Relating Changes in Extreme Streamflow Events to Changes in Extreme Rainfall Events in Canada

by

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

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Abstract

The changes in extreme events caused by climate change are likely to have significant impacts in the future. It is expected that climate change will cause changes in rainfall intensities and magnitudes and consequently extreme streamflow events. Incorporation of nonstationarity and improved understanding of the changes expected to occur from climate change will lead to improved management of our water systems. In this study, the effects of climate change in Canada are examined; specifically changes in extreme rainfall are related with corresponding changes in flood events.

The Mann-Kendall non-parametric trend test was used to identify trends in Intensity-Duration-Frequency (IDF) data for various rainfall durations at stations across Canada. Although most of the IDF sites found with a significant trend were showing signs of increasing rainfall amounts, more streamflow sites were found to have a decreasing trend for both trends in the annual maximum and peaks over threshold streamflow event series. No increasing streamflow trends were found where a decreasing IDF trend was identified, however a decreasing streamflow trend was identified for increasing IDF trends of all duration lengths. Trends in the peaks over threshold streamflow series were similar to the annual maximum streamflow with a higher level of agreement obtained. Reviewing the seasonality of the sites supports that many of the streamflow sites that are decreasing in trend are from a nival snowmelt regime, and may be changing towards a mixed regime, making rainfall driven events more important. The number of peak streamflow events per year also was generally increasing across the country.

The majority of decreasing streamflow trends were a result of decrease in the spring freshet. After removing the snowmelt period, rainfall driven streamflow events were evaluated for trend and found to be mainly increasing. While the overall agreement in trend direction between the extreme rainfall and streamflow events increased, disagreement still occurred in the East Coast sites and much of southern Ontario, where unlike the rest of the country, a cluster of IDF stations experienced decreasing trends in extreme rainfall.

Acknowledgements

I would like to thank my supervisor, Dr. Don Burn for his continued support, guidance and patience.

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Dedication

I would like to dedicate this thesis to my Mom, Dad, and Bradley for their continued love, and encouragement.

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Chapter 1

Introduction

1.1 Background

Average global daily temperature rose 0.6 °C over the 20th century and is expected to rise between 1.4 and 5.8 °C over the 21st century (Lemmen & Warren, 2004). Karoly (2003) concluded that increasing atmospheric concentrations of greenhouse gasses and aerosols likely have caused the observed warming in North America between 1950-1999. Greenhouses gasses have been the largest contributor to radiative forcing causing global warming (Solomon, 2007). Concentrations of $C0_2$ in the atmosphere today have exceeded 400 ppm (C02Now, 2014), significantly higher than the range of 180-300 ppm, established for 650,000 years as the bounds of $C0_2$ due to natural variability (Solomon, 2007). As a result, since the 1950's, temperature has also increased beyond what can be explained by natural variability (Solomon, 2007). As depicted in Figure 1, climate models are able to demonstrate that the global and continental temperature changes over the 20th century are instead a result of the combination of natural variability and anthropogenic forcings (Solomon, 2007).

With climate warming, there will be changes to the hydrologic cycle. There will be changes in the intensity, frequency, and duration of rainfall events (Trenberth et al., 2003) as well as the temporal and spatial distribution of water (Burn and Taleghani, 2013). Wet regions will become wetter and dry areas dryer (Held and Soden, 2006). In theory, climate warming will cause an intensification of the water cycle as a result of increases in evaporation and precipitation (Huntington, 2006).

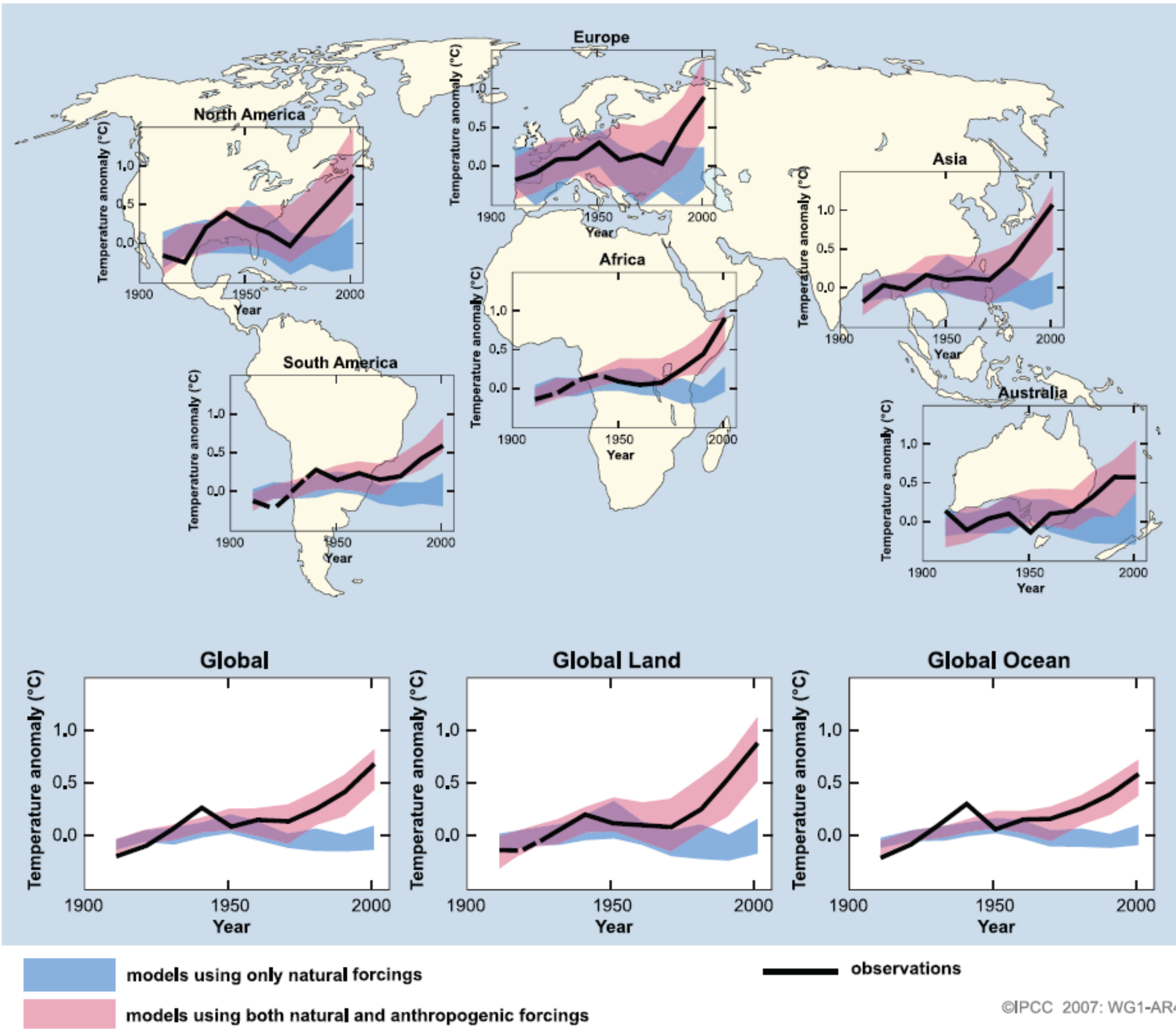

Figure 1. Global and continental temperature change explained by natural and anthropogenic forcings (Solomon, 2007).

With climate change, increases in extreme rainfall are expected to be greater than increases in mean rainfall (Burn and Taleghani, 2013). Since the 1970's there has been an observed increase in average moisture content of 4% (Coumou and Rahmstorf, 2012). As explained by the Clausius-Clapeyron equation, for every 1°C increase in temperature there will be a corresponding 7% increase in water holding capacity of the atmosphere (Trenberth *et al.*, 2003). Since extreme precipitation events occur when all of the air moisture is dispelled, there will be an increase in intensity of heavy events (Allen and Ingram, 2002). Climate models project under a doubling of CO_2 that global mean precipitation would increase only by 3.4%/°C due to constraints in the energy budget, however it is expected that the intensity of extreme events will increase at 6.5%/°C with the availability of moisture as a result of the Clausius–Clapyeron relationship (Allen and Ingram, 2002).

Stationarity is the assumption that "natural systems fluctuate within an unchanging envelope of variability" (Milly et al., 2008). It is common practice throughout the world for engineers to implement stationary-based designs and to operate and manage water systems under the assumption of stationarity (Milly et al., 2008; Vogel et al., 2011). However, stationarity no longer exists in today's natural systems because considerable anthropogenic change is altering the earth's climate and consequently the hydrologic cycle (Milly et al., 2008). Nonstationarity can result from changes in climate, land use, and water infrastructure (Vogel et al., 2011). Some challenges to studying stationarity in streamflow data are the contrasting impacts of different forcings and the existence of long-term persistence, a stationary process that can appear to cause nonstationary trend (Renard et al., 2008; Vogel et al., 2011).

Nonstationarities in extreme events can result from changes in the mean, the shape or variability of the probability distribution or a combination of these (Coumou and Rahmstorf, 2012; Lemmen and Warren, 2004). The World Meteorological Organization has stated that the recent decade of record breaking extreme events is in line with the changes anticipated by the Intergovernmental Panel on Climate Change (IPCC) (Coumou and Rahmstorf, 2012). This recent clustering of extreme events supports a change in the probability distribution more than just a shift in the mean and beyond that likely to occur by chance (Coumou and Rahmstorf, 2012).

Intensity-duration-frequency (IDF) curves are based on historical rainfall data at a location and are used for the design of water infrastructure. IDF curves and design rainfall will change as precipitation changes, and thus infrastructure designed with current or former IDF curves may not be appropriate under a changing climate (Burn and Taleghani, 2013). Return periods are the average time spacing between same-magnitude events and are used by engineers to determine design flow values for infrastructure. The return period of extreme events may decrease with climate change. Under a doubling of CO_2 scenario, return periods for extreme precipitation may reduce by a factor of 2 to 5 (Hennessy et al., 1997). An increase in extreme events will also lead to more flash floods, flooding in urban areas, and sewer overflows (Burn et al., 2011; Mailhot and Duchesne, 2010). Kundzewicz (2008) suggest a need for a new approach for design of water infrastructure under climate change, stating the existing procedures lead to under- or over-designing infrastructure. Mailhot *et al.* (2007) believe that expected changes in heavy rainfall should be incorporated into drainage design.

Changes in hydrology due to climate change will have socio-economic impacts on water resources, affecting many sectors from "water supply and sanitation, agriculture, energy, human health, settlements, infrastructure, industry, transportation, tourism, insurance and financial services, etc" (Kundzewicz et al., 2008). For example, hydroelectric power satisfies 2/3 of the country's energy demands. Changes to the distribution of water will likely increase hydroelectric generation in the north and decrease in Ontario due to lower levels in the Great Lakes (Lemmen and Warren, 2004).

Each year flood related disasters cost billions (USD) and kill thousands globally (Hirabayashi et al., 2013). Flood risk is determined by a combination of hazard, vulnerability, and exposure. Global flood risk is expected to rise due to climate change (Jongman et al., 2012), however results from climate models can be highly variable, ranging in one study of 21 models from -9% to 376% increase (Arnell and Gosling, 2014). Climate models have the potential to underestimate flood risk because they are based on changes in mean precipitation and do not consider changes in intensity and frequency of large rainfall events that could cause flooding (Arnell and Gosling, 2014).

Changes in floods in relation to climate change are complex. Floods can be caused by a number of factors depending on the region and current conditions. For example, soil saturation and infiltration capacity, rainfall intensity and frequency, rainfall accumulation and evaporation, snow accumulation and snowmelt are all factors that could impact flood response (Arnell and Gosling, 2014). Although there is a lot of evidence for changes in the timing of flood events, few studies have reported trends in the magnitude (Kundzewicz et al., 2013; Vogel et al., 2011). Due to the complexities surrounding flood response on a regional basis and insufficient evidence, the IPPC does not have the same confidence in changes in floods as it does for changes in precipitation (Field, 2012).

