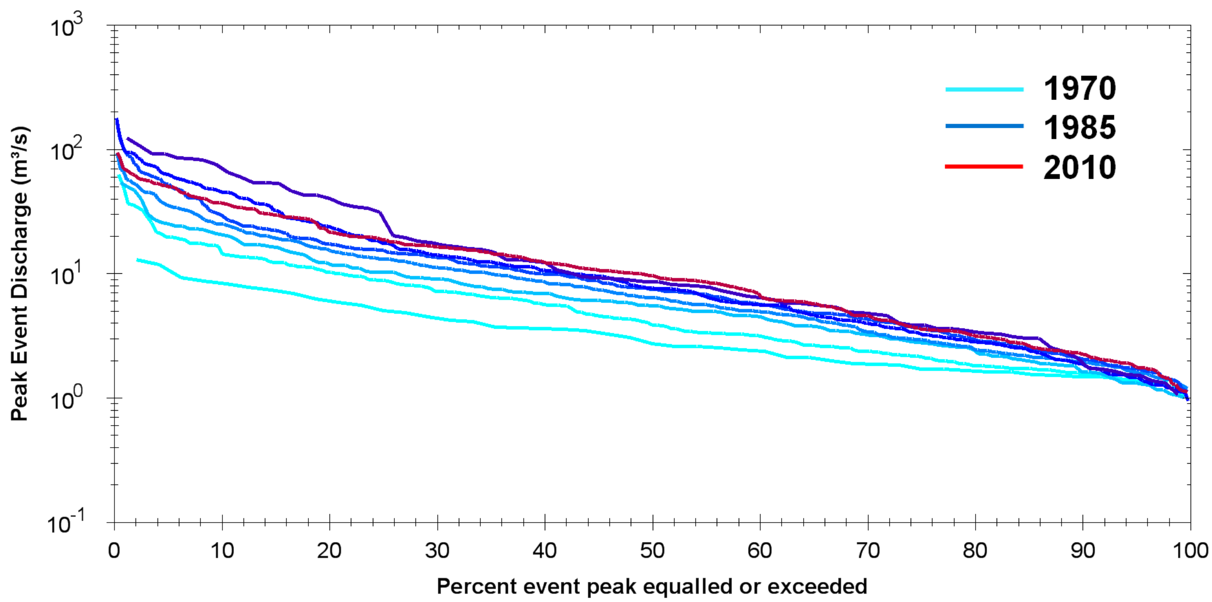


Figure D.64: Peak Exceedance Curve (5 Year Moving Average)

02HD013 - Harmony Creek at Oshawa

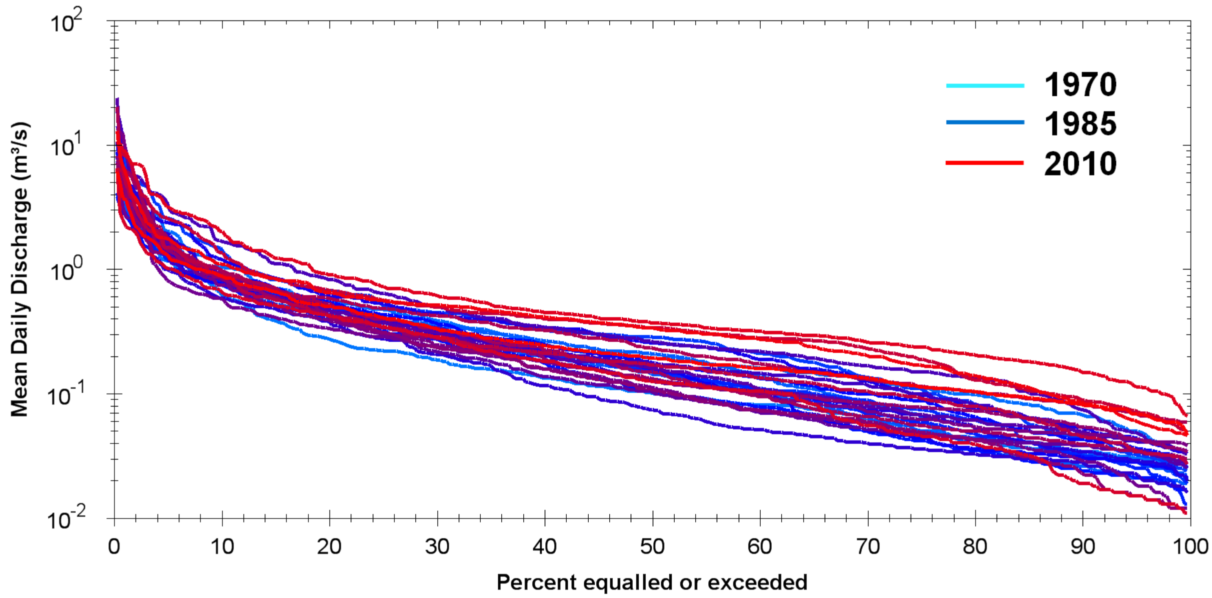


Figure D.65: Mean Daily Flow Duration Curve (by Year)

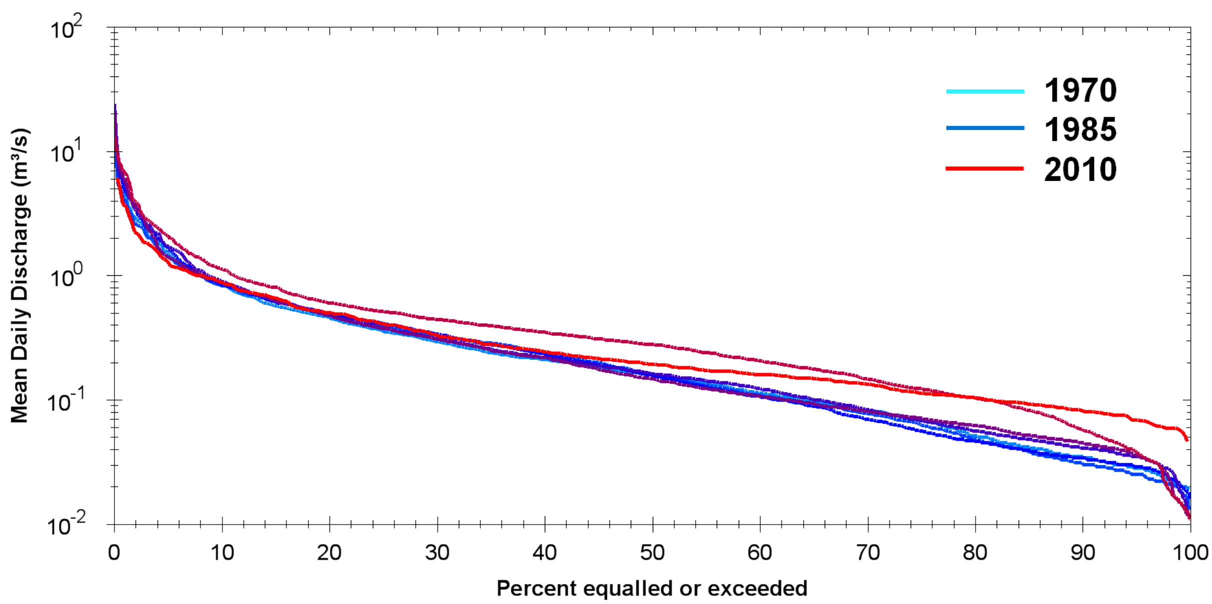


Figure D.66: Mean Daily Flow Duration Curve (5 Year Moving Average)

02HD013 - Harmony Creek at Oshawa

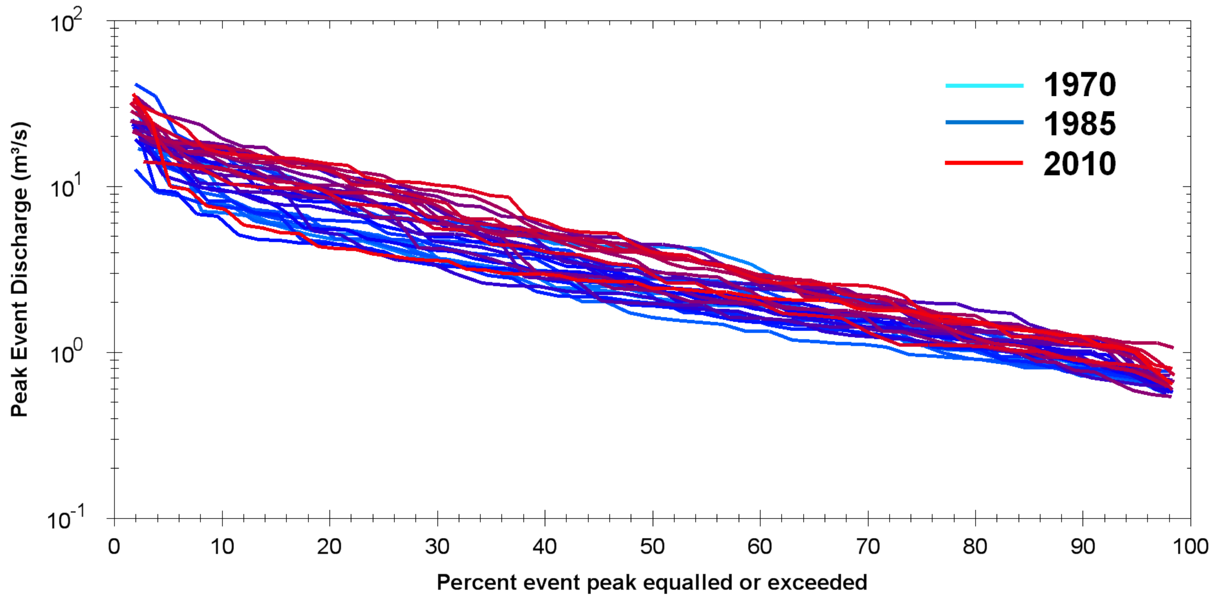


Figure D.67: Peak Exceedance Curve (by Year)

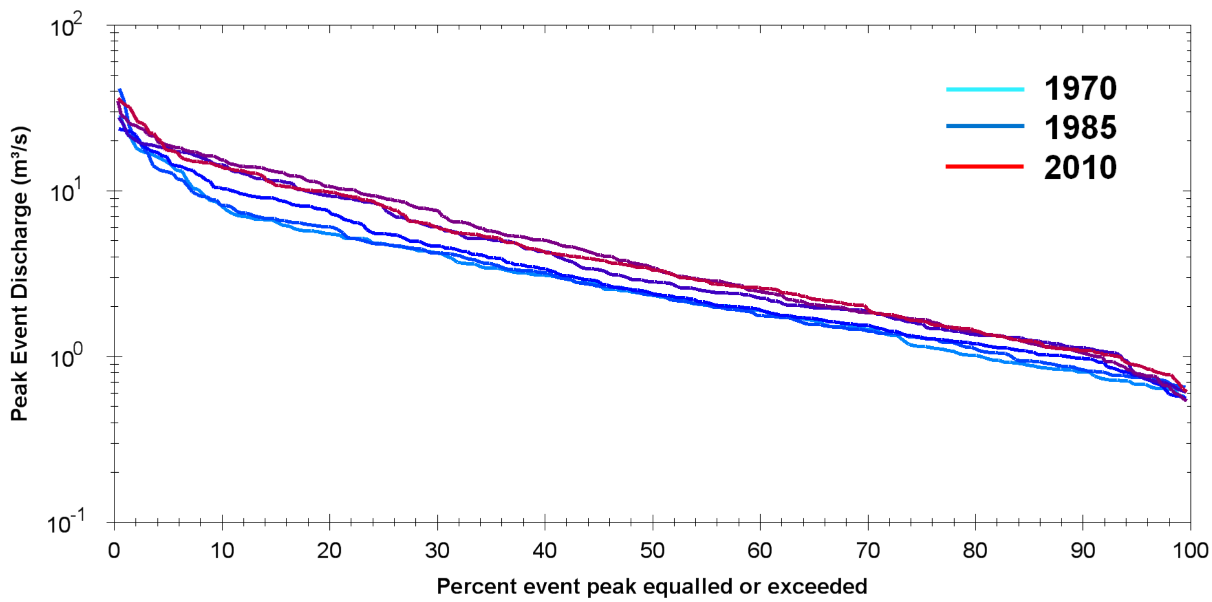


Figure D.68: Peak Exceedance Curve (5 Year Moving Average)

Appendix E

Low Frequency Analysis

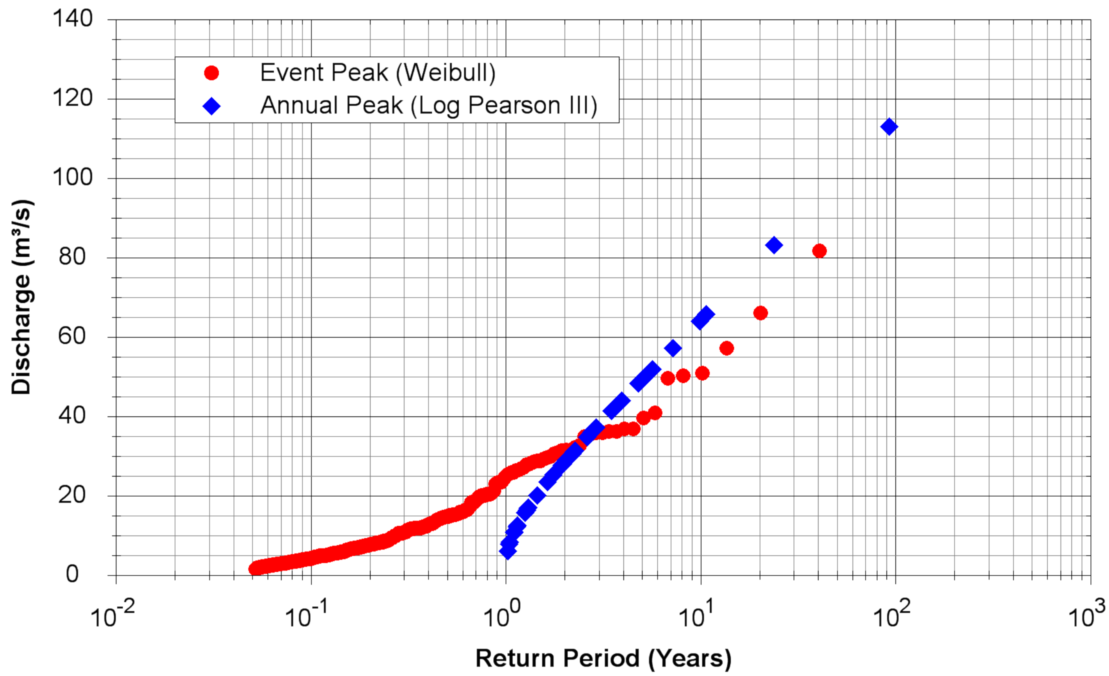


Figure E.1: Event Recurrence Interval - Duffins Creek above Pickering (02HC019)