1.2 Objectives

It is established that increased greenhouse gasses due to anthropogenic changes is causing global warming and that the increase in temperature will have significant effects on the hydrologic cycle. Unlike temperatures, global climate models find a considerable amount of variability and uncertainty in projected global changes in precipitation due to regional variability and the complexity of weather patterns/mechanisms. Changes in flooding are even less clear due to regional effects and antecedent conditions. There is further uncertainty around changes in the extremes than in the means of these variables, due to changes in the probability distributions. Flooding is one of most expensive climate related disasters and can result from extreme precipitation. These extreme events can not only affect the management of water and water related infrastructure, but also the property and lives of people. The change in climate, combined with a growing population, deteriorating environment and evolving society will result in future challenges in water management (Kundzewicz et al., 2008). To understand future changes in climate, past changes must be studied (Zhang et al., 2001). Thus it is important to study not only the changes in extreme rainfall and streamflow, but how they relate to each other.

The objectives of this study are to improve the understanding of climate change in Canada through examining changes in extreme rainfall events and extreme floods, and to study the relationship between the two variables. Specifically, the changes in those variables will be examined through trend testing of historical data. This study expands on the research conducted by Burn and Taleghani (2012), by including more stations, increasing sample size, and conducting more analyses such as peaks over threshold and assessing rainfall driven streamflow trends. Changes in extreme rainfall and streamflow will be compared to determine factors that affect agreement between changes in these variables. In some cases, increased rainfall is resulting in an increase in flooding, while in other cases there may be a trend in the opposite direction of streamflow in relation to rainfall. This study examines both where there is agreement and disagreement between these changes and investigates what is unique about these situations. This is done by looking at factors such as the hydrologic regimes, watershed size and characteristics, and rainfall duration, as well as by isolating out only the rainfall driven streamflow events to compare directly to the changes in rainfall.

1.3 Thesis Organization

The contents of this thesis are organized into the following chapters:

- Chapter 2 provides a review of climate change studies in relation to precipitation and streamflow, with a focus on changes in extreme events and changes in Canada. This chapter also outlines some of the methods used for trend analysis and peaks over threshold analysis.
- Chapter 3 presents the methods used in this study.
- Chapter 4 introduces the study area and data used.
- Chapter 5 presents the results and discusses the findings.
- Chapter 6 summarizes the results and highlights some of the limitations and areas for future work.

Chapter 2

Literature Review

Chapter 2 provides a review of climate change studies in relation to precipitation and streamflow. These are introduced on a global scale and then discussed with a focus on changes in extreme events and changes in Canada. This chapter also introduces some of the methods used by researchers on trend analysis and peaks over threshold analysis.

2.1 Climate Change

2.1.1 Global climate change

2.1.1.1 Precipitation

Global climate models (GCMs) predict how precipitation will change globally under future conditions. Global climate models show a redistribution of precipitation, increasing at high latitudes and decreasing in the sub-tropical latitudes (Zhang et al., 2007). Additionally, precipitation at the equator is projected to increase (Allan and Soden, 2008). High latitude regions are predicted to experience more wet days while the number of wet days for mid-latitudes will decrease (Hennessy, 1997). Precipitation is expected to decrease where evaporation is high and increase where precipitation is already high due to increased specific humidities (Allan and Soden, 2008). While intense convective events in the mid and low latitudes will become more common, non-convective events at high latitudes will become heavier (Hennessy, 1997) while under a doubling of $C0_2$ climate models predict zonal mean precipitation increases up to 40% in some areas, global mean precipitation increases only by 10% (Hennessy, 1997). It is more difficult to attribute changes in precipitation to anthropogenic change on a global scale because regional changes can cancel each other out when averaged globally (Zhang *et al*., 2007).

As there are many aspects of precipitation that may be changing (i.e., timing, process, intensity, magnitude, etc.), many indices of precipitation have been used to evaluate changes in precipitation. To examine changes in precipitation intensity, Tebaldi *et al.* (2006) looked at a number of precipitation indices and found changes in the number of days with precipitation greater than 10mm and maximum 5-day precipitation to be the most significant and have the clearest spatial pattern (Tebaldi *et al.*, 2006). Alexander *et al.* (2006) examined several indices of precipitation over the 20th century and found that the most significant global increase occurred in the annual precipitation total, where an increase was observed in 37% of the stations. Increases were also observed in maximum daily rainfall, maximum 5-day rainfall, and the number of very wet days and extremely wet days. Significant differences in temperature and the various precipitation indices were observed between the first half and second half of the century, suggesting a widespread global trend of warming and wetting (Alexander *et al.*, 2006).

Emori (2005) found that the greater increase in extreme precipitation compared to mean precipitation was due to thermodynamic changes rather than dynamic changes (atmospheric moisture content rather than atmospheric motion). Emori (2005) found that globally the total change in mean and extreme precipitation (99th percentile) averaged 6% and 13% respectively, when comparing a 20-year baseline climate to a future climate a century later. Groisman (1999) applied a statistical precipitation model to Canada, US, Mexico, former Soviet Union, China, Australia, Norway, and Poland to assess changes in heavy summer month precipitation. Under a 5% increase in mean precipitation with no changes to the shape of the distribution and the probability of precipitation, most places observed an increase in heavy events of 20%. However, the distribution of extremes is changing. The increase in frequency of extreme events observed is characteristic of both a widening and shift in the probability distribution function (Coumou and Rahmstorf, 2012).

In Europe, a change in the structure of precipitation has been observed. In a study of nearly 700 gauges across Europe, precipitation was found to not only increase over the period of

1950 to 2008, but also to shift from shorter rain events into extended wet spells. These longer wet spells have intensified between 12% and 18% (Zolina *et al.*, 2010). It is these changes in the intensity and distribution of precipitation, as well as changes in the duration of sustained drought, that are likely to be more valuable in assessing impacts of climate change than looking at changes in mean precipitation (Allan and Soden, 2008).

Under CO_2 doubling scenario, GCM's predict a 9 mm/day increase in 20-yr return values. These 20 year events are becoming more frequent, with return periods in most parts of the world halved (Zwiers and Kharin, 1998). In another doubling of CO_2 study, precipitation intensity in Europe, USA, Australia and India increases by 10 to 25% and the average return period for different precipitation intensities shortens between 2 to 5 times (Hennessy, 1997). In northern Europe, design intensities will increase by 10 – 50% within the next 100 years, dependent upon duration and return period (Arnbjerg-Nielsen, 2008). Madsen (2009) looked at IDF data in Denmark and found a 10% increase in the average annual number of exceedances. Increases were larger for shorter durations while mean exceedances decreased for durations greater than 12 hours.

Some studies have linked variations in precipitation to decadal atmospheric circulation patterns and fluctuations in sea surface temperatures (Cayan, 1998). These account for 20%–45% of the annual precipitation variance (Cayan, 1998). Changes in these atmospheric circulation patterns have been observed and may be changing as a result of climate change (Trenberth, 2003). Recent increasing winter temperatures in North America and Eurasia are linked with the North Atlantic Oscillation (NAO), the Pacific–North American (PNA) teleconnection pattern, and El Niño–Southern Oscillation (ENSO) (Trenberth, 2003).

Wehner (2004) argues that changes in seasonal maximum precipitation have a greater impact on humans and natural systems, as the implications of larger snowstorms or seasonal disasters such as floods could be severe. In the mid latitudes, increases in winter return values were observed (Wehner, 2004). As the climate warms, the transient snow rain zone is shifting to a higher elevation (Surfleet and Tullos, 2013) and further north. Rain on snow events are decreasing in low and mid elevations and increasing in higher elevation (Surfleet and Tullos, 2013).

2.1.1.2 Streamflow

Increased precipitation and reduced evapotranspiration as a result of climate change will cause a global increase in river discharge (Hirabayashi et al., 2008). Increases in streamflow have already been observed across the United States since the early 1940s (Lins, 1994). While there is considerable agreement about changes in temperature as a result of climate change, there is less confidence in changes in precipitation, and even further uncertainty in changes in streamflow.

Vogel *et al.* (2011) examined flood magnification factors in streams across the US from regulated, unregulated, and pristine (USGS Hydro-Climatic Data Network) sites. Flood magnification factors are expressed as the ratio of the T-year flood in a future time period to the T-year flood today. Flood magnification factors were much greater for the non-pristine locations that experience a variety of anthropogenic influences (Vogel et al., 2011).

Climate change can result in changes in the magnitude, timing, and frequency of streamflow events. While some areas, such as the Mediterranean, are seeing decreases in magnitude of large floods due to a decrease in precipitation, other areas are seeing an increase in flood magnitude from an increase in precipitation: humid tropical Africa, south and east Asia, much of South America, and in high latitude Asia and North America (Arnell and Gosling, 2014). Larger return periods were found to experience more substantial increases in magnitude of flood events (Arnell and Gosling, 2014). In central Europe and north eastern North America, an increase in rain is causing a decrease in flood magnitudes. This comes as a result from a shift from snow to rain, reducing snowmelt (Arnell and Gosling, 2014). In high latitude rivers, an increase in annual streamflow does not necessarily correspond to an increase in flood magnitude since the annual maximum streamflow is driven by snowmelt

(Hirabayashi et al., 2008). Snowmelt regions are also experiencing changes in event timing. While some areas experience an earlier snowmelt and thus an earlier peak flow, other areas are experiencing a shift in flood season, where summer rainfall events are becoming a more important driving factor of peak flow (Hirabayashi et al., 2008)

Arnell and Gosling (2014) found a similar pattern of change in the return period of the 100-year flood as for the magnitude. Across 40% of world, return periods will occur twice as often in 2050 (Arnell and Gosling, 2014). Milly (2002) looked at 100 year floods in large drainage basins (>200,000km^2) and found that under a quadrupling of $C0_2$ there can be dramatic changes in flood frequency. All but one basin saw a decrease in return period, and half of the study basins had a 100-year return period occurring every 12.5 years or less (Milly, 2002). Hirabayashi *et al.* (2008) found that the return periods of floods decrease in most parts of the world, with the exception for parts of North America and central and western Eurasia.

The effects of climate change on floods is not always simply a function of precipitation changes. Lins and Michaels (1994) have suggested that an increase in cloud cover could result in reduced evaporation and explain the increasing winter streamflow observed in the US between 1941 and 1988 without an observed increase in precipitation (Lins and Michaels, 1994). While in some places floods may result from heavy precipitation, other areas depend more on antecedent soil conditions, and thus accumulated rainfall and evapotranspiration have a larger influence on flooding than changes in intense rainfall. Flood events may also depend on snowmelt and be influenced by accumulated snowfall and changes in temperature that alter the time of the peak freshet (Arnell and Gosling, 2014). Hirabayashi *et al.* (2008) found that even with increased precipitation and discharge, and reduced evapotranspiration, the number of drought days can still increase due to changes in precipitation patterns.

The limited number of long term daily streamflow observation records makes analyzing historical trends challenging (Hirabayashi et al., 2008). Conversely, using GCM's to predict future changes in flooding is challenging do to the inability of GCM's to consider the effects of anthropogenic water usage (Hirabayashi et al., 2008). These models also do not account for the redistribution of precipitation into larger events, or changes in the frequency or spacing of precipitation events (Arnell and Gosling, 2014). Although CGM's may provide great foresight into changes in monthly means and annual variability, their inability to replicate future storms on an event basis limits their ability to estimate changes in flooding, and may result in an underestimation (Arnell and Gosling, 2014).

2.1.2 Climate Change in Canada

2.1.2.1 Hydrologic regimes in Canada

Whitfield and Cannon (2000) conducted one of the most extensive studies on variation in hydrology and climate in Canada, incorporating 642 hydrologic stations. The focus was on recent changes in temperature, precipitation, and corresponding changes in streamflow, comparing changes across two decades (1976-1985, 1986-1995). In examining mean daily streamflow records, they observed four types of hydrographs in Canada. Streams with the largest streamflow event in March or April, low summer flows, and higher flows in the fall were observed in southern Ontario and Quebec, New Brunswick and Newfoundland. These "mixed" regimes have both snowmelt driven events in the spring and rainfall events later in the year. Many stations in western Canada experience a large summer freshet that lasts several months as the snowmelt period is drawn out over a long time because the changes in elevation contribute to the longer lasting effect. In the Prairies and interior plateaus of British Columbia, these snowmelt (nival) driven systems have a more defined sharp peak. Rainfall (pluvial) driven systems were found to occur in regions along the coast in British Columbia and Nova Scotia. In these sites multiple peaks occur during a rainy season and snow pack does not accumulate for long periods (Whitfield and Cannon, 2000).

2.1.2.2 Changes in Precipitation in Canada

Annual precipitation has been increasing across Canada. Annual precipitation has increased in southern Canada by 13% from 1890 to 1990 and by 20% in northern Canada from 1950 to 1990 (Groisman and Easterling, 1994). Despite a small overall increasing trend in annual precipitation observed in the Prairies from 1966-2005, annual snowfall has experienced a decreasing trend. This suggests a shift from snow to rain (Burn *et al.,* 2008). In the Maritimes, the opposite is observed. Increasing snowfall suggests more winter storms on the east coast (Vincent and Mekis, 2006).

Whitfield and Cannon (2000) identified seasonal changes in precipitation for different regions in Canada. They made six groupings of changes in monthly precipitation totals across Canada between the two decades 1976-1985 and 1986-1995:

- Slight decreases throughout most of the year, increases in August (Maritimes)
- Increases throughout most of the year (except August) (Northwest Territories, Nunavut, and the northern coast of British Columbia)
- Increases in the winter and decreases in September and October (south coast of British Columbia)
- Increases during summer and late fall, decreases in September to December (located in the prairies, Ontario, and Quebec)
- Increases during April and November, decreases in May, August and September (south-central British Columbia with a band across the center of western Canada)
- Increases in late fall, decreases in December, spring and summer (Ontario, Quebec, and the Maritimes).

Mailhot *et al.* (2012) used climate models to assess and predict changes in maximum precipitation for different return periods and durations. Comparing the historical period (1968-2000) to future period (2041-2070), the largest increases in annual maximum precipitation occurred in southern Ontario and southern Quebec, and the Prairies. The Great Lakes and St Lawrence region will experience the greatest impact, with the annual maximum precipitation for the 20-year return period increasing by 25% for all durations (Mailhot *et al.*, 2012). The Prairies were most affected by changes in event timing, but least affected by changes in event frequency (Mailhot *et al.*, 2012), contrary to the findings of Mailhot *et al*. (2010).

Mailhot *et al.* (2010) simulated daily, multiday, and seasonal annual maximum precipitation in Canada for the period of 1850-2100 using the Canadian Global Climate Model. Increasing trends were found in daily and multiday annual maximum precipitation. Seasonally, fewer summer events were found while more fall and spring events were predicted. The frequency of events changed substantially in many locations, with return periods decreasing by half in Quebec and Northern Canada, and reducing to as little as a fifth for some west coast areas. In Ontario, bimodal seasonality is developing, with the maximum probability of annual maximum events tending towards occurring in May and November (Mailhot *et al.*, 2010).

Burn and Taleghani (2013) applied bootstrap analysis in their study on design precipitation to determine how different the most recent 20-year and 30-year portion of the record are to the full period of record. Longer duration events were found to have more increasing trends and larger magnitude increases than shorter duration events (Burn and Taleghani, 2013). Short duration storms saw fewer significant increasing trends in the more recent period of record (Burn and Taleghani, 2013). Return periods have decreased by as much as half, especially for durations larger than 30 minutes (Burn and Taleghani, 2013). Disagreeing trends in rainfall magnitudes within close proximity, as observed in southern Ontario, emphasize the need to evaluate climate change on a local basis (Burn and Taleghani, 2013).

Contrary to findings of Burn and Taleghani (2013), a study focusing on annual maximum rainfall in 5 regions within Ontario found it was the shorter duration events that had more significant trends (Adamowski and Bougadis, 2003). While the northern region experienced increasing trends in all 8 durations (5 minutes to 24 hours), the St Lawrence region experienced only decreasing trends (Adamowski and Bougadis, 2003). The southern area experienced mainly decreasing trends, while the central region experienced mainly positive trends (Adamowski and Bougadis, 2003). Very few significant trends were found for durations greater than 10 minutes (Adamowski and Bougadis, 2003).

A few studies in Canada have used a peaks over threshold (POT) approach to study changes in precipitation in Canada. Burn *et al.* (2011) selected thresholds based on the 90th percentile when studying design storms in BC. With the exception of the daily maximum event, the other smaller events (1hr to 12hr) experienced more decreases (Burn *et al.*, 2011). The number of events per year exceeding the threshold was found to be increasing in most cases (Burn *et al.*, 2011). Stone *et al.* (2000) also used a POT approach to assess trends in precipitation intensity for light, intermediate and heavy events across Canada. Significant trends in the more intense events supports a shift to more intense precipitation (Stone *et al.*, 2000).

In northern Canada the frequency of heavy daily winter precipitation has increased between 1950 and 1990 (Stone *et al.*, 2000). While some of Stone *et al.'s* (2000) findings support climate change arguments, other findings in the study attribute changes to natural variability caused by teleconnections. When the Pacific North American pattern is in a negative phase, more extreme precipitation is identified, particularly in the fall and winter in Ontario and southern Quebec (Stone *et al.*, 2000).

2.1.2.3 Changes in Streamflow in Canada

Despite many predictions for increased precipitation in northern Canada, some studies have observed decreasing streamflow trends in these areas. Déry (2005) studied trends in annual streamflow at 64 rivers discharging in northern Canada. Between 1964 and 2003, streamflow to the Artic and North Atlantic Ocean was found to decrease 10% (22mm/year), corresponding to a 21 mm/year decline in precipitation over the same time period. The decreasing precipitation trend was linked to changes in El Nino/Southern Oscillation and the

Pacific Decadal Oscillation, suggesting teleconnections may be more of a driver than climate change for the reduction (Déry 2005).

Rood *et al.* (2005) studied rivers in western Canada discharging to the Pacific, Atlantic, and Arctic Ocean, and found that two thirds of the rivers had a significant decline in mean annual discharge, reducing 20% over 100 years (Rood *et al.*, 2005). Mean annual streamflow across southern Canada has decreased over the second half of the 20^{th} century, corresponding to increases in temperature and nearly no change in precipitation over the same period. With the increase in temperature, snowmelt occurs earlier and more gradually, causing reduced peak flows. Since the majority of rivers in Canada are snowmelt driven, annual maximum streamflow is decreasing across most of southern Canada (Zhang *et al.*, 2001).

Whitfield and Cannon (2000) found that across Canada, small changes in temperature and precipitation caused substantial changes in streamflow. The following regional patterns of change in streamflow were observed between 1976-1995 (Whitfield and Cannon, 2000):

- The boreal shield and boreal plains experienced decreasing year round streamflow as a result of warmer, drier conditions
- Northwestern Canada experienced increasing year-round streamflow as a result of warmer and wetter conditions
- North BC and the Rocky Mountains experienced higher winter flows, earlier spring peaks, lower summer flows as a result of warmer, wetter winters
- The Maritimes experienced lower late winter flows, earlier spring runoff, and lower streamflow following the peak snowmelt that can be linked to cooler winters
- Southern Ontario, Quebec, coastal BC experienced higher winter flows, later spring peaks, and lower summer flows due to warmer, wetter winters
- Southcentral British Columbia experienced lower flows through the late summer and fall, preceded by an earlier spring peak

Burn and Hag Elnur (2002) identified considerably more trends in the magnitude of annual maximum flow than could be expected by chance as determined by a bootstrap analysis. They used the Mann-Kendall trend test on natural rivers as identified by the Reference Hydrometric Basin Network (RHBN), on gauges with a minimum period of record of 25 years. These trends also had a distinct spatial pattern, increasing in the north and decreasing in the south (Burn and Hag Elnur, 2002).

Burn *et al.* (2010) separated the spring snowmelt period out of stations in a mixed regime, to assess annual maximum spring and non-spring events independently. For the non-spring period, it was assumed all maximum events were rainfall driven and both the magnitude of these events and the number of rain high flow events were assessed using a peaks over threshold method (Burn *et al.*, 2010). A significant number of decreasing trends were found for both the annual maximum flows and spring maximum flows along with an earlier occurrence of events. The number of rainfall driven events was generally found to be increasing (Burn *et al.*, 2010). Spatially, these trends were found in eastern and central Canada, while some decreasing trends were found in western Canada. There were few significant trends in the magnitude of annual rainfall events, perhaps due to the nature of the watersheds selected, having minimal impact from urbanization (Burn *et al.*, 2010).

There is a shift from a snowmelt driven maximum flow in the spring, to a maximum flow event occurring from a rainfall event in a rainy season. This is due to reduced snowfall and increased rainfall under climate change (Burn *et al.*, 2010). When comparing the earlier portion of the dataset to the later portion, this shift is evident given changes in the frequency of event timing (spring snowmelt and rainy season) (Burn *et al.*, 2010). For pluvial sites that do not have a significant snowmelt contribution, the timing of events was still found to shift, with the later portion of the record experiencing delay in event timing (Burn *et al.*, 2010).

Cunderlik and Ouarda (2009) also studied snowmelt and rainfall driven streamflow separately for trends. They examined trends at 162 stations across Canada between 1974 and

2003. Nearly 90% of sites experienced an earlier occurrence of spring snowmelt events, 10% of which were statistically significant. The 14 stations with significant decreasing trends were grouped in southeastern Canada, while the 2 significant positive trends were found in the northwest. The average rate of the negative trends, -1day/year, meant that in the 30-year period spring events were occurring 1 month earlier. A significant trend in the magnitude of spring events was found at 17% of sites, the majority of which were decreasing (Cunderlik and Ouarda, 2009). In the fall rainfall season, no significant trends were found in both the timing and magnitude of events (Cunderlik and Ouarda, 2009). However, the development of these trends in bimodal flood is only recently developing (Cunderlik and Ouarda, 2009).

2.2 Methods

2.2.1 Trend Analysis

While change in hydrologic data can occur gradually as a trend, it can also occur as a step change. It is important to examine results carefully and determine if an identified trend is the result of climate change, land use, or other physical changes, or from quality issues such as: changes in measurement practice or location; typographical errors; instrument malfunction (zero-drift, bias); or in data conversions such as rating curves (Kundzewicz and Robson, 2004).

There are many tests for change points. The student's t test and Worsley likelihood ratio test are appropriate for normally distributed data and identify changes in the mean. The Worsley likelihood ratio is preferred over the student's t test when the timing of the change point is unknown. Another test based on normality assumption is the cumulative deviation test, which uses cumulative deviations from the mean to test for homogeneity. There is also a rank based distribution "CUSUM test." Since hydrologic data are rarely normally distributed, distribution free tests are more appropriate. Other ranked based tests for change points include the Wilcoxon-Mann-Whitney test and the Pettitt test. The Wilcoxon-Mann-Whitney test compares subsets of a series to identify the point of change in the mean between two independent sample groups. It assumes the time of change is known. The Pettitt test looks for changes in the median of a series. The Pettitt test is preferred over the Wilcoxon-Mann-Whitney test when the time of the change point is unknown (Kundzewicz and Robson, 2004).

Some change point tests, such as the Bayesian change point (BCP) (Erdman and Emerson, 2007) method are capable of finding multiple change points. Bayesian analysis requires a posterior probability – where a prior probability is assigned to a hypothesis, then the data are used to inform the model (Friedman *et al.*, 2016). The BCP tool will first check the data for normality and then assesses whether the "posterior probability that the entire series is drawn from the same distribution is higher than the posterior probability that different segments of the series are drawn from different distributions" (Friedman *et al.*, 2016). Some limitations of the BCP are that it does not handle short time series or small changes in magnitude well (Friedman *et al.*, 2016).