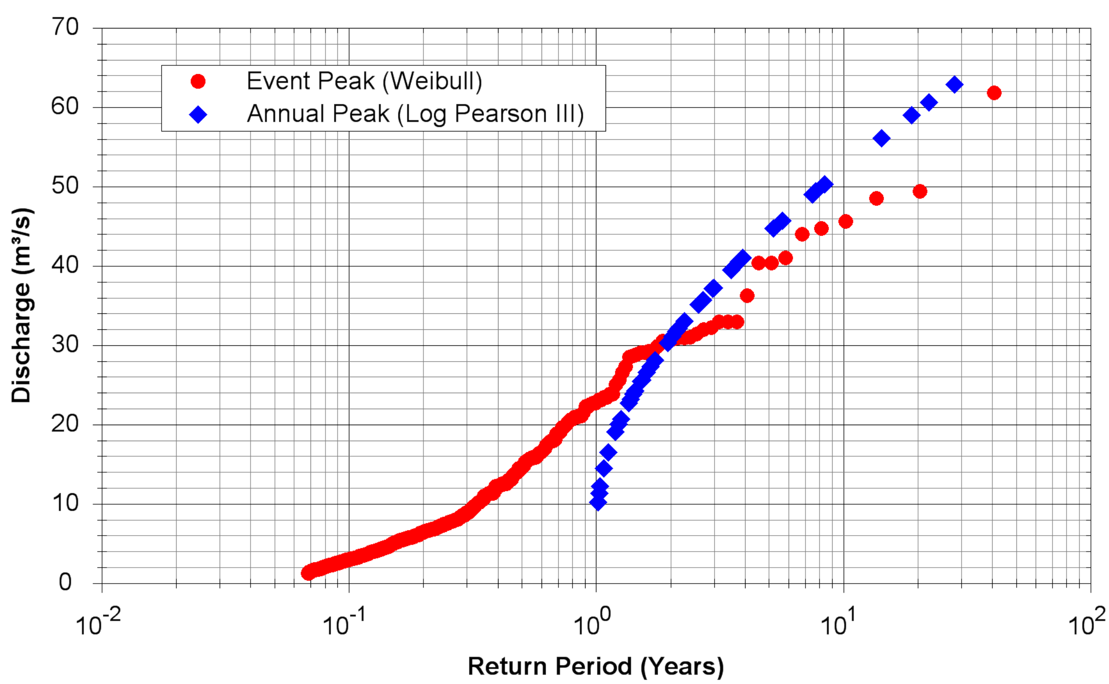


Figure E.2: Event Recurrence Interval - East Humber River near Pine Grove (02HC009)

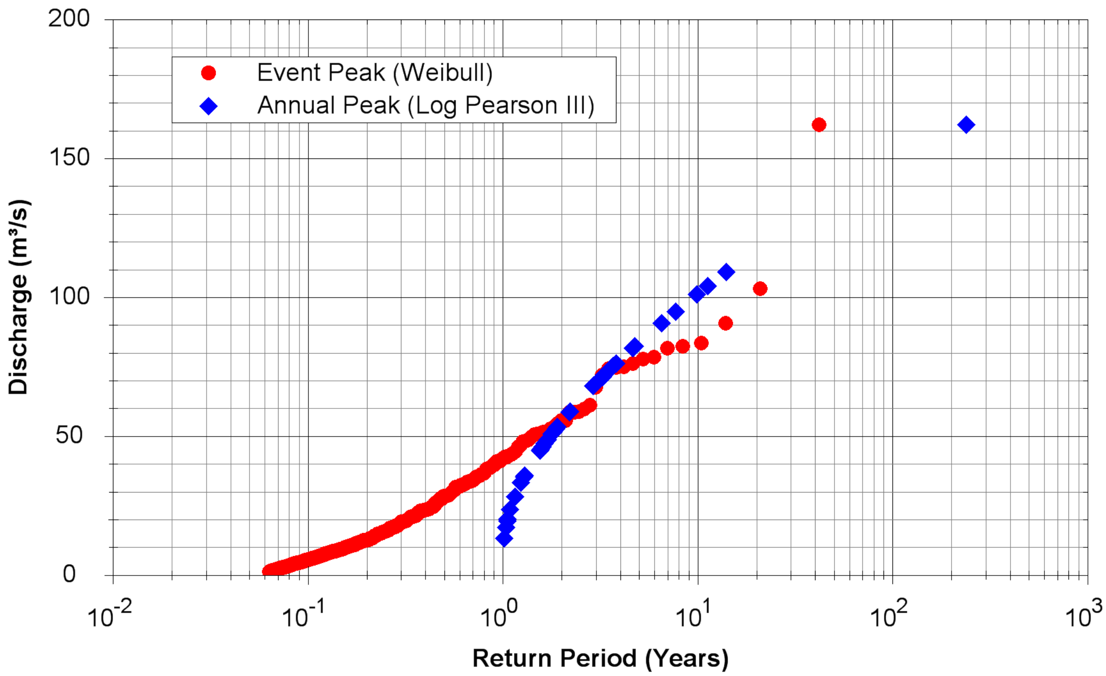


Figure E.3: Event Recurrence Interval - East Oakville Creek near Omagh (02HB004)

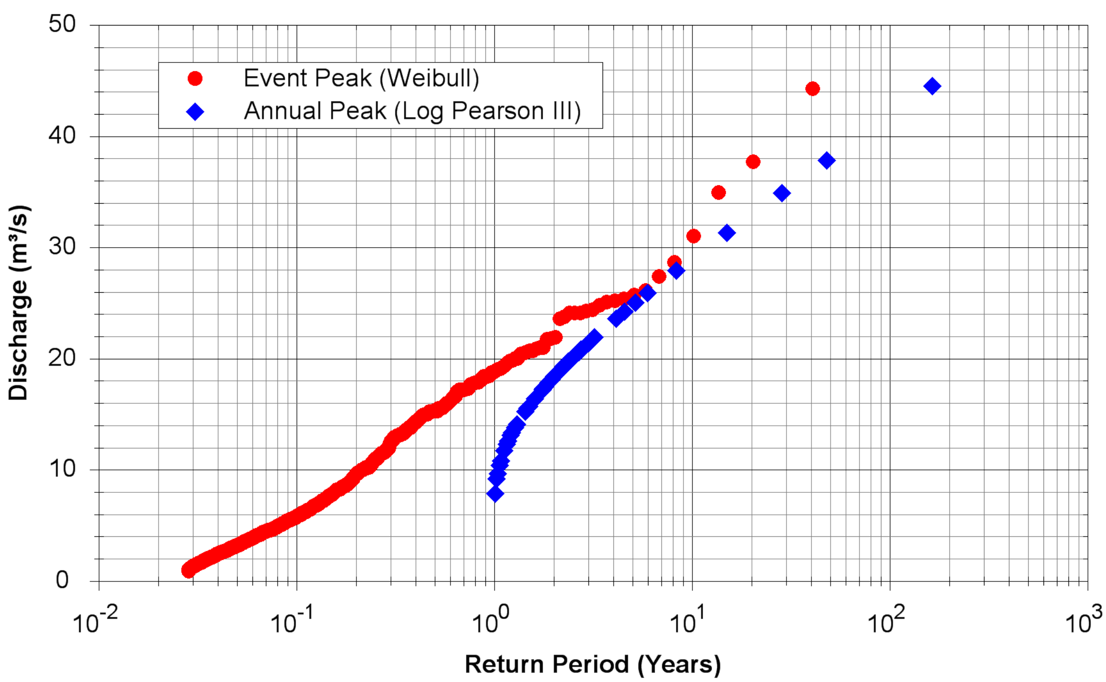


Figure E.4: Event Recurrence Interval - Oakville Creek at Milton (02HB005)

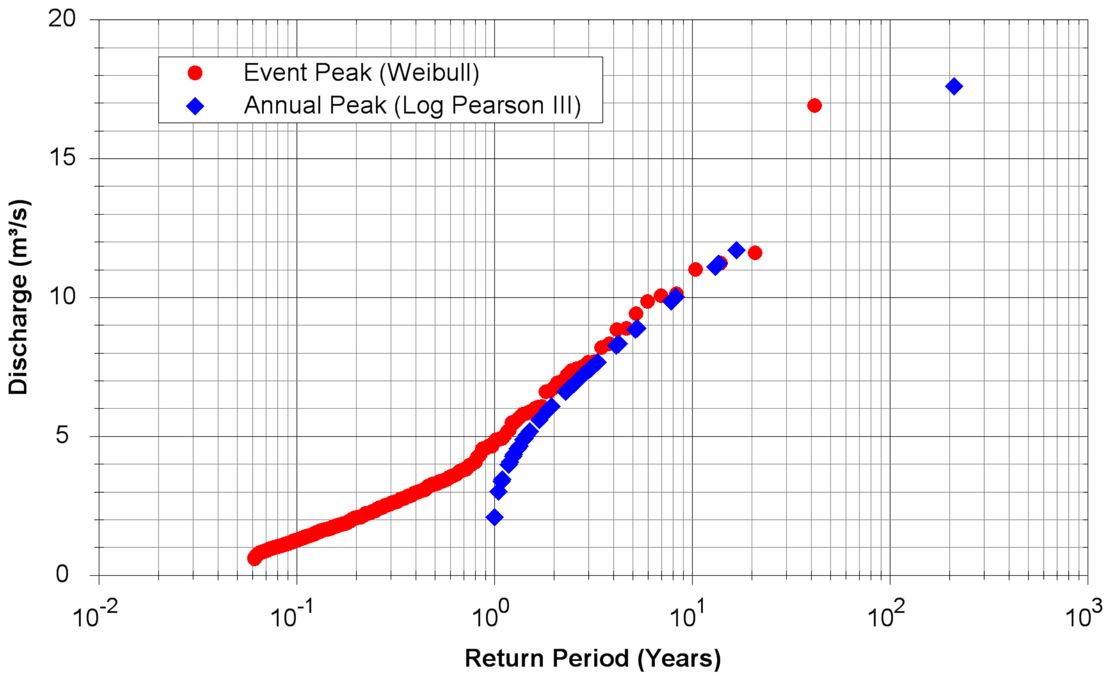


Figure E.5: Event Recurrence Interval - Credit River near Orangeville (02HB013)

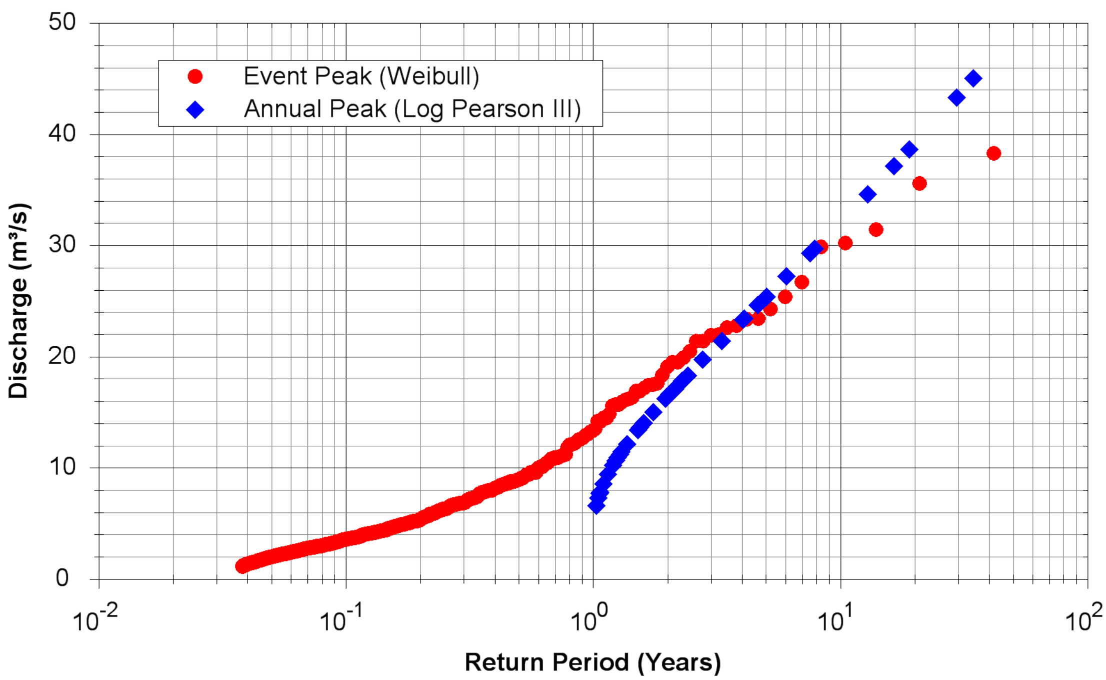


Figure E.6: Event Recurrence Interval - Laurel Creek at Waterloo (02GA024)