There are also many tests used for trend detection. One of the most common tests for trend is linear regression: however linear regression assumes data are normally distributed. Two common rank based tests which don't require normality in the data are the Spearman's rho and Mann-Kendall test. There is also a seasonal version of the Mann-Kendall test that can handle seasonality in the data. Other regression tests, such as M-estimates of regression, can also be used to detect trend (Kundzewicz and Robson, 2004). The Mann-Kendall trend test has been used in several climate change studies of hydrologic variables (i.e., Adamowski et al., 2010; Burn et al., 2010; Mailhot et al., 2010; and Zhang et al., 2001).

A common challenge with trend testing is dealing with correlation. The spatial fields of atmospheric and hydrologic data often exhibit strong spatial correlation which can raise the issue of field significance. While each individual trend test is conducted at a local significance level (α_{local}), evaluating the results of the multiple tests is more complicated (Wilks, 2006). When cross-correlation is present in the data, it increases the expected number of trends (Burn and Hag Elnur, 2002). If each of K local null hypotheses that there is no trend are true, on average Kα_{local} of them will be erroneously rejected and trends will be identified (Wilks, 2006). Field significance tests determine the percentage of trends expected to occur by chance at a given location (Burn and Hag Elnur, 2002). Wilks (2006) compared three different methods for field significance: the counting test, Walker's test, and the false discovery rate, of which the latter two are resampling approaches. The false discovery rate was found to be the preferred test as the counting test was unable to handle correlation as well and resulted in many false rejections, while the Walker test only identified the most significant local tests (Wilks, 2006).

Autocorrelation or serial correlation is present when an observation directly depends on one or more previous observations plus a white noise term (Hipel and McLeod, 1994). Yue et al (2002) used a Monte Carlo simulation to demonstrate that positive serial correlation can inflate the variance of a series and as a result increase the chance of type I error (detecting a trend when there is none). They compared a variety of techniques to the Mann-Kendall test to evaluate their performance in dealing with AR (1) correlation. The von Storch Pre Whitening approach removed some of the trend when the pre-whitening was done leading to an underestimation of trends, while the Variance Correction Approach (VCA) resulted in higher Z values, leading to poorer results than the original Mann-Kendall trend test. The Trend Free Pre-Whitening approach was the found to be the best method for dealing with AR (1) in series while detecting trends (Yue et al., 2002).

2.2.2 Peaks over Threshold

Trends in block maximum precipitation and streamflow events are studied much more commonly than trends in floods identified using a peaks over threshold (POT) approach. A common block size used in hydrology is 1 year, representing the annual maximums. Smaller block sizes result in more data for analysis, while a larger block size reduces model bias (Engeland et al., 2004). Therefore, there is a trade off when selecting the block size (Engeland et al., 2004). A limitation to an annual maximum approach is that the annual maxima are not always true extremes (Engeland et al., 2004). A peaks over threshold approach allows for better selection of extreme events as it uses more data and is not restricted to having one event per year. This “allows for a more rational selection of events to be considered as “floods”” (Lang et al., 1999). A flood defined by the annual maxima may not even be considered a flood under the peaks over threshold method (Lang et al., 1999). When an entire time series of data is available, the POT is the preferred approach because an annual maximum would result in a substantial loss of information (Solari and Losada, 2012). Lang *et al.* (1999) consider the POT method to be a compromise between the annual maximum approach and time series modelling. The peaks over threshold method also offers more functionality, as it can be used to analyze the magnitude, timing, and frequency of events (Lang et al., 1999).

The POT has been identified as the preferred method when an entire time series is available, having numerous advantages over the annual maxima method. However, the added flexibility comes with additional complexity (Lang et al., 1999). The lack of a standardized methodology, the subjectivity in threshold selection, and the difficulty to automate the process (Solari and Losada, 2012) have resulted in the method being unpopular and under-implemented (Lang et al., 1999). The method described by Coles (2001) cannot be automated and requires human judgment, which adds a level of subjectivity (Solari and Losada, 2012). One shortfall is the need for a predefined threshold to define the data series. Afterwards the location parameter of the Generalized Pareto distribution is essentially the threshold (Solari and Losada, 2012). While the annual maxima approach naturally results in a series of identically distributed flood events, not all thresholds can satisfy the independence and distribution of flood events requirement of the distribution (Lang et al., 1999).

In general, block maxima are independent and identically distributed (iid). According to extreme value theory the maxima or minima of an iid series tends to follow a Generalized Extreme Value (GEV) distribution (Solari and Losada, 2012). In addition to the GEV, annual maxima have been fitted to several distributions including Log-Pearson type III, log-normal, Generalized Pareto (GP), Weibull and more (Engeland et al., 2004). Extreme value theory also states that when a high threshold is chosen for a series of iid data, the values exceeding the threshold tend to follow a Generalized Pareto distribution (Solari and Losada, 2012; Coles 2001). This is the theoretical foundation of the peaks over threshold method for modelling extreme values. In hydrology, these peak over threshold series have been fitted to gamma, Weibull, lognormal, GP, exponential distributions and others (Engeland et al., 2004).

The cumulative distribution function for the GEV is defined as

$$H_{\xi,\mu,\sigma}(x) = \begin{cases} exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]\right\} & if\ \xi \neq 0 \\ exp\left\{-exp\left(\frac{x-\mu}{\sigma}\right)\right\} & if\ \xi = 0 \end{cases}$$

where $1+\xi\left(\frac{x-\mu}{\sigma}\right) > 0$, and ξ, μ, σ are the shape parameter, location parameter and scale parameter respectively (Engeland *et al.*, 2004).

The cumulative distribution function for the Generalized Pareto (GP) distribution is

$$G_{\xi,\beta}(x) = \begin{cases} 1-\left(1+\xi\frac{x}{\beta}\right)^{-\frac{1}{\xi}} & if\ \xi \neq 0 \\ 1-exp\left(-\frac{x}{\beta}\right) & if\ \xi = 0 \end{cases}$$

where x are the excesses over the threshold, ξ is a scale parameter and β a shape parameter (Engeland *et al.*, 2004).

Consecutive flood events often come from the same flood generating process or storm event or can be related due to long term storage (Engeland *et al.*, 2004). The degree of basin saturation from an earlier event can play a role in a subsequent peak event. Since the second event is partly dependent on the first event, selecting an inter-event duration can be complex and subjective (Lang *et al.*, 1999). Having an independent series is necessary to perform statistical frequency analysis on the data (Lang *et al.*, 1999). To address the dependency, the most commonly accepted practice is to decluster the data (Solari and Losada, 2012).

The method most commonly used by hydrologists and coastal engineers to decluster data involves specifying a time period between which all peaks are considered to be generated by the same event. These time periods are known as “clusters” and only the highest value recorded for each cluster is selected to form the POT series (Solari and Losada, 2012). An initial threshold is required to determine peak events and a time period to define clusters (Solari and Losada, 2012). The Water Resource Council (USWRC, 1976) sets out two criteria for inter-event dependence. The first requirement is that the time between events (in days) must be at least 5 plus the natural logarithm of the drainage area in square miles (Lang et al., 1999). The second requirement is that flow between two peak events must drop below 75% of the lowest peak for the two peaks to be counted as separate (Lang et al., 1999). Engeland *et al.* (2004) had a less formal method and studied the streamflow from Haugland River to determine that a 2-day inter-event duration was appropriate to remove dependencies. To ensure that the appropriate time span has been selected, the autocorrelation of the POT data series should not be significantly different from zero and the occurrence of peaks must satisfy the Poisson hypothesis. Spearman’s rank correlation can be used to estimate the lag one autocorrelation and a dispersion coefficient can be used to determine if the Poisson hypothesis is satisfied (Solari and Losada, 2012).

There is no standard method for threshold selection. Thresholds can either be selected based on physical criteria or mathematical and statistical considerations (Lang *et al*., 1999). Some researchers suggest selecting a threshold to fix the average number of peaks per year based on geographic region or climate conditions (Lang *et al*., 1999). Some guidance on this approach is to use a return period of 1.15 years (Dalrymple, 1960), or 1.2-2 years for Canadian rivers (Waylen and Woo, 1983; Irvine and Waylen, 1986). Cunnane (1973) showed that for POT with exponentially distributed peaks, the mean number of peaks should be greater than 1.65. Another approach is to use a fixed quantile with a high nonexceedance probability, such as the 95th or 99th percentile (Solari and Losada, 2012). Other researchers have used standard frequency factors, such as Rosbjerg and Madsen (1992) who calculated thresholds based on the mean and variance of daily discharge series (Lang *et al.*, 1999).

Other methods for threshold selection include the graphic method (GM) and optimal bias robust estimation (OBRE) method. The GM approach selects thresholds that will result in stable scale and shape parameters of the GPD. The OBRE is an M estimator that assigns weight to the data used in parameter estimations (Solari and Losada, 2012). While the GM provides a straightforward approach making it easy to implement, it involves human judgement and is difficult to automate (Solari and Losada, 2012). To implement the GM, the mean excesses and/or scale and shape parameters should be plotted against a range of thresholds. The first plot is known as a Mean Residual Life Plot (MRLP), and can be more difficult to interpret than the scale and shape parameter plots (Coles, 2001). The MRLP is constructed as

$$\left\{\left[u, \frac{1}{n_u}\sum_{i=1}^{n_u}(x_i - u)\right] : u < x_{max}\right\}.$$

where n_u is the number of observations x above the threshold u, x_i is the i^{th} observation above the threshold μ, and x_{max} is the maximum of the observations x (Ribatet, 2006). The MRLP should be linear for $u>u_0$ and the scale and shape parameter plots should be constant for $u>u_0$, where u_0 is the desired threshold corresponding to a good approximation of the data by the GPD (Solari and Losada, 2012). It is also recommended to use the standard errors of the estimated parameters, qq-plot (Miquel, 1984; Engeland *et al.*, 2004), probability plots, return level plots, and density plots (Coles, 2001) to aid in threshold selection.

Another threshold selection method is to satisfy the Poisson peak count hypothesis. A threshold is selected that results in a dispersion index equal to 1 (Lang *et al.*, 1999).

Choosing a threshold that satisfies the Poisson hypothesis and meets exponentially based tests can be challenging (Lang *et al.*, 1999).

Chapter 3

Methodology

Chapter 3 presents the methods used in this study. The Mann-Kendall trend test was used to test for trends in climate data. These trends were validated by also testing for change points in the time series. While these tests determine changes in the magnitude (and variability in change point), a streamflow analysis was used to look at event timing and to determine changes in event timing. A peaks over threshold analysis was conducted to define appropriate thresholds above which all events are considered to be an independent time series of extreme events. To examine exclusively rainfall driven streamflow events, the snowmelt period was removed from the time series; a snowmelt period was defined for each site. This chapter describes these methodologies.

3.1 Mann-Kendall Trend Test

Trends in extreme rainfall and streamflow events were analyzed using the Mann-Kendall trend test at both 5 and 10% significance levels. The Mann-Kendall test statistic for a data series of length n is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \tag{3.1}$$

where

$$sgn(\theta) = \begin{cases} 1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{3.2}$$

and X_i and X_j are sequential data points (Burn and Hag Elnur, 2002). The standardized test statistic Z is calculated to determine if trends are significant

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \theta > 0 \\ 0 & \theta = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \theta < 0 \end{cases} \tag{3.3}$$

The variance of S is described by

$$V(S) = \left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j \left(t_j - 1\right)\left(2t_j + 5\right) \right\} / 18 \tag{3.4}$$

where p is the number of tied groups and t_j is the number of data points in the j^{th} tied group. The expected value of S is equal to 0.

The trend slope, β, is estimated using the Theil-Sen approach (Theil, 1950; Sen, 1968)

$$\beta = median\left\{\frac{X_i - X_j}{i - j}\right\} \qquad \text{for all } i < j \tag{3.5}$$

where X_i and X_j are consecutive data points.

To account for serial correlation in the data, the trend free pre-whitening approach developed by Yue *et al*. (2002) is used. A linear trend T_t is removed from the sample data X_t to obtain the detrended series Y_t

$$Y_t = X_t - T_t = X_t - \beta t \tag{3.6}$$

The detrended series is then assessed for serial correlation. If the lag-1 correlation coefficient is not significantly different from zero, the series is not correlated and the Mann-Kendall trend test can be directly applied to the original series, X_t. If the lag-1 correlation coefficient is significantly different from zero, the data are serially correlated and the autoregressive-1 process is removed through pre-whitening. The residuals are found to be

$$Y_t' = Y_t - r_1 Y_{t-1} \tag{3.7}$$

where r_1 is the serial correlation at lag 1. The residuals of autoregressive-1 model are assumed to be independent.

The linear trend of the original data series is added onto the detrended residuals to create the blended series.

$$Y_t'' = Y_t' + T_t \tag{3.8}$$

The Mann-Kendall trend test is applied to the blended series as it no longer contains serial correlation but has not altered the true trend (Burn *et al.*, 2004; Yue *et al.*, 2003).

3.2 Change Point Analysis

The Pettitt test is used to detect changes in the mean of the data series (Pettitt, 1979). A change point is found when two different distribution functions exist for a data series before and after a point. The test is limited to finding only one change point per series and where multiple change points exist, will identify only the location of the largest change in mean (Pettitt, 1979). Since the test can be used when the locations of the change points are unknown, it is preferred to the Wilcoxon-Mann-Whitney test (Kundzewicz and Robson, 2004). The test is also less sensitive to data outliers and skewed distributions (Villarini et al., 2011), which was observed after comparing results of the Pettitt test to those found using the BCP Bayesian change point method in R (Erdman and Emerson, 2007).

Let $X_1, X_2, \ldots, X_T$ be a data series and $F_1(X)$ be the distribution function for the series up to point τ, and $F_2(X)$ be the distribution function for the series after point τ. For a change point to exist, $F_1(X) \neq F_2(X)$. To test if a change point exists, a non-parametric statistical test is set up using a hypothesis test, with the null hypothesis being $H_0: \tau = T$, and the alternative hypothesis being $H_1: 1 \leq \tau < T$. $U_{t,T}$ is equivalent to the Mann-Whitney statistic,

$$U_{t,T} = \sum_{t=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j) \tag{3.9}$$

where sgn(θ) is described in equation 3.2. The test statistic, K_T, and the significance probability, P, are computed as:

$$K_T = \max_{1 \leq t < T} \left| U_{t,T} \right| \tag{3.10}$$

$$P = -2 \exp\left\{ \frac{-6{K_T}^2}{T^3 + T^2} \right\} \tag{3.11}$$

A large value of K_T will indicate a change in the mean. The existence of a change point can be confirmed by comparing P to the significance level, α (Pettitt, 1979). If $P < \alpha$, the null hypothesis should be rejected and alternative hypothesis accepted, meaning a change point occurs in the data. If $P > \alpha$ then the null hypothesis of no change point occurring is accepted. The Pettitt test was performed at both 5 and 10% significance levels.

3.3 Seasonality Analysis

The timing and regularity of streamflow events can characterize the seasonality of a site. Using the method described by Burn *et al.* (2010), the mean event date, MD, is determined by first converting each event date to an angular value (in radians)

$$\theta_i = (Julian\ Date_i)\left(\frac{2\pi}{lenyr}\right) \tag{3.12}$$

where lenyr is the number of days in year i. The coordinates of the mean event date, $\bar{x}$ and $\bar{y}$, are given as

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} cos\, \theta_i \tag{3.13}$$

and

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} sin\, \theta_i \tag{3.14}$$

The mean event date, MD, is then found to be

$$MD = tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right)\left(\frac{2\pi}{lenyr}\right) \tag{3.15}$$

The regularity, $\bar{r}$ which is a measure of the spread of the data, is obtained from

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{3.16}$$

Regularity is a measure of variability and ranges from 0 to 1. A regularity of 1 indicates no variability in the timing of the events, and in the case of an annual maximum series, would be representative of an event that consistently occurred on the same date each year. On a seasonality plot, the angle is a measure of timing and the radius indicates the regularity of the event. Figure 2 gives an example of a seasonality plot for station 02HD012. The plot shows the timing of the annual maximum events (blue) and the mean event timing and regularity (red) for streamflow site 02HD012. This seasonality plot demonstrates that this site is predominately snowmelt driven as the annual maximum events typically occur during the spring melt period resulting in a comparatively large value of $\bar{r}$.

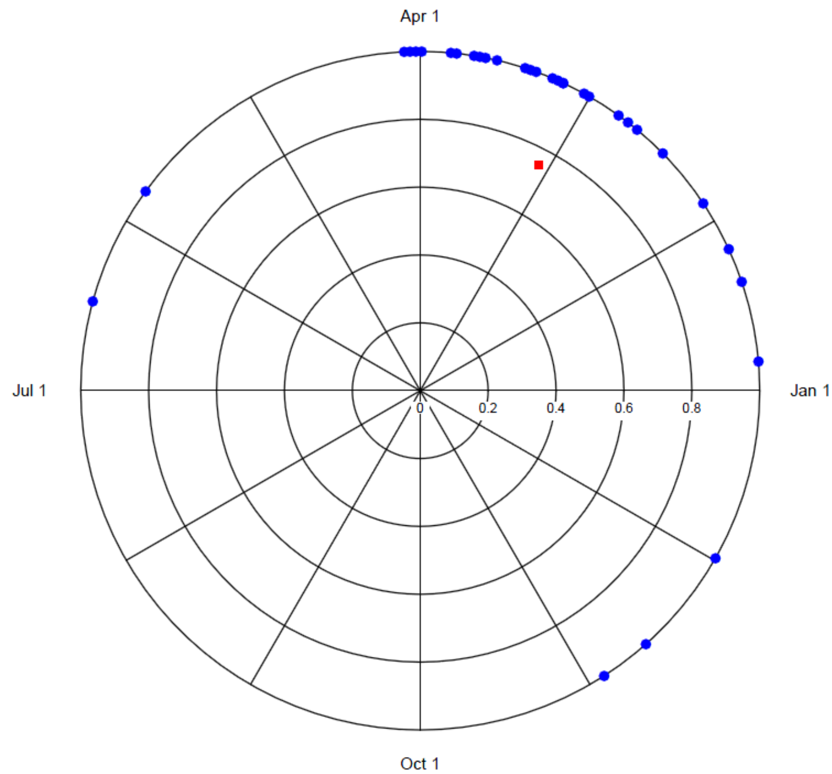

Figure 2. Seasonality of annual maximum streamflow events at station 02HD012.

3.4 Peaks over Threshold

3.4.1 Selecting a Threshold

The POT package in R (Ribatet, 2011) was used to select appropriate thresholds and transform daily streamflow time series into peaks over threshold series. Thresholds were selected such that they met two criteria (Lang *et al.*, 1999; Solari and Losada, 2012):

1) Events must be independent
2) Occurrence of resulting series satisfies the Poisson hypothesis

The first condition was addressed by specifying θ, a minimum time condition separating events:

$$\theta < 5\ days + \log(A) \tag{3.17}$$

where A is the drainage area (mi^2) (Lang et al., 1999). While this equation is more applicable to rural sites (urban systems may respond more quickly resulting in a shorter time required to define independent events), one standardize equation was applied to all sites. Given the limited number of streamflow sites in this study located in urbanized areas and the likelihood of consecutive extreme events, few peaks would be lost using this approach. The second condition was satisfied by ensuring a dispersion index equal to one, which is true for Poisson distributions (Solari and Losada, 2012). As defined by Cunnane (1979), the dispersions index is the ratio of the variance to the mean (Lang, 1999), which in the case of the Poisson distribution is equal to 1. A third criteria for this study required the number of peaks per year (npy) ratio to be greater than 1 to obtain further benefit relative to the annual maximum series.

Scripts were developed in R to automate the use of the POT package. An initial low threshold is required for the POT package to generate Mean Residual Life plots (MRLP) and scale and shape parameter plots for each site. Initial thresholds were defined as a percentile. Multiple percentiles (0.25, 0.50, 0.65, and 0.80) were evaluated to ensure the initial threshold selected was appropriate. The time criterion was used to generate clusters of independent events. Final thresholds were then selected using the plots, such that the MRLP was linear and scale and shape parameter plots were constant for thresholds above the chosen threshold. Thresholds were verified using confirmatory plots, inspecting time series plots, and ensuring an npy greater than 1.

Figure 3 demonstrates how a threshold was selected for site 02GC002 using the threshold selection plots generated in R. For this site a threshold of 40 was selected. The MRLP was linear and the scale and shape parameter plots were constant for thresholds above 40. A threshold of 40 yielded a npy of 2, satisfying the criteria of being greater than 1. The dispersion index was found to be within the confidence interval, approximately equal to 1.

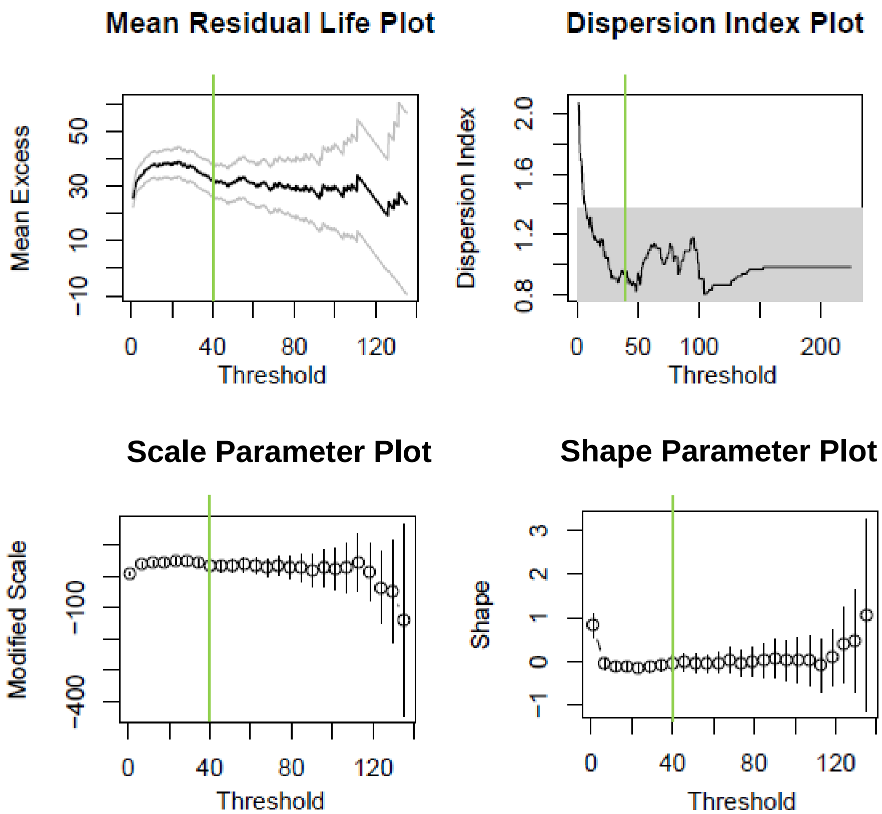

Figure 3. Threshold selection plots for site 02GC002 (threshold of 40 m^3/s selected shown in green).

In addition to the threshold selection plots, confirmatory plots were generated for the selected threshold as demonstrated in Figure 4. These plots verify the fit of the distribution. Where choosing a threshold using the MRLP was unclear as to the best selection, multiple thresholds were tested and evaluated using the confirmatory plots.