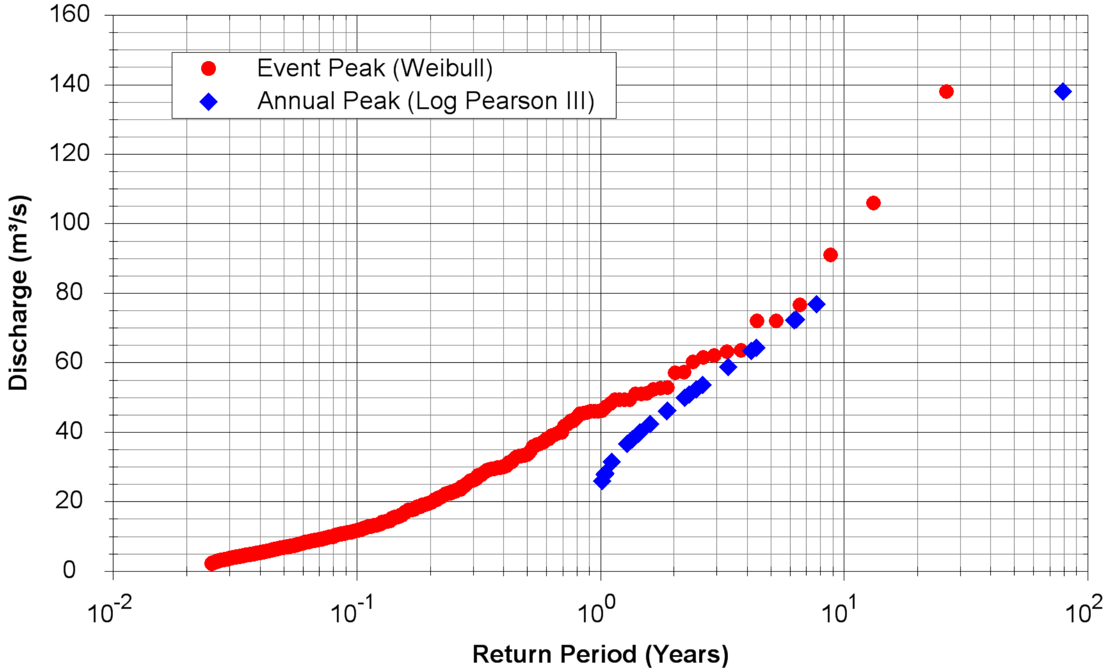


Figure E.7: Event Recurrence Interval - Red Hill Creek at Hamilton (02HA014)

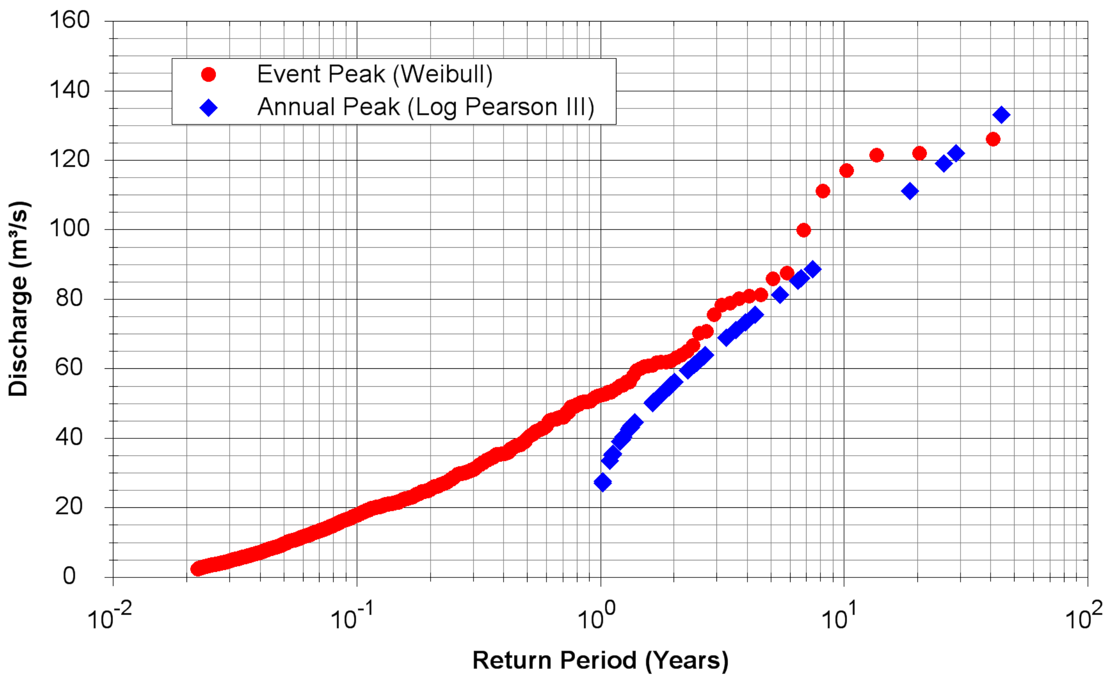


Figure E.8: Event Recurrence Interval - Black Creek near Weston (02HC027)

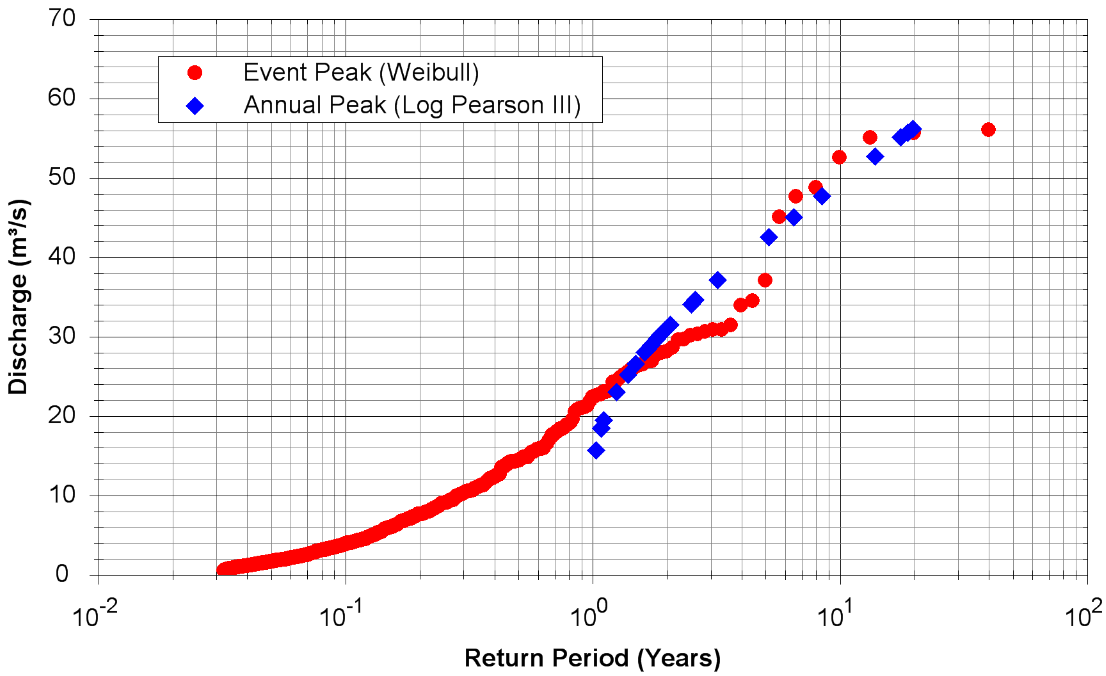


Figure E.9: Event Recurrence Interval - Etobicoke Creek at Brampton (02HC017)

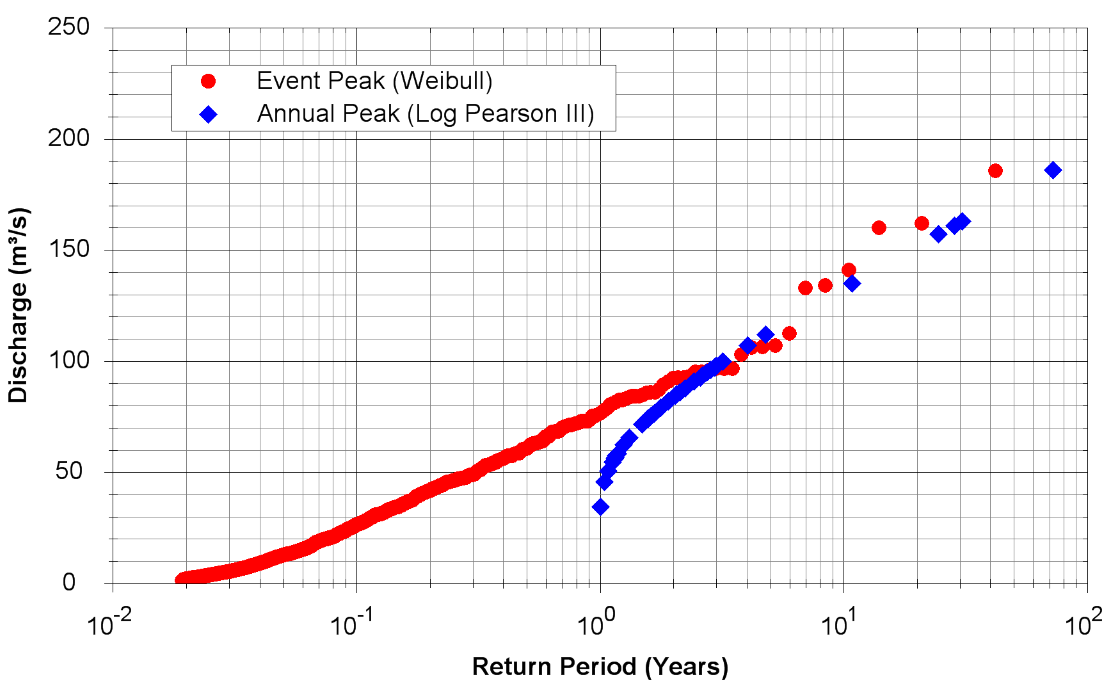


Figure E.10: Event Recurrence Interval - Etobicoke Creek below QEW (02HC030)

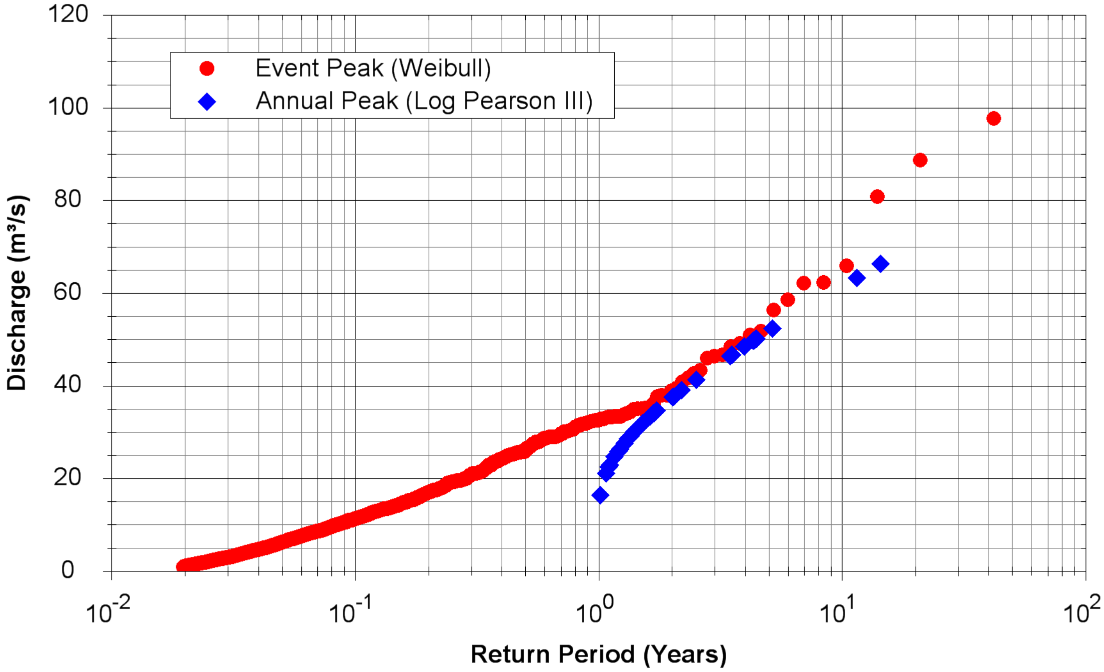


Figure E.11: Event Recurrence Interval - Mimico Creek at Islington (02HC033)

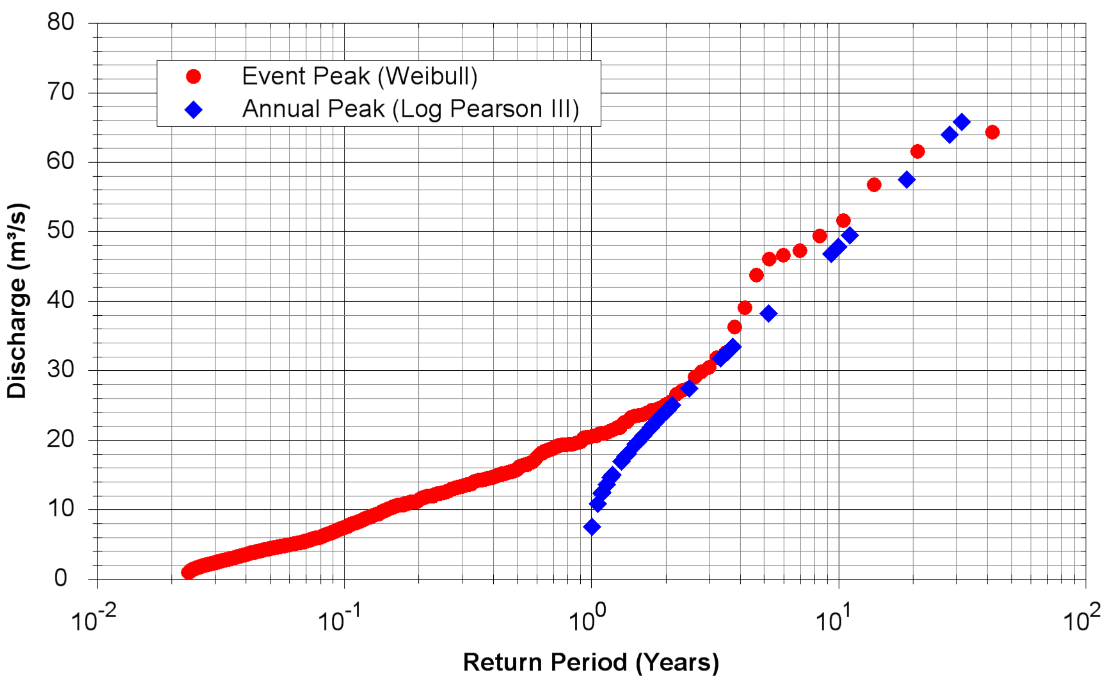


Figure E.12: Event Recurrence Interval - Don River at York Mills (02HC005)