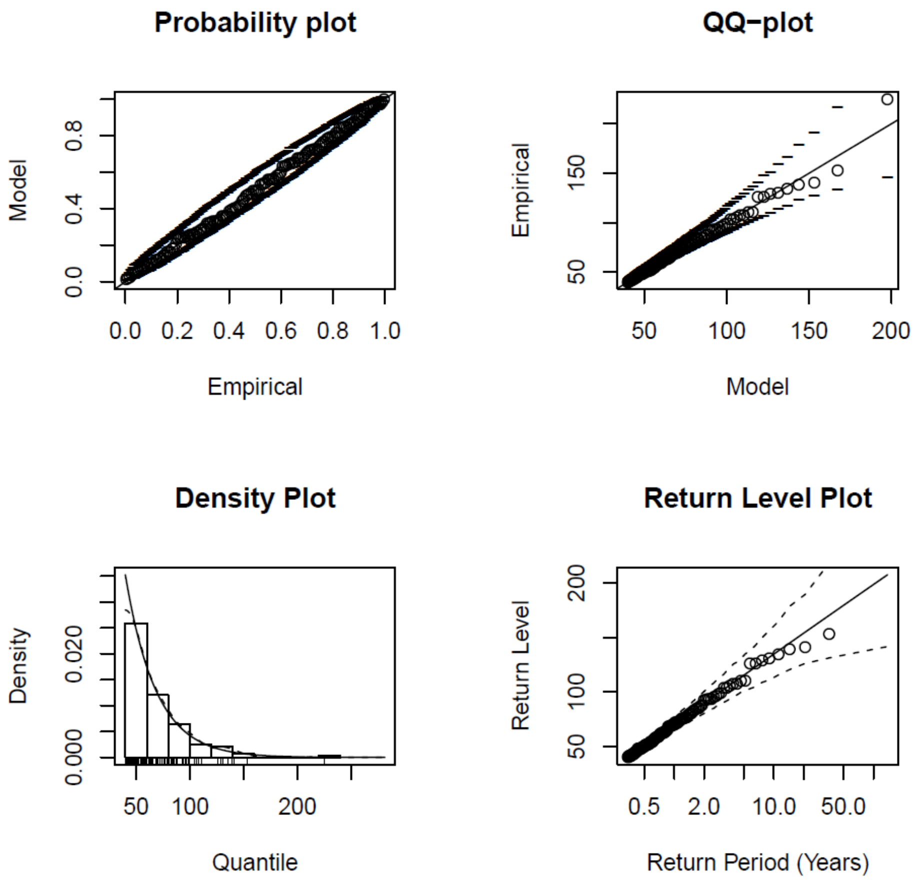

Figure 4. Threshold confirmatory plots for site 02GC002.

As a check a time series plot showing the identified peaks was generated. This allowed for a visual inspection to see if the threshold made sense, or if there was a more natural break such that the threshold could be shifted. This is shown in Figure 5.

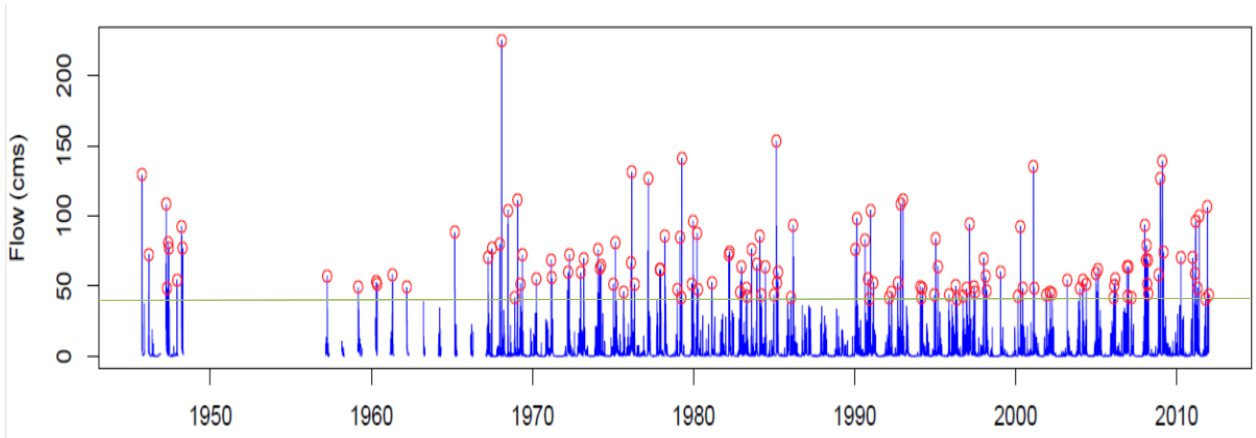

Figure 5. Time series plot of daily flow data (blue) and peaks over threshold series (red) for site 02GC002.

3.5 Removing Snowmelt Period

To compare exclusively rainfall driven streamflow events with changes in rainfall, a snowmelt period was estimated for each site by examining daily hydrographs so that events during the snowmelt period could be removed. Although the snowmelt period varies year to year, only one seasonal period for snowmelt was selected for each site. The snowmelt period was estimated on the conservative side, such that the remaining events after excluding this period are exclusively rainfall driven events. For pluvial sites where events are already exclusively rainfall driven, no snowmelt period was estimated.

Figure 6 illustrates how a snowmelt period was visually identified by examining overlapping hydrographs for each year. To avoid overcrowding on plots and to maintain visual clarity of the snowmelt events, the period of record for the streamflow station were segmented into four equal time periods and plotted on four separate charts. This also allowed for examining changes in hydrologic regime and timing of the event over the different time periods. For the site shown in Figure 6, the period March 1st to July 1st was selected as the snowmelt period.

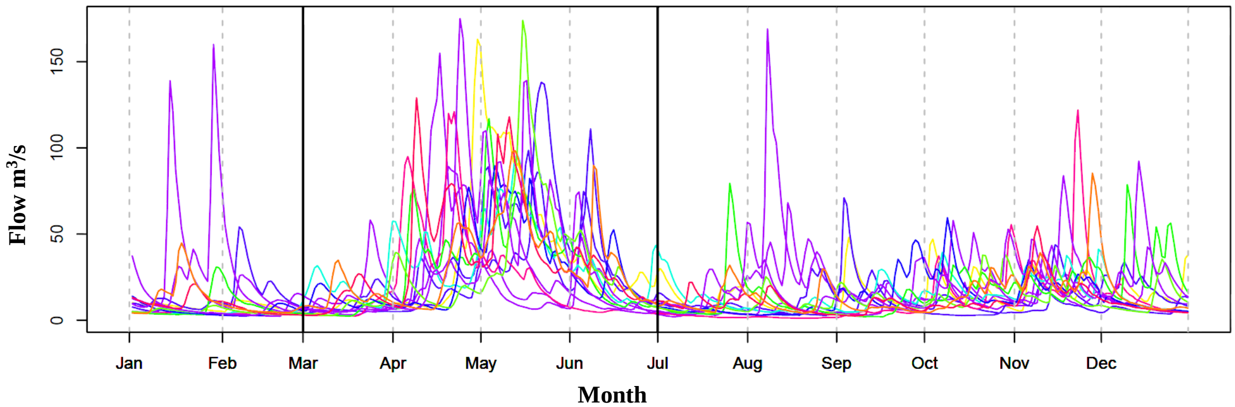

Figure 6. Daily hydrograph overlapped on annual time scale for site 02YK002 for years 1982 to 1995.

The identification of snowmelt period for some sites was more challenging; particularly some East Coast and southern Ontario. In southern Ontario, some sites did not have a defined snowmelt period. In these cases, the duration determined by other nearby stations was applied.

Chapter 4

Study Area and Data

4.1 IDF Stations

4.1.1 Site Selection Criteria and Data

IDF rainfall data for stations across Canada were obtained from Environment Canada (http://climate.weather.gc.ca). Following the study conducted by Burn and Taleghani (2013), the sites used in the study were then selected based on two criteria:

- record length of 35 or more years, with minimal gaps in recent years
- gauge station is active (currently still being sampled).

These criteria resulted in the selection of 51 study sites. The station names and record length information are identified in Table 1. Record lengths ranged from 34 to 76 years of data, with an average length of 45 years. Ten of the sites had at least 50 years of data. The locations of these stations are shown on Figure 7. To satisfy the minimum record requirement of 35 years, many of the sites are limited to the southern part of the country. No sites are included from Quebec as data were not available for stations in this province past 1999 (Burn and Taleghani, 2013).

Table 1. IDF Stations Included in Study

Station ID	Station Name	Province	Start Year	End Year	Record Length
1018620	VICTORIA INT'L A	BC	1965	2005	41
1021830	COMOX A	BC	1963	2004	40
1038205	TOFINO A	BC	1970	2005	35
1096450	PRINCE GEORGE A	BC	1960	2002	43
1105192	MISSION WEST ABBEY	BC	1963	2005	43
1106180	PITT POLDER	BC	1965	2005	39

Station ID	Station Name	Province	Start Year	End Year	Record Length
1108447	VANCOUVER INT'L A	BC	1953	2005	53
1126150	PENTICTON A	BC	1953	2002	46
1160899	BLUE RIVER A	BC	1970	2005	36
2101300	WHITEHORSE A	YT	1960	2001	37
3012205	EDMONTON INT'L A	AB	1961	2006	42
3025480	RED DEER A	AB	1959	2006	43
3031093	CALGARY INT'L A	AB	1947	2007	56
3034480	MEDICINE HAT A	AB	1971	2006	36
3075040	PEACE RIVER A	AB	1966	2006	36
3081680	COLD LAKE A	AB	1966	2006	40
4012400	ESTEVAN A	SK	1964	2006	43
4043900	KINDERSLEY A	SK	1966	2006	40
5050960	FLIN FLON A	MB	1970	2006	34
5052880	THE PAS A	MB	1971	2006	36
5062922	THOMPSON A	MB	1971	2007	35
6012198	EAR FALLS	ON	1952	2006	50
6034075	KENORA A	ON	1966	2004	38
6037775	SIOUX LOOKOUT A	ON	1963	2006	39
6042716	GERALDTON A	ON	1952	2006	50
6057592	SAULT STE MARIE A	ON	1962	2006	45
6076572	PORCUPINE	ON	1952	2006	48
6085700	NORTH BAY A	ON	1964	2006	41
6104175	KINGSTON PS	ON	1914	2007	63
6106000	OTTAWA A	ON	1967	2007	39
6116132	OWEN SOUND	ON	1965	2006	38
6127514	SARNIA A	ON	1962	2006	40
6131415	CHATHAM WPCP	ON	1966	2007	40
6131982	DELHI CS	ON	1962	2007	43
6137362	ST THOMAS WPCP	ON	1926	2007	76
6139525	WINDSOR A	ON	1946	2007	61
6144475	LONDON CS	ON	1943	2007	59
6148105	STRATFORD MOE	ON	1966	2004	37
6150689	BELLEVILLE	ON	1960	2006	39

Station ID	Station Name	Province	Start Year	End Year	Record Length
6153300	HAMILTON RBG CS	ON	1962	2007	45
6158733	TORONTO PEARSON	ON	1950	2007	55
8100880	CHARLO A	NB	1959	2009	49
8103200	MONCTON A	NB	1946	2009	60
8202000	GREENWOOD A	NS	1964	2008	42
8204700	SABLE ISLAND	NS	1962	2009	48
8205090	SHEARWATER A	NS	1955	2009	53
8205700	SYDNEY A	NS	1961	2009	47
8206500	YARMOUTH A	NS	1971	2009	39
8401700	GANDER INT'L A	NL	1939	2009	67
8403800	STEPHENVILLE A	NL	1967	2009	41
8501900	GOOSE A	NL	1961	2008	46