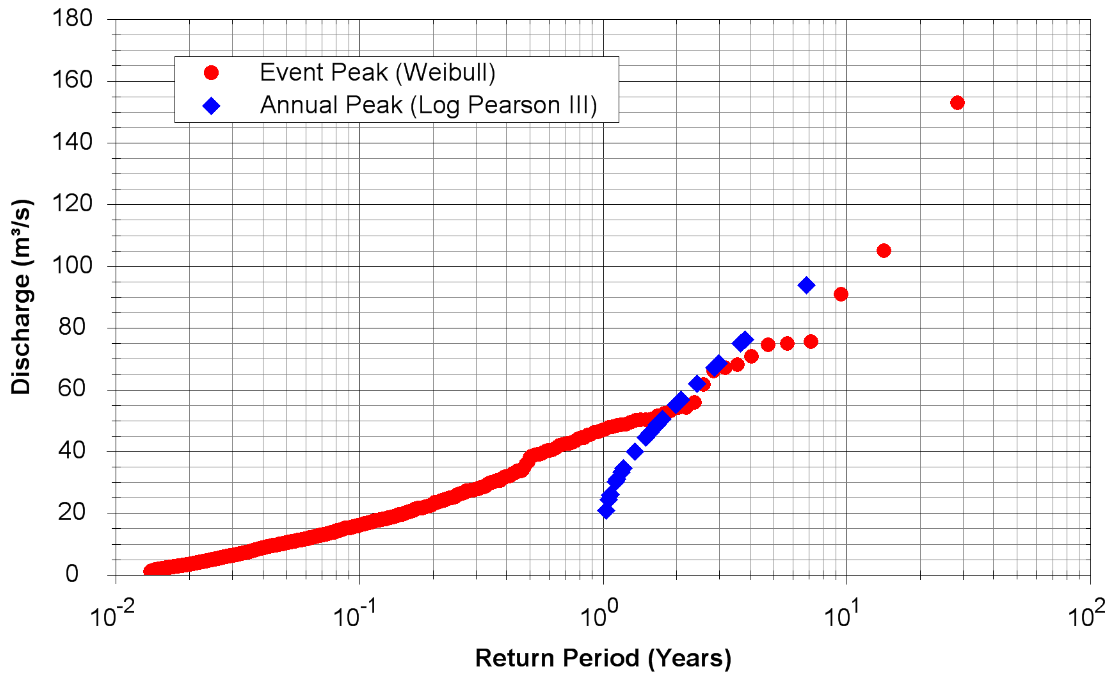


Figure E.13: Event Recurrence Interval - Little Don River at Don Mills (02HC029)

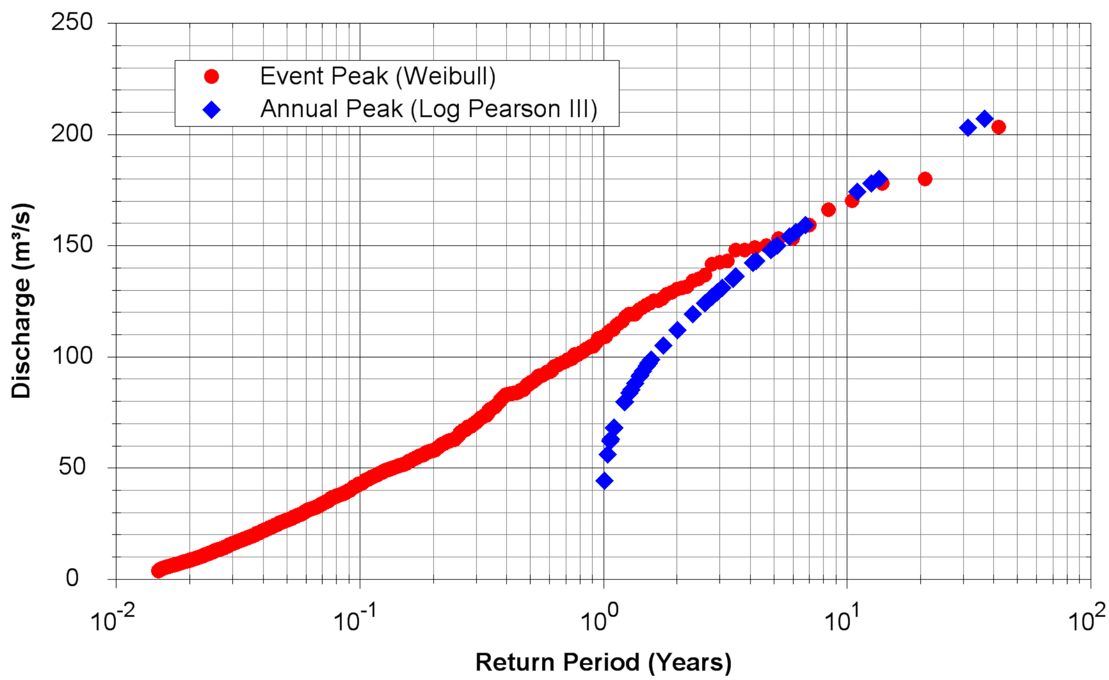


Figure E.14: Event Recurrence Interval - Don River at Todmorden (02HC024)

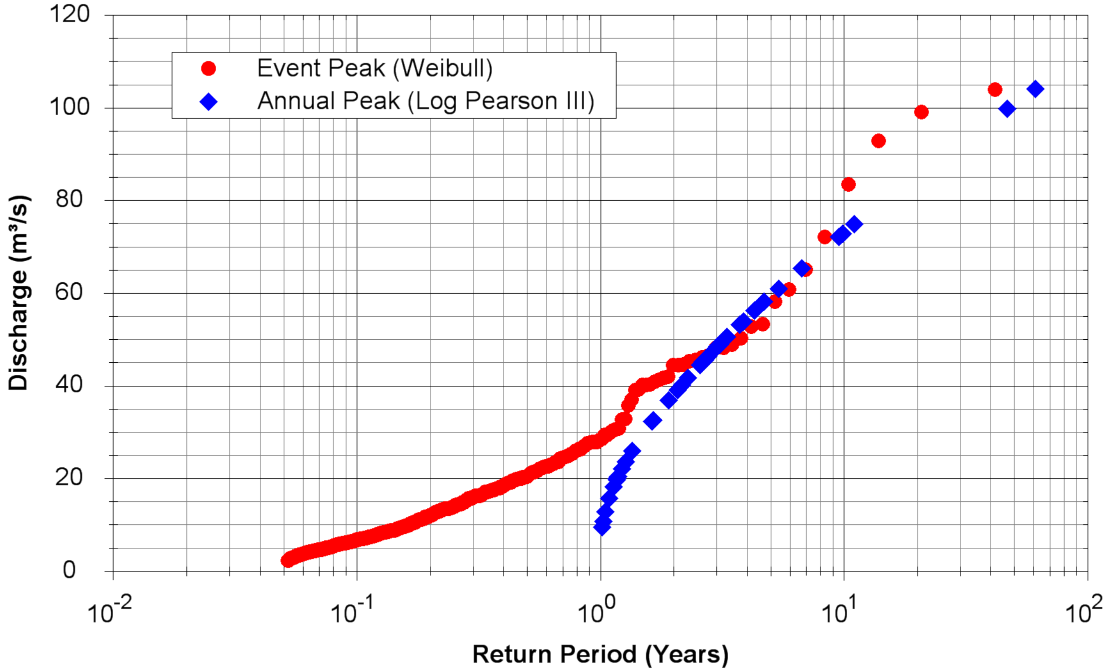


Figure E.15: Event Recurrence Interval - Rouge River near Markham (02HC022)

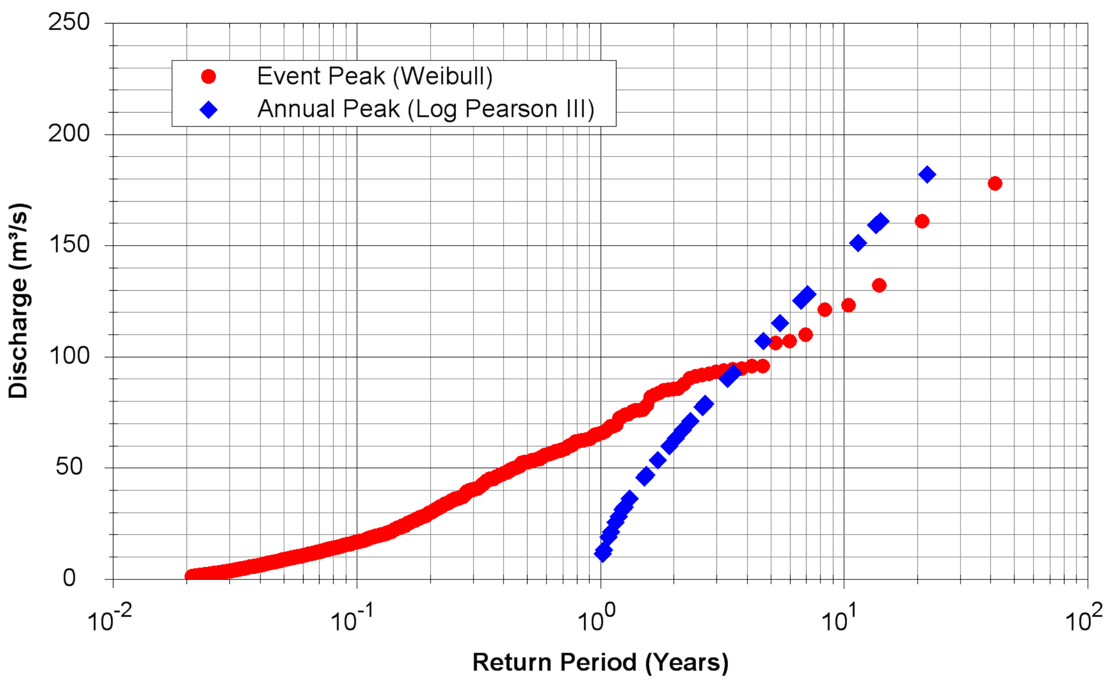


Figure E.16: Event Recurrence Interval - Highland Creek near West Hill (02HC013)

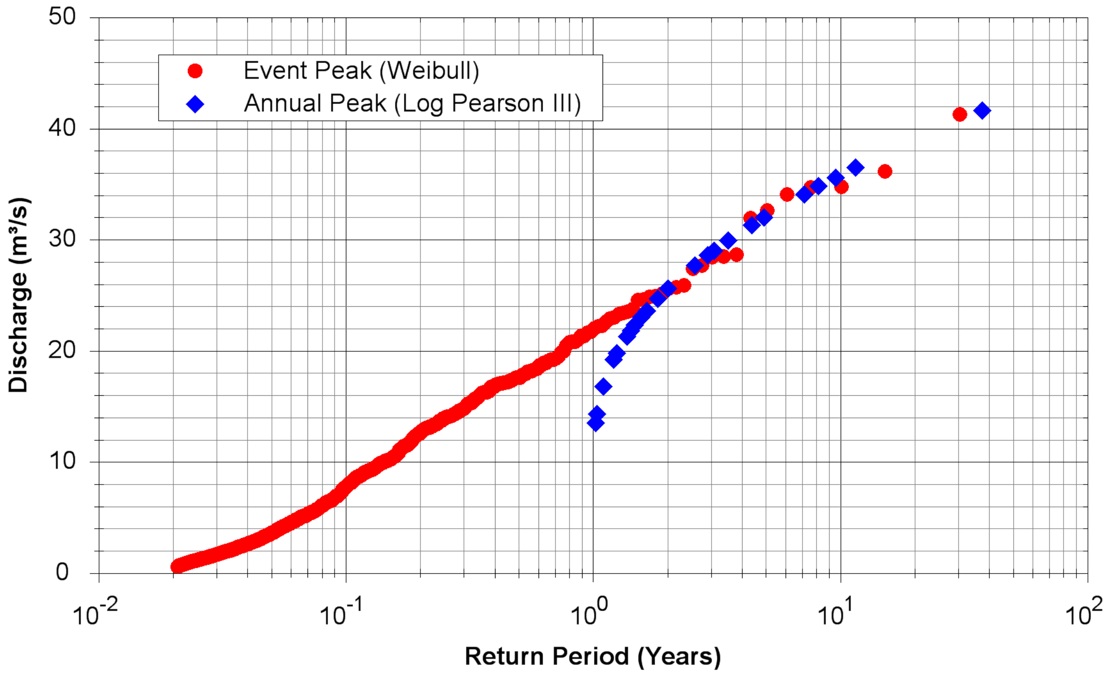


Figure E.17: Event Recurrence Interval - Harmony Creek at Oshawa (02HD013)

Appendix F

High Frequency Analysis

02GA024 - Laurel Creek at Waterloo

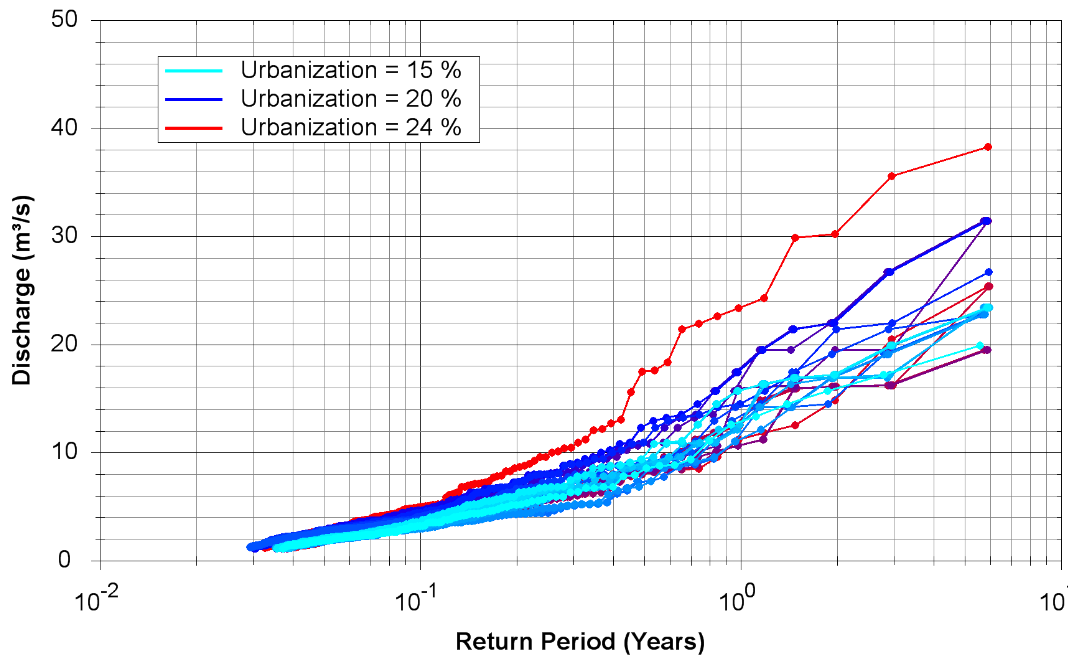


Figure F.1: Change in Event Return Period with Urbanization (5-Year Moving Window)

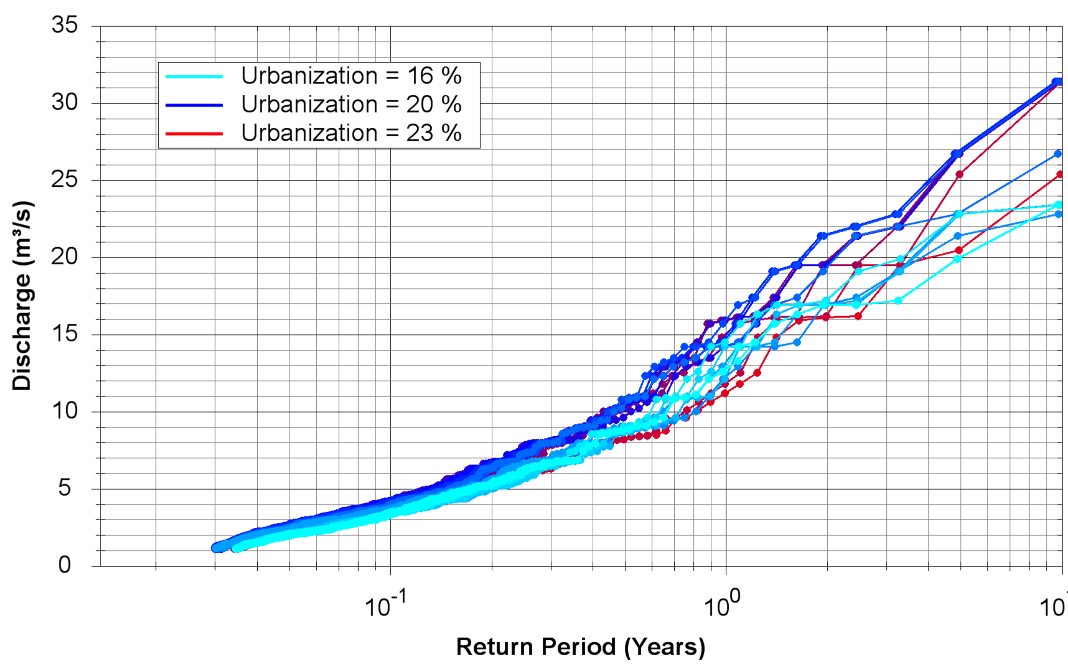


Figure F.2: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HA014 - Red Hill Creek at Hamilton

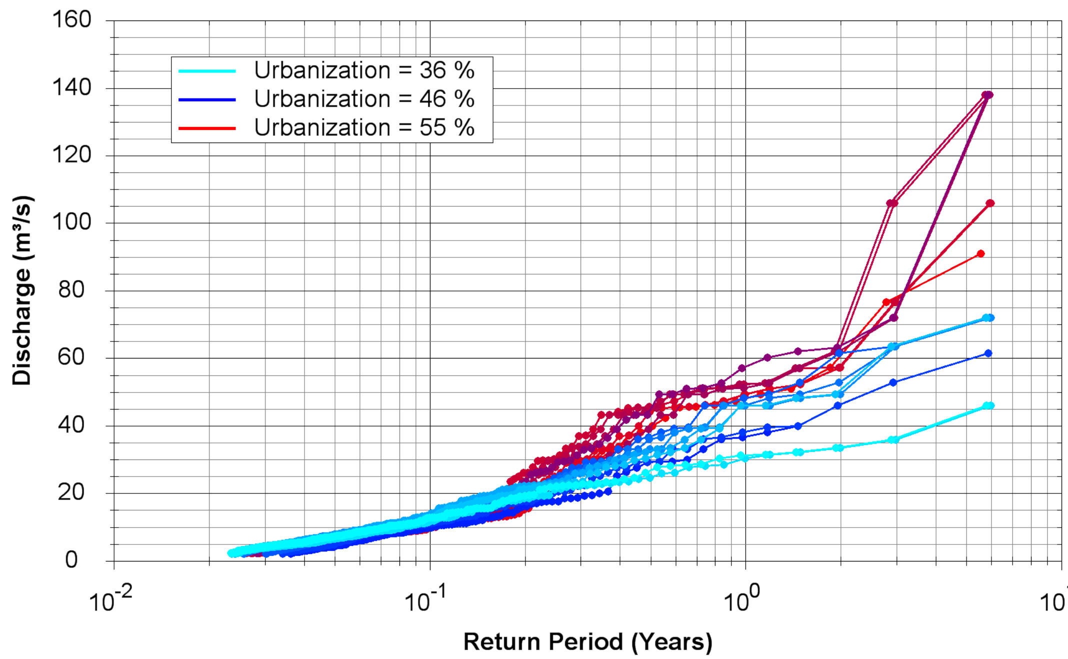


Figure F.3: Change in Event Return Period with Urbanization (5-Year Moving Window)

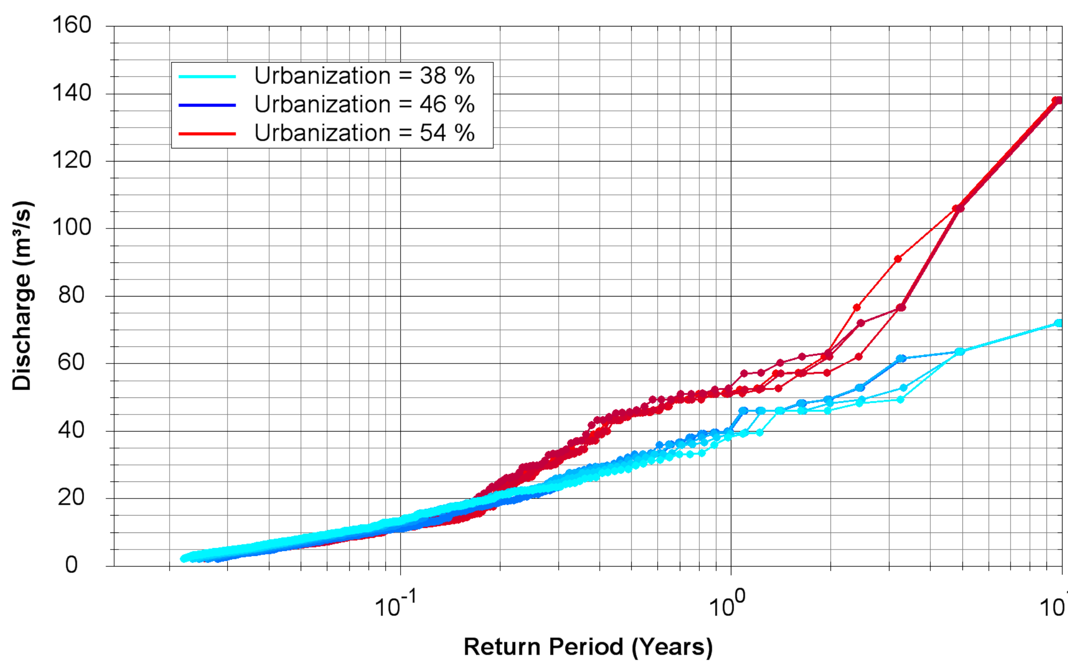


Figure F.4: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC027 - Black Creek near Weston

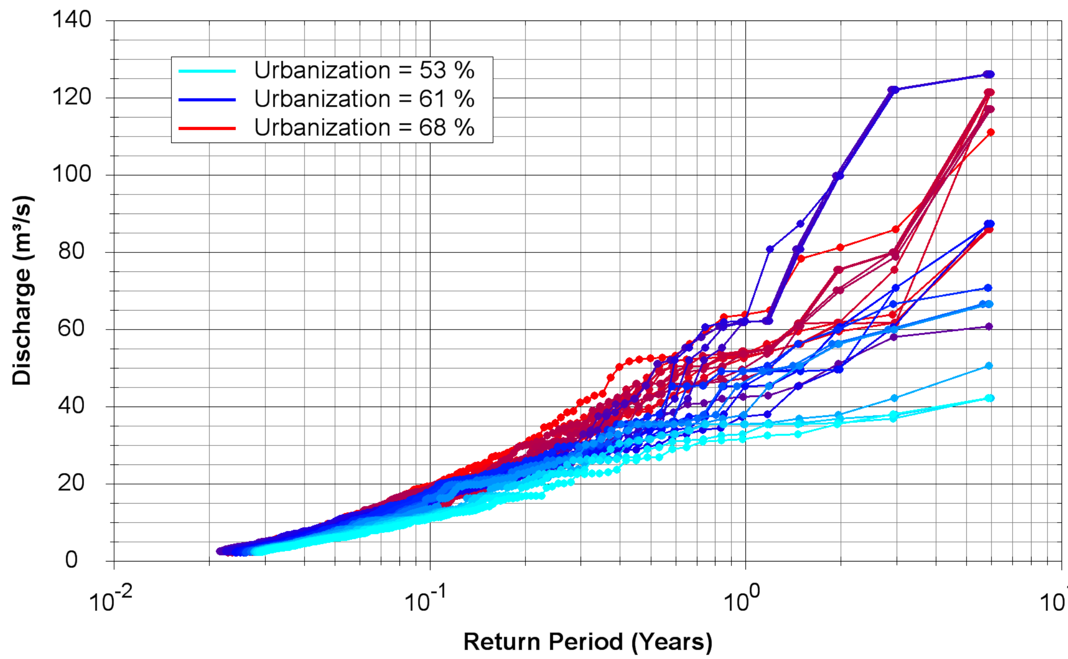


Figure F.5: Change in Event Return Period with Urbanization (5-Year Moving Window)

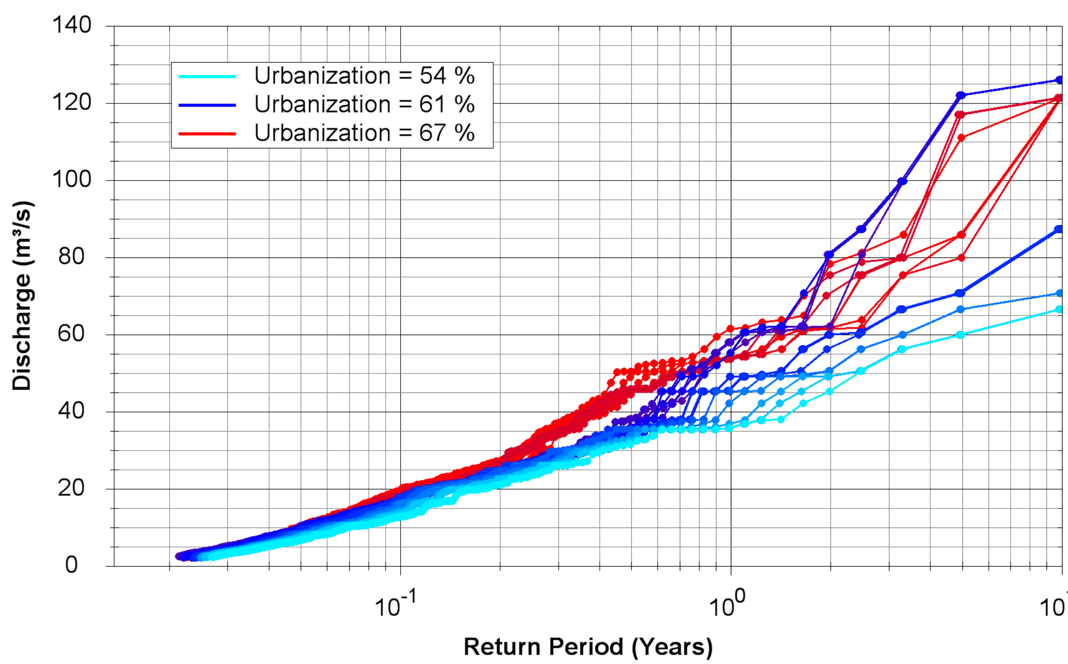


Figure F.6: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC017 - Etobicoke Creek at Brampton