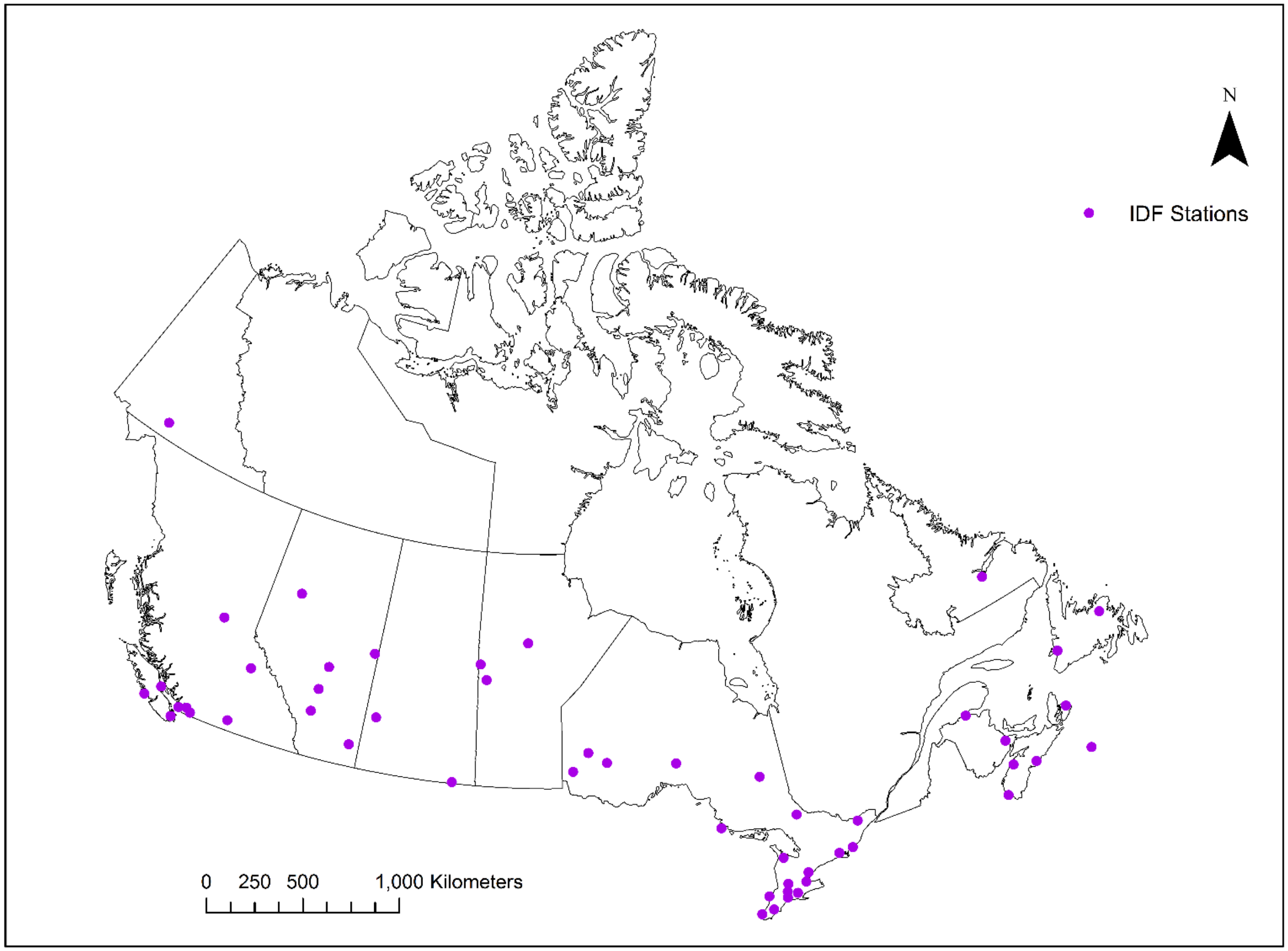

Figure 7. Location of IDF stations used in study.

Annual maximum rainfall depths were obtained from each of the sites for nine storm durations (5, 10, 15, 30 minutes, 1, 2, 6, 12, and 24 hours). To filter out where changes in extreme rainfall are occurring, the 9 storm durations at each of the 51 sites were analyzed for trends using the Mann-Kendall trend test. To make best use of the available data, trends in IDF data were analyzed for the full period of record at each station rather than for a common time period. At 20 of the stations, a trend was identified for at least one storm duration at the 10% significance level. The directions of these trends are shown in Figure 8.

4.2 Streamflow Stations

4.2.1 Site Selection Criteria

Streamflow stations were chosen near rainfall stations exhibiting trends in IDF data to relate changes in extreme precipitation and streamflow events. For each rainfall station where a trend was identified in maximum rainfall amounts for one or more storm duration, roughly 10 streamflow stations for each site were selected based on the following criteria:

- record length of 30 or more years
- less than 200 km from the selected rainfall station
- gauge station is active (currently still being sampled)
- gauge station is natural (not regulated).

Where possible, sites that were a member of the Reference Hydrometric Basin Network (RHBN) were selected. Sites belonging to the RHBN are appropriate for climate change studies because they meet the following criteria (Harvey et al, 1999):

- minimal basin development (<10% modified from natural state)
- no significant regulations or diversions upstream of the gauge
- record length of 20 or more years

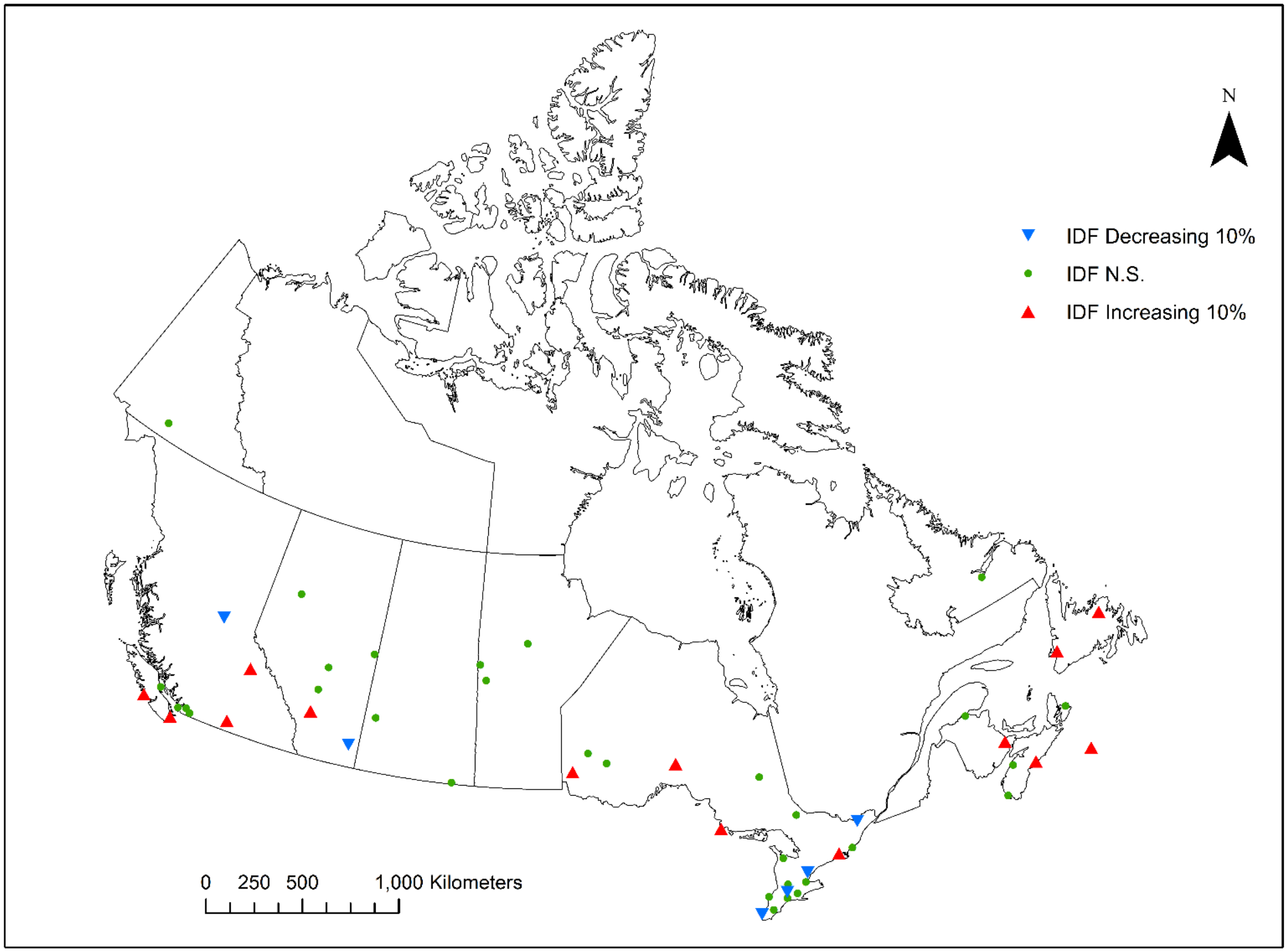

Figure 8. Location of IDF stations used in study and direction of trends. Trends found at the 10% significance level are indicated by a triangle (red = increasing; blue = decreasing). Stations with no trends found are indicated in green.

- active station with sampling expected to continue in the future
- accurate data.

For some locations it was not possible to obtain streamflow sites with adequate data within 200 km of the associated rainfall gauge and so exceptions were made (i.e., Sable Island and Sault Ste Marie). Selecting streamflow stations to be affiliated with Medicine Hat was difficult as many of the streamflow gauges in the prairies are seasonal or do not have annual maximums recorded prior to 1990. In some cases, a streamflow station was selected for more than one IDF station because it satisfied the criteria for multiple IDF stations (i.e., in southern Ontario where streamflow gauges are more densely located).

While an effort was placed to ensure natural catchments, several sites included in this study, particularly in southern Ontario, have urbanized areas within their watershed (e.g. 02HC030, 02HC032, 02HC033, etc.). This may have an impact on results presented in Southern Ontario

The Mann-Kendall trend test is robust enough to handle missing data. However, significantly large gaps may distort or limit the ability to detect a trend. If data from a station were missing for 15 or more consecutive years, data prior to the gap were excluded and the series shortened to include only the most recent portion of record.

These criteria resulted in the selection of 159 streamflow sites, 16 of which are assigned to multiple IDF rainfall stations. The station names and record length information are identified in Table 2. For the full streamflow duration, record lengths ranged from the minimum number of years of data to 103 years, with an average length of 49 years. The location of these stations relative to their associated IDF station is shown on Figure 9.