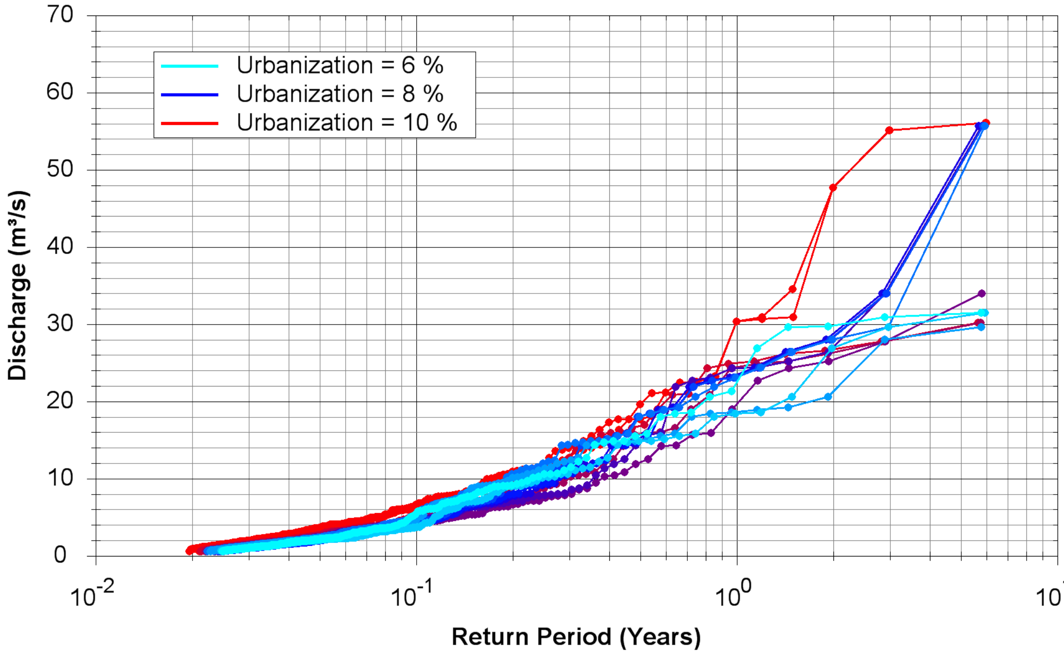


Figure F.7: Change in Event Return Period with Urbanization (5-Year Moving Window)

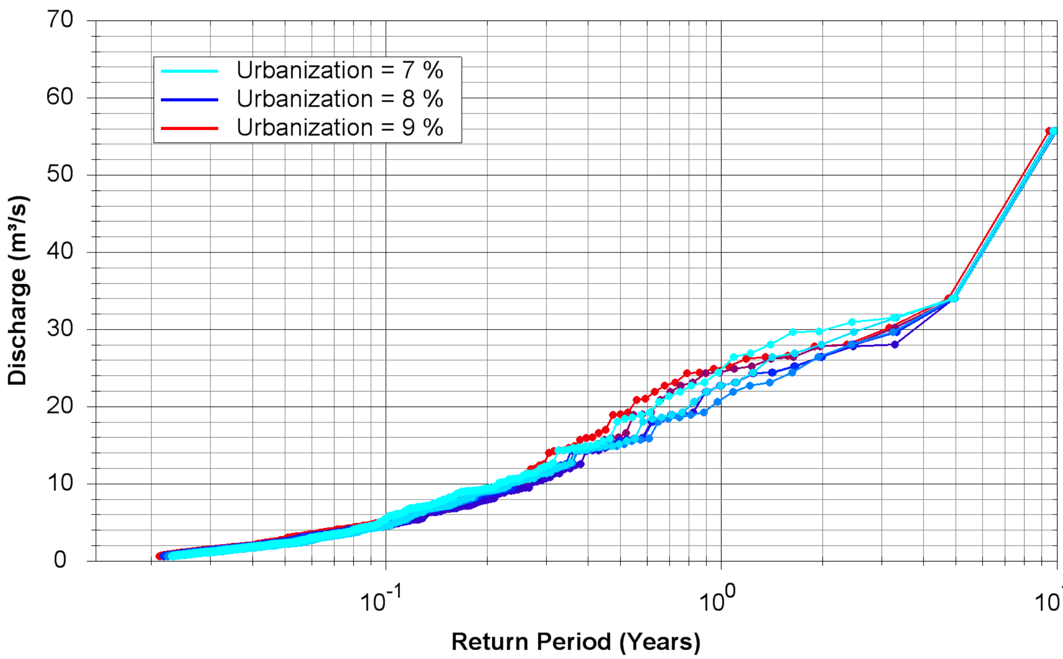


Figure F.8: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC030 - Etobicoke Creek below QEW

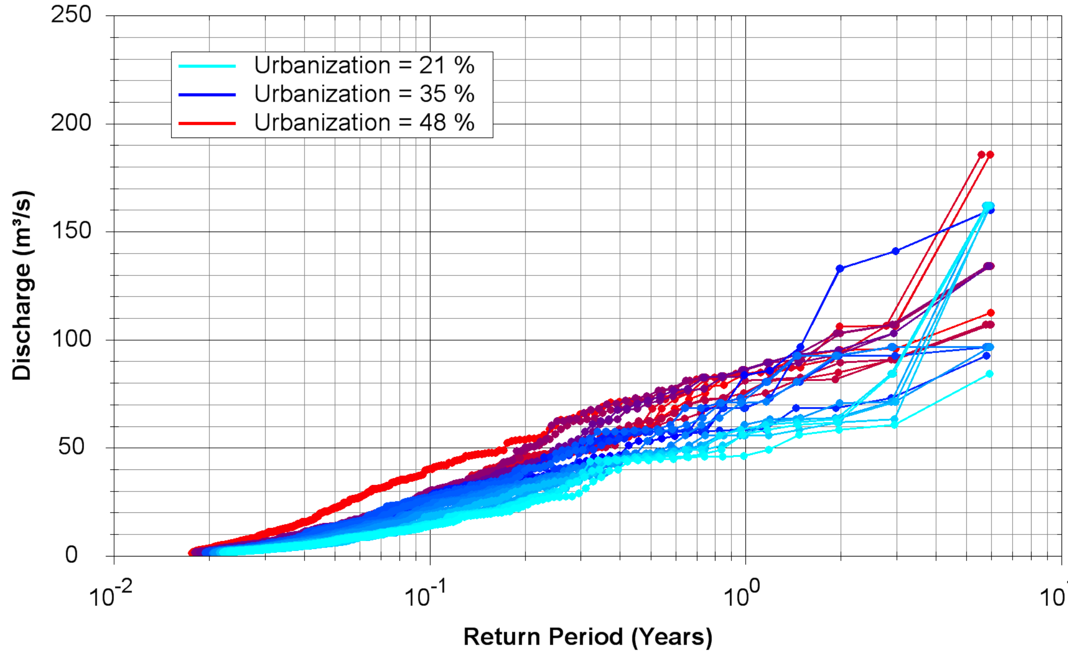


Figure F.9: Change in Event Return Period with Urbanization (5-Year Moving Window)

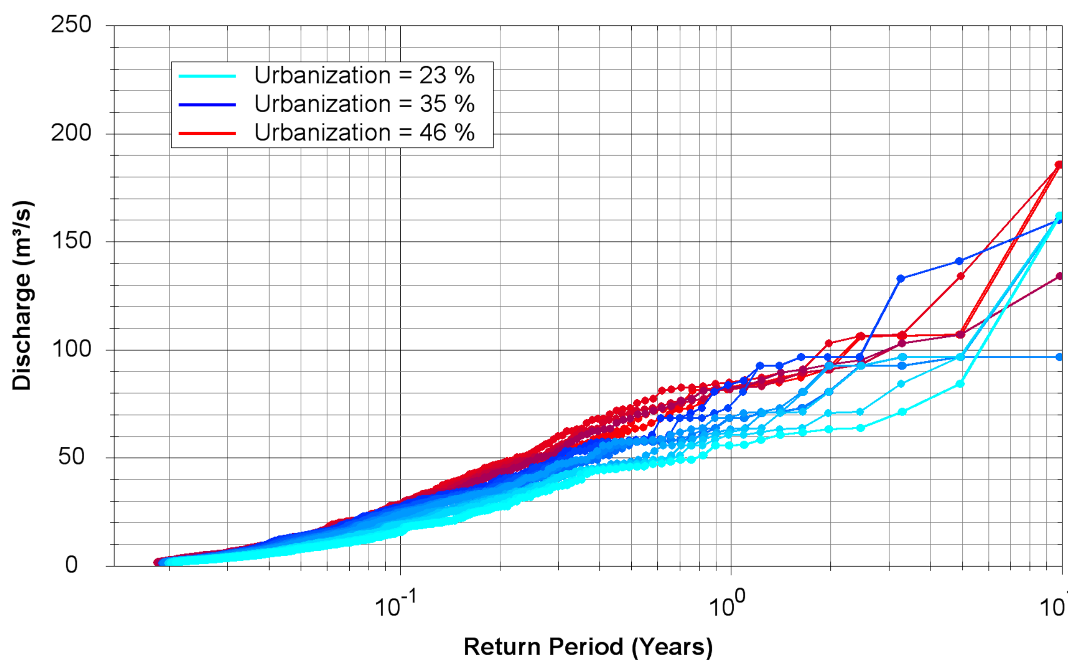


Figure F.10: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC033 - Mimico Creek at Islington

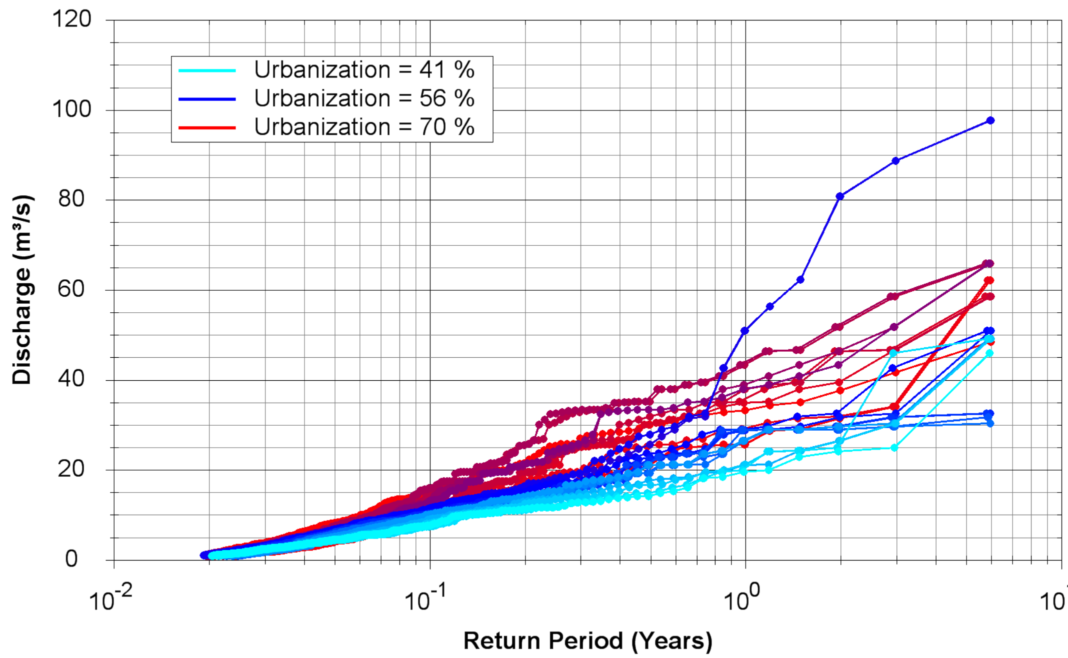


Figure F.11: Change in Event Return Period with Urbanization (5-Year Moving Window)

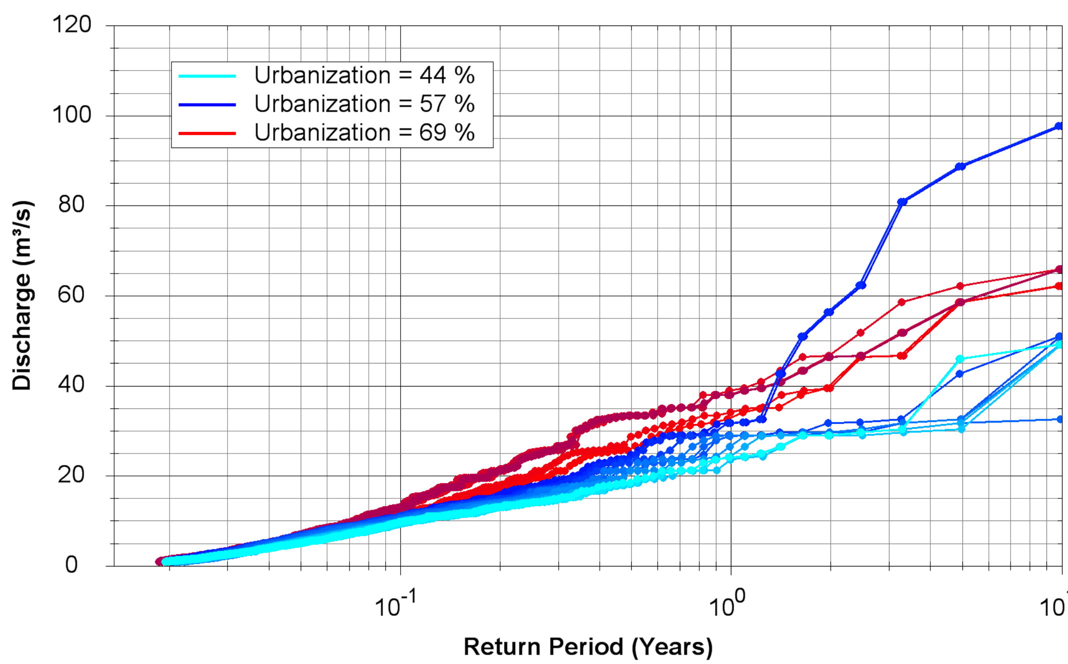


Figure F.12: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC005 - Don River at York Mills

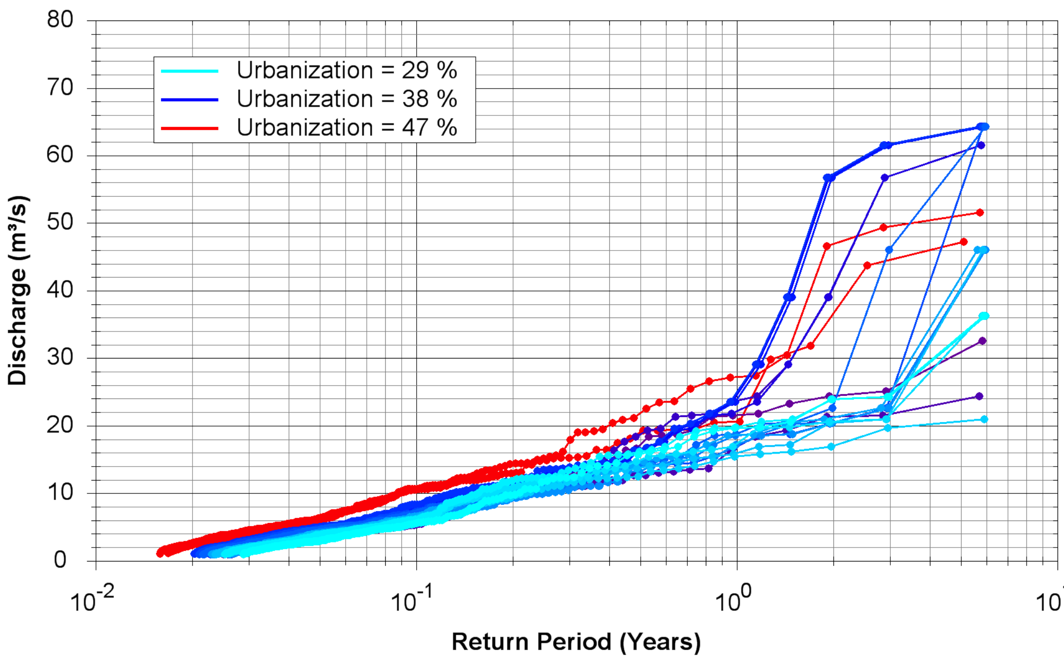


Figure F.13: Change in Event Return Period with Urbanization (5-Year Moving Window)

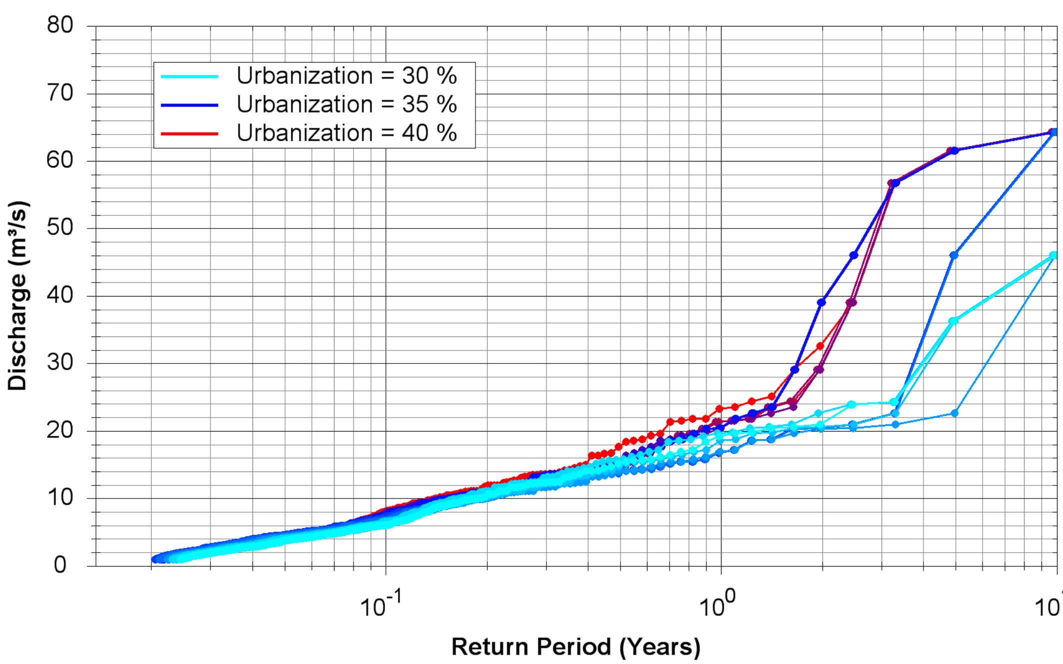


Figure F.14: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC029 - Little Don River at Don Mills

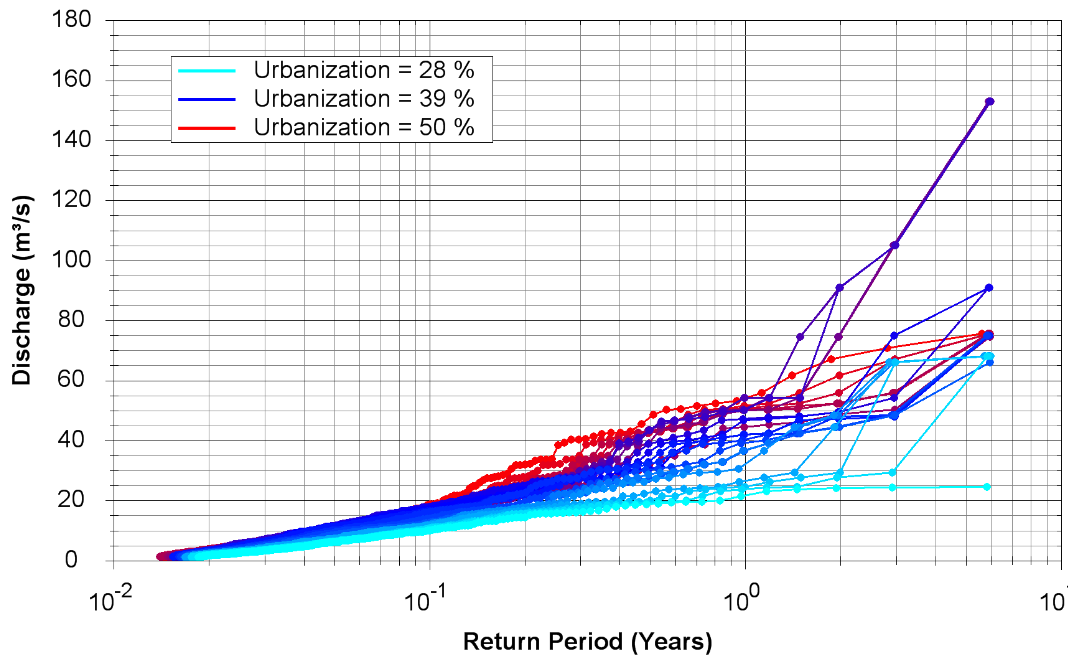


Figure F.15: Change in Event Return Period with Urbanization (5-Year Moving Window)

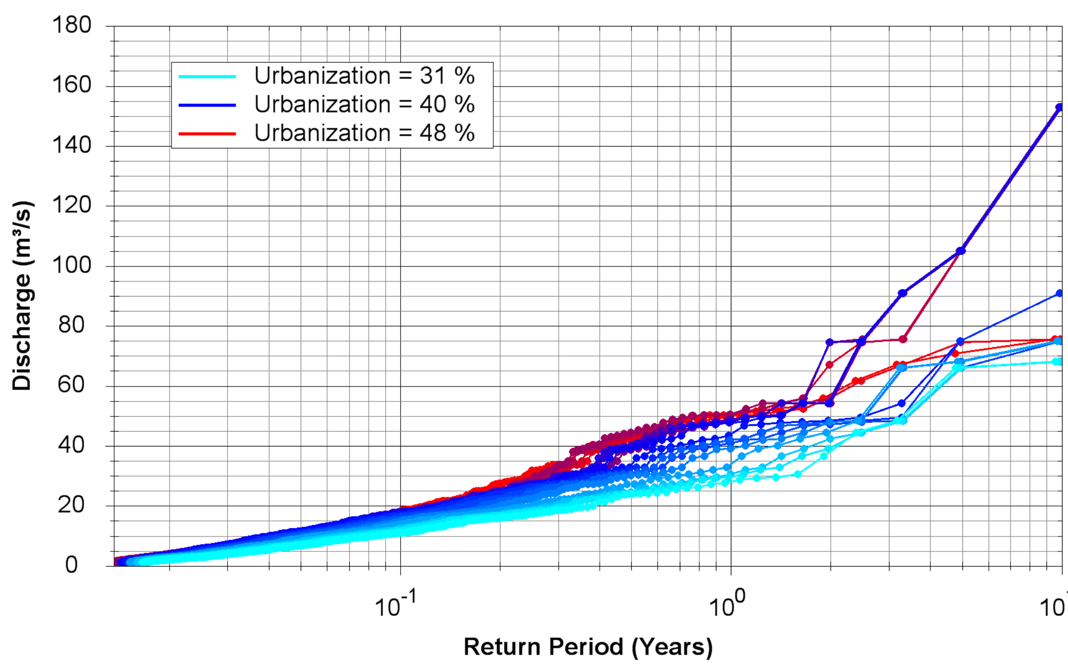


Figure F.16: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC024 - Don River at Todmorden

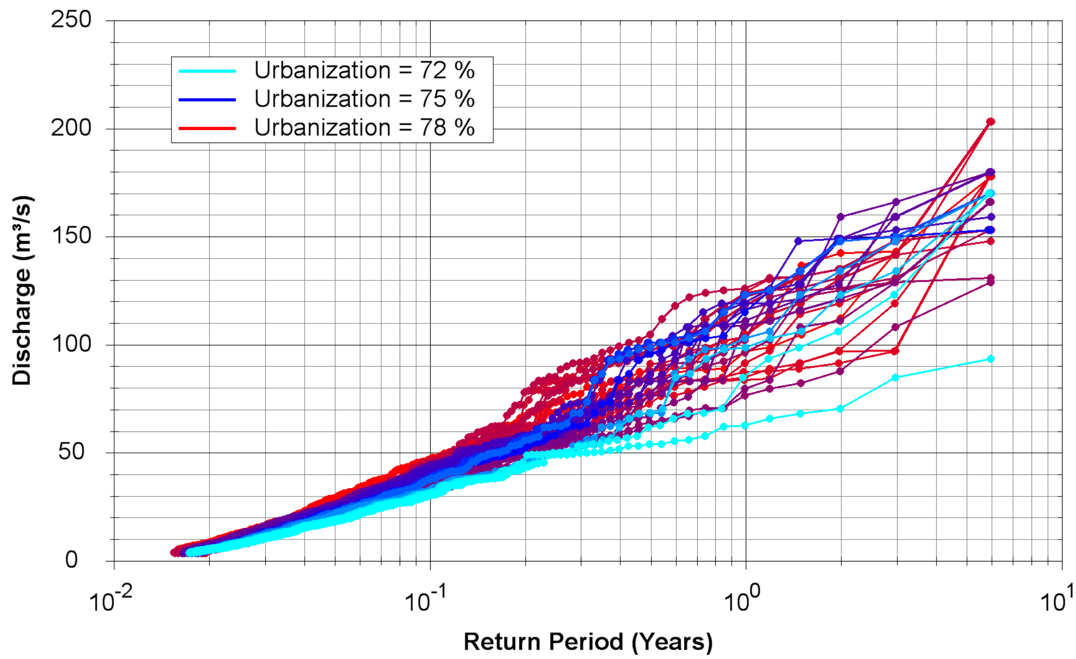


Figure F.17: Change in Event Return Period with Urbanization (5-Year Moving Window)

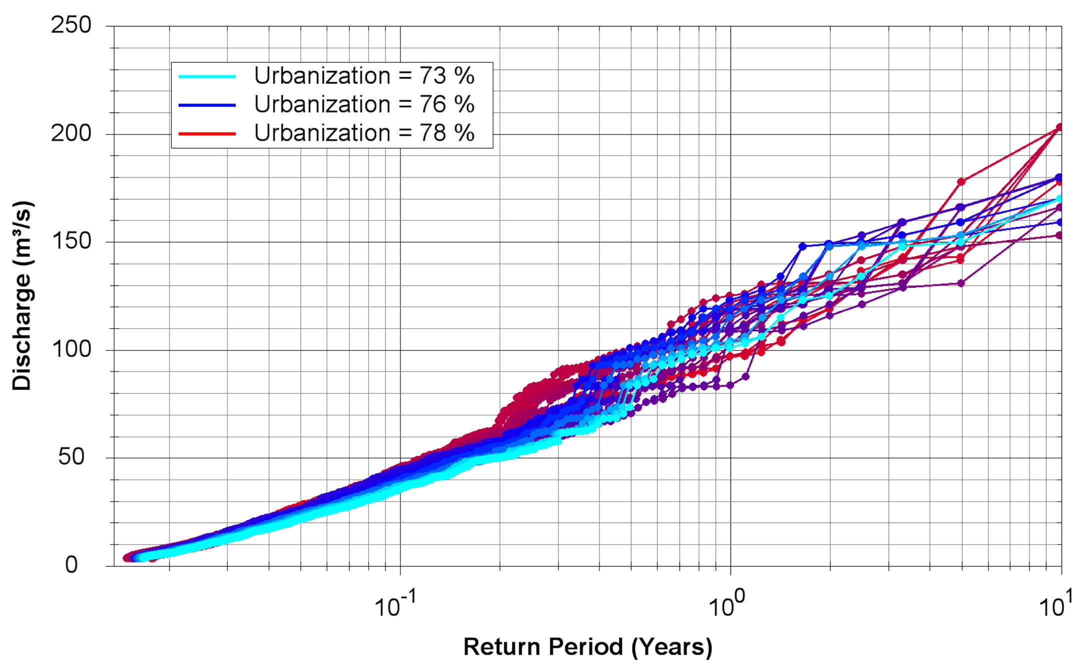


Figure F.18: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC022 - Rouge River near Markham

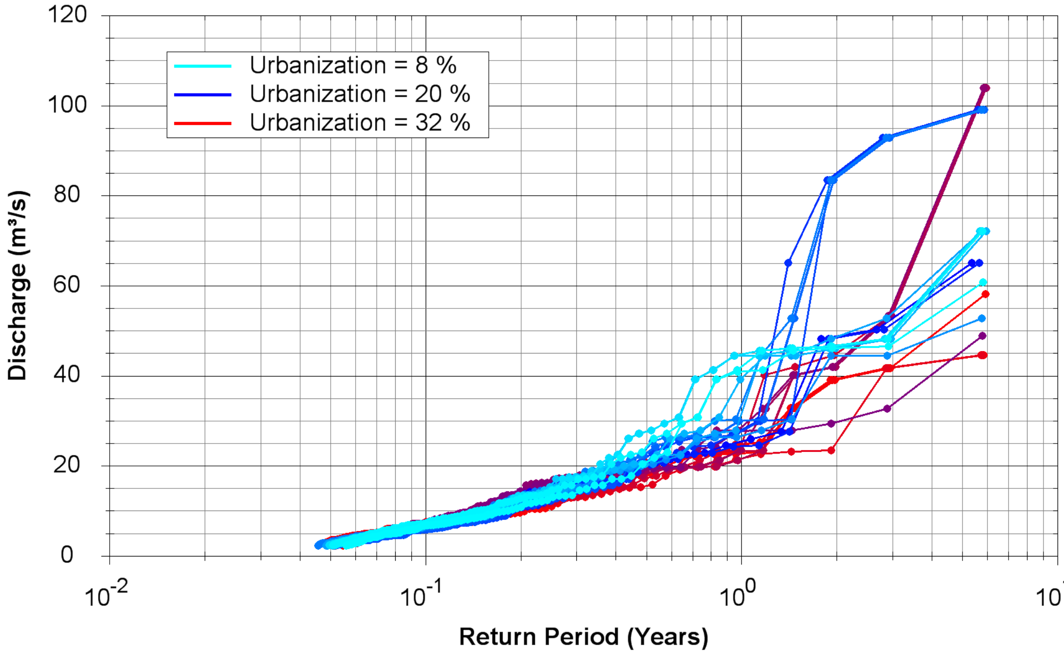


Figure F.19: Change in Event Return Period with Urbanization (5-Year Moving Window)

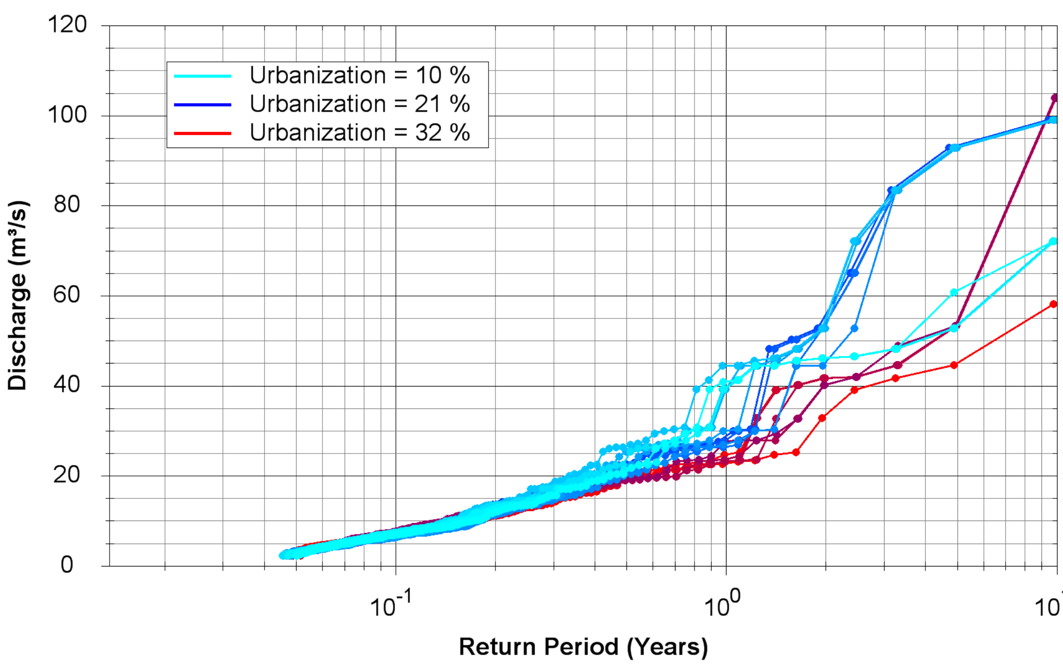


Figure F.20: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HC013 - Highland Creek near West Hill

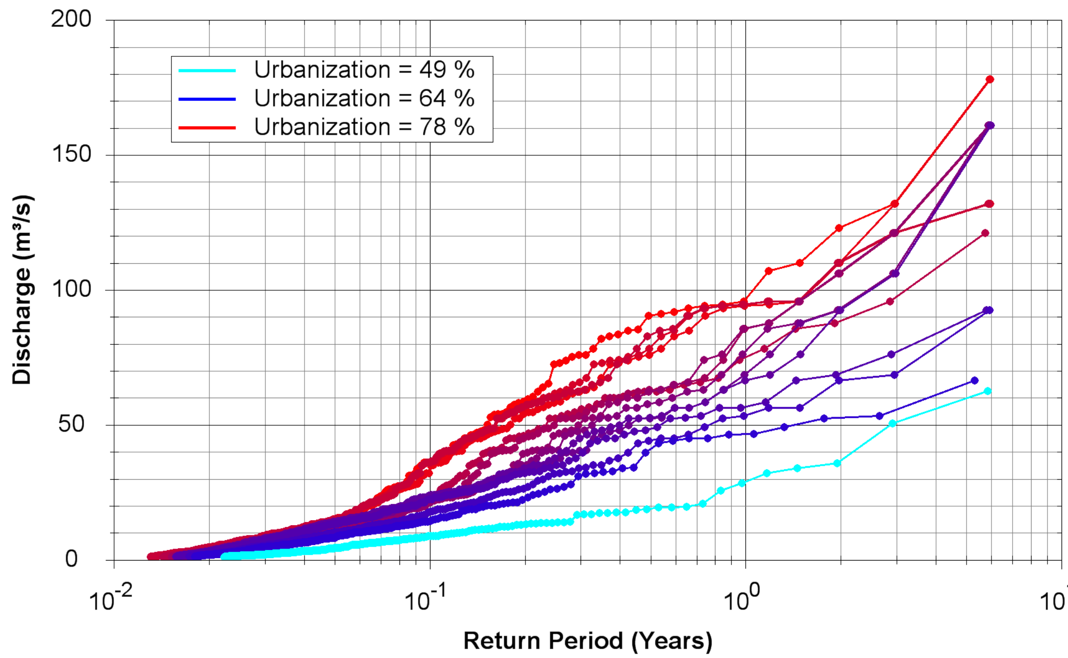


Figure F.21: Change in Event Return Period with Urbanization (5-Year Moving Window)

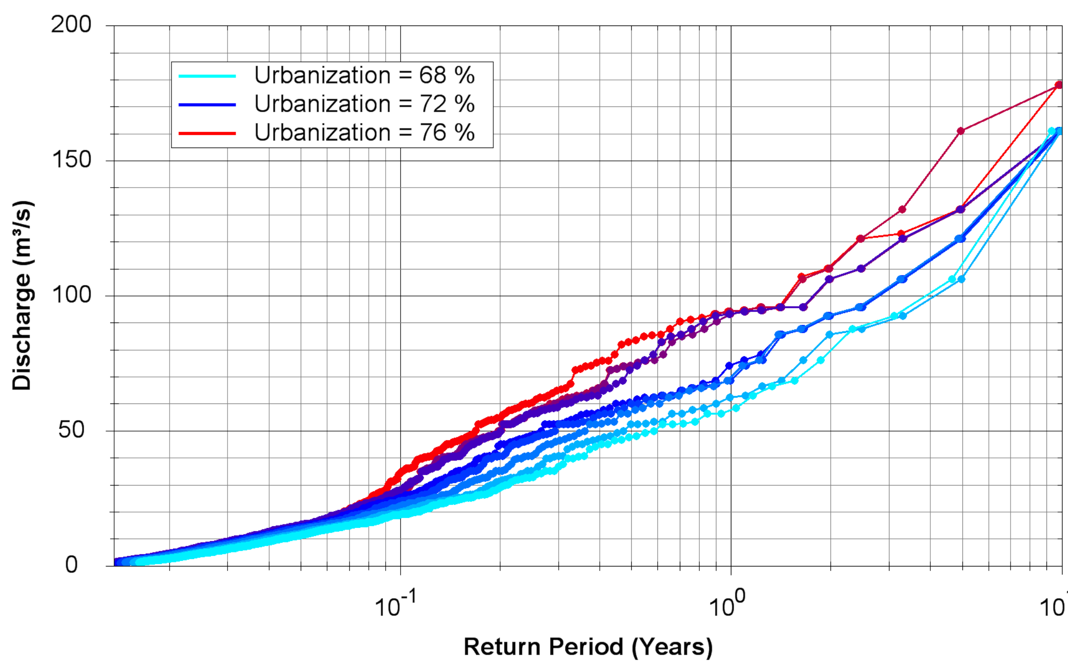


Figure F.22: Change in Event Return Period with Urbanization (9-Year Moving Window)

02HD013 - Harmony Creek at Oshawa

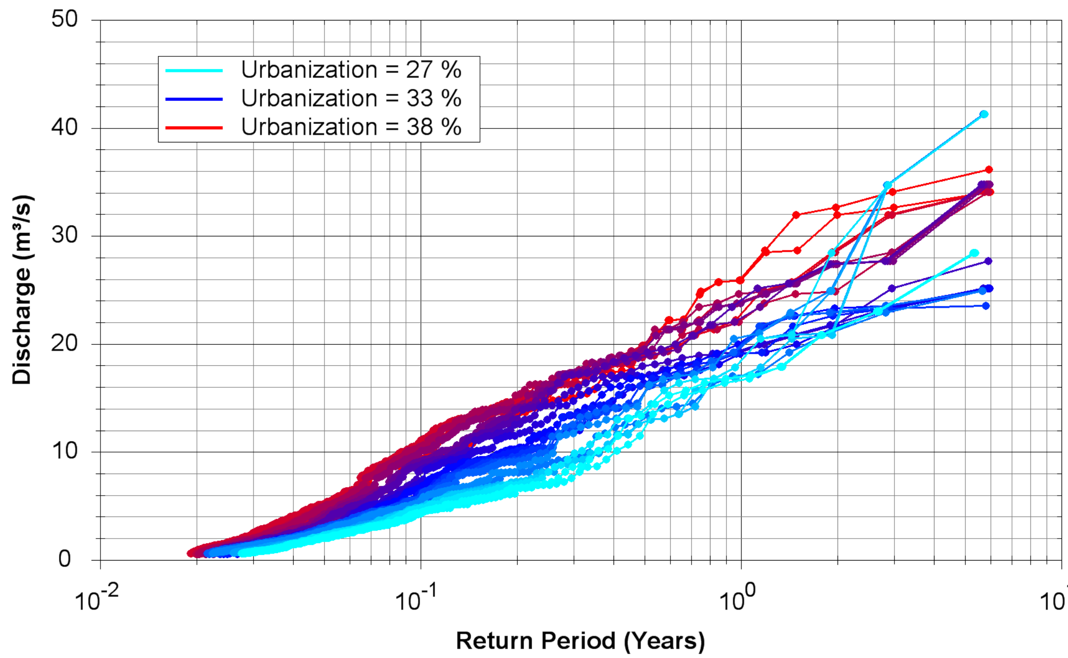


Figure F.23: Change in Event Return Period with Urbanization (5-Year Moving Window)

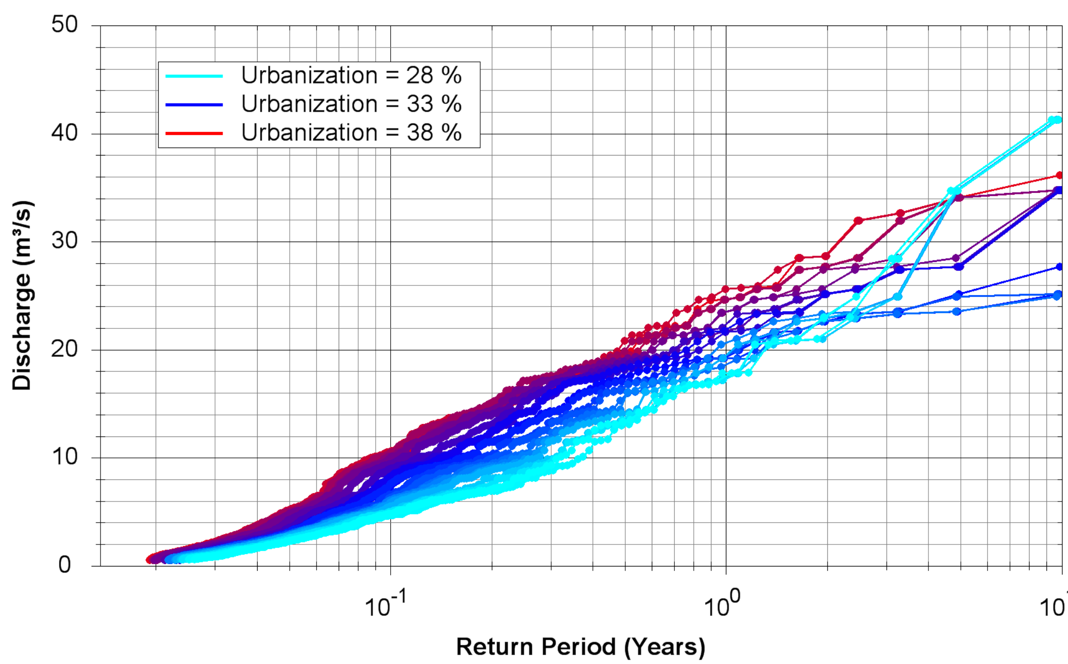


Figure F.24: Change in Event Return Period with Urbanization (9-Year Moving Window)