Table 2. Streamflow Stations Included in Study and associated IDF Station

Station ID	Province	RHBN	From	To	Drainage Area (km^2)	Distance (km)	IDF Station Name
02HD006	ON	N	1960	2010	82.9	107.91	BELLEVILLE
02HD009	ON	N	1966	2010	82.6	101.22	BELLEVILLE
02HD012	ON	N	1977	2010	232	77.01	BELLEVILLE
02HJ001	ON	N	1963	2010	110	76.13	BELLEVILLE
02HL004	ON	Y	1956	2010	712	44.70	BELLEVILLE
02HL005	ON	N	1966	2010	308	42.92	BELLEVILLE
02HM004	ON	N	1965	2010	112	44.22	BELLEVILLE
02HM005	ON	N	1970	2009	155	63.09	BELLEVILLE
02KD002	ON	N	1916	2010	837	106.61	BELLEVILLE
08KA007	BC	N	1955	2011	1710	96.82	BLUE RIVER A
08KA009	BC	Y	1972	2010	253	158.72	BLUE RIVER A
08LA001	BC	Y	1914	2011	10300	74.98	BLUE RIVER A
08LB038	BC	N	1926	2010	272	1.49	BLUE RIVER A
08LB076	BC	N	1973	2010	166	95.08	BLUE RIVER A
08LD001	BC	Y	1912	2011	3210	134.76	BLUE RIVER A
08LE027	BC	N	1915	2011	805	99.49	BLUE RIVER A
08NC004	BC	Y	1972	2010	305	67.14	BLUE RIVER A
08ND012	BC	N	1955	2011	934	70.44	BLUE RIVER A
08ND013	BC	Y	1964	2011	1150	149.96	BLUE RIVER A
05BB001	AB	Y	1909	2011	2209.6	108.48	CALGARY INT'L A
05BF016	AB	N	1962	2011	9.1	81.18	CALGARY INT'L A
05BG006	AB	N	1966	2011	332.5	60.18	CALGARY INT'L A
05BJ004	AB	N	1935	2011	790.8	42.49	CALGARY INT'L A
05BK001	AB	N	1915	2011	260.5	32.93	CALGARY INT'L A
05BL014	AB	N	1911	2011	592.2	49.49	CALGARY INT'L A
05BL022	AB	Y	1966	2011	165.5	100.07	CALGARY INT'L A
02YO006	NL	N	1981	2011	177	62.65	GANDER INT'L A
02YQ001	NL	Y	1950	2011	4450	21.77	GANDER INT'L A
02YR001	NL	Y	1959	2011	275	29.95	GANDER INT'L A
02YR003	NL	N	1981	2011	554	50.97	GANDER INT'L A
02YS003	NL	Y	1968	2010	36.7	57.66	GANDER INT'L A

Station ID	**Province**	**RHBN**	**From**	**To**	**Drainage Area (km²)**	**Distance (km)**	**IDF Station Name**
02ZF001	NL	Y	1950	2011	1170	148.44	GANDER INT'L A
02ZH001	NL	Y	1953	2011	764	113.54	GANDER INT'L A
02ZH002	NL	N	1961	2009	43.3	123.49	GANDER INT'L A
02ZJ001	NL	N	1977	2009	67.4	91.31	GANDER INT'L A
02ZM006	NL	Y	1953	2011	3.63	194.51	GANDER INT'L A
02AC001	ON	N	1971	2010	736	157.76	GERALDTON A
02AD010	ON	N	1972	2010	650	77.20	GERALDTON A
02BA003	ON	N	1973	2010	1320	106.12	GERALDTON A
02BB003	ON	N	1970	2010	4270	120.92	GERALDTON A
04GB004	ON	Y	1972	2010	11200	186.64	GERALDTON A
04JC002	ON	Y	1951	2010	2410	171.83	GERALDTON A
04JD005	ON	N	1968	2010	2020	122.37	GERALDTON A
05OE004	MB	N	1960	2010	423	152.70	KENORA A
05PB014	ON	Y	1915	2010	4870	158.60	KENORA A
05PH003	MB	N	1943	2011	3750	114.93	KENORA A
05QC003	ON	N	1970	2010	2370	153.66	KENORA A
05QE008	ON	N	1970	2010	1690	112.42	KENORA A
05QE009	ON	N	1961	2010	1530	62.90	KENORA A
05QE012	ON	N	1980	2010	548	102.65	KENORA A
05SA002	MB	Y	1943	2010	1580	151.03	KENORA A
02FB007	ON	Y	1916	2009	181	166.87	LONDON CS
02GA010	ON	Y	1914	2010	1030	59.15	LONDON CS
02GC002	ON	N	1967	2010	329	28.54	LONDON CS
02GC010	ON	N	1961	2010	342	39.67	LONDON CS
02GC018	ON	N	1965	2010	287	32.47	LONDON CS
02GD004	ON	N	1946	2010	306	13.02	LONDON CS
02GD009	ON	N	1946	2010	140	27.31	LONDON CS
02GD010	ON	N	1946	2010	150	22.32	LONDON CS
02GD019	ON	N	1967	2010	36	32.83	LONDON CS
02GE005	ON	N	1966	2010	146	19.54	LONDON CS
02GG005	ON	N	1967	2010	172	39.60	LONDON CS
11AB075	SK	Y	1927	2011	174	155.93	MEDICINE HAT A

Station ID	Province	RHBN	From	To	Drainage Area (km^2)	Distance (km)	IDF Station Name
01AN002	NB	N	1974	2010	1050	82.27	MONCTON A
01AP002	NB	Y	1926	2011	668	52.25	MONCTON A
01AP004	NB	Y	1961	2010	1100	83.31	MONCTON A
01BO001	NB	Y	1919	2010	5050	112.16	MONCTON A
01BP001	NB	Y	1952	2010	1340	131.59	MONCTON A
01BQ001	NB	Y	1962	2010	948	141.09	MONCTON A
01BS001	NB	Y	1964	2010	166	47.89	MONCTON A
01BU002	NB	Y	1962	2011	391	40.68	MONCTON A
01BV006	NB	Y	1964	2010	130	65.29	MONCTON A
02HL004	ON	Y	1956	2010	712	156.11	OTTAWA A
02HM004	ON	N	1965	2010	112	152.01	OTTAWA A
02HM005	ON	N	1970	2009	155	139.70	OTTAWA A
02KF011	ON	N	1972	2010	269	42.70	OTTAWA A
02LA007	ON	N	1970	2010	559	12.27	OTTAWA A
02LB006	ON	N	1948	2010	433	26.31	OTTAWA A
02LB007	ON	Y	1948	2010	246	54.03	OTTAWA A
02LB008	ON	N	1949	2009	440	42.05	OTTAWA A
02MB006	ON	N	1971	2010	111	89.04	OTTAWA A
02MC001	ON	N	1961	2009	404	82.85	OTTAWA A
08LG016	BC	Y	1920	2010	87.6	67.97	PENTICTON A
08NL004	BC	N	1915	2011	1050	40.48	PENTICTON A
08NL007	BC	Y	1914	2011	1810	65.19	PENTICTON A
08NL050	BC	N	1974	2010	388	35.70	PENTICTON A
08NM134	BC	N	1966	2011	34.6	39.81	PENTICTON A
08NM171	BC	N	1971	2011	117	31.77	PENTICTON A
08NM173	BC	N	1971	2010	40.7	40.36	PENTICTON A
08NM174	BC	Y	1971	2010	114	82.65	PENTICTON A
08NN015	BC	Y	1965	2011	233	44.94	PENTICTON A
08NN019	BC	N	1966	2010	145	40.91	PENTICTON A
07EE009	BC	Y	1976	2011	310	71.26	PRINCE GEORGE A
08JB002	BC	Y	1930	2012	3600	152.71	PRINCE GEORGE A
08JE001	BC	Y	1930	2010	14200	119.31	PRINCE GEORGE A

Station ID	Province	RHBN	From	To	Drainage Area (km^2)	Distance (km)	IDF Station Name
08KB001	BC	N	1950	2010	32400	14.09	PRINCE GEORGE A
08KB003	BC	N	1960	2010	4780	76.30	PRINCE GEORGE A
08KB006	BC	N	1977	2010	103	119.94	PRINCE GEORGE A
08KC001	BC	N	1953	2007	4230	22.92	PRINCE GEORGE A
08KD006	BC	N	1976	2010	2860	26.50	PRINCE GEORGE A
08KD007	BC	N	1977	2010	3330	38.20	PRINCE GEORGE A
08KE016	BC	N	1964	2010	1550	102.51	PRINCE GEORGE A
08KE024	BC	N	1972	2010	127	124.09	PRINCE GEORGE A
01DP004	NS	Y	1966	2011	92.2	279.78	SABLE ISLAND
01DR001	NS	N	1917	2011	177	234.94	SABLE ISLAND
01EO001	NS	Y	1915	2010	1350	208.58	SABLE ISLAND
01FA001	NS	Y	1966	2011	193	223.05	SABLE ISLAND
01FB001	NS	Y	1916	2011	368	281.56	SABLE ISLAND
01FB003	NS	Y	1919	2010	357	269.89	SABLE ISLAND
01FJ002	NS	N	1978	2011	17.2	243.28	SABLE ISLAND
02BB003	ON	N	1970	2010	4270	288.07	SAULT STE MARIE A
02BF001	ON	N	1968	2010	1190	58.22	SAULT STE MARIE A
02BF002	ON	Y	1968	2010	1160	59.00	SAULT STE MARIE A
02CA002	ON	N	1971	2010	108	19.75	SAULT STE MARIE A
02CF007	ON	N	1961	2010	272	253.51	SAULT STE MARIE A
02CF008	ON	Y	1975	2010	179	266.29	SAULT STE MARIE A
02CF012	ON	N	1977	2010	207	261.39	SAULT STE MARIE A
02FA002	ON	N	1976	2009	50.5	293.84	SAULT STE MARIE A
01DG003	NS	Y	1922	2011	96.9	26.43	SHEARWATER A
01DL001	NS	Y	1970	2011	63.2	128.58	SHEARWATER A
01DP004	NS	Y	1966	2011	92.2	111.24	SHEARWATER A
01ED005	NS	Y	1968	2010	723	138.73	SHEARWATER A
01ED007	NS	Y	1968	2010	295	137.54	SHEARWATER A
01EF001	NS	Y	1916	2010	1250	88.32	SHEARWATER A
01EJ001	NS	N	1916	2010	146	15.65	SHEARWATER A
01EJ004	NS	N	1981	2010	13.1	19.71	SHEARWATER A
01EO001	NS	Y	1915	2010	1350	134.35	SHEARWATER A

Station ID	Province	RHBN	From	To	Drainage Area (km^2)	Distance (km)	IDF Station Name
02YJ001	NL	Y	1969	2011	640	14.70	STEPHENVILLE A
02YK002	NL	N	1953	2011	470	46.52	STEPHENVILLE A
02YK005	NL	N	1973	2011	391	164.25	STEPHENVILLE A
02YL001	NL	Y	1929	2011	2110	117.69	STEPHENVILLE A
02YN002	NL	N	1981	2011	469	62.31	STEPHENVILLE A
02ZA002	NL	N	1982	2011	72	49.96	STEPHENVILLE A
02ZB001	NL	Y	1962	2011	205	107.50	STEPHENVILLE A
02ZD002	NL	N	1969	2011	1340	148.43	STEPHENVILLE A
08HA001	BC	Y	1914	2011	355	152.57	TOFINO A
08HA010	BC	N	1960	2010	578	120.60	TOFINO A
08HB002	BC	Y	1913	2011	319	111.22	TOFINO A
08HB014	BC	N	1949	2011	162	62.32	TOFINO A
08HB025	BC	Y	1960	2010	87.9	84.85	TOFINO A
08HB048	BC	N	1973	2011	10.3	59.23	TOFINO A
08HC002	BC	N	1957	2010	187	73.84	TOFINO A
08HD011	BC	N	1974	2011	302	98.27	TOFINO A
02EC002	ON	Y	1916	2010	1520	118.25	TORONTO PEARSON
02FB007	ON	Y	1916	2009	181	139.82	TORONTO PEARSON
02GA010	ON	Y	1914	2010	1030	86.08	TORONTO PEARSON
02HB004	ON	N	1957	2010	199	23.32	TORONTO PEARSON
02HC009	ON	N	1954	2010	197	12.78	TORONTO PEARSON
02HC023	ON	N	1963	2010	62.2	24.47	TORONTO PEARSON
02HC025	ON	N	1963	2010	303	14.60	TORONTO PEARSON
02HC030	ON	N	1967	2010	204	10.53	TORONTO PEARSON
02HC031	ON	N	1966	2010	148	9.56	TORONTO PEARSON
02HC032	ON	N	1966	2010	94.8	24.81	TORONTO PEARSON
02HC033	ON	N	1965	2010	70.6	9.59	TORONTO PEARSON
08GA061	BC	Y	1971	2011	3.63	82.16	VICTORIA INT'L A
08HA001	BC	Y	1914	2011	355	32.35	VICTORIA INT'L A
08HA003	BC	Y	1915	2010	209	19.59	VICTORIA INT'L A
08HA010	BC	N	1960	2010	578	65.29	VICTORIA INT'L A
08HA016	BC	N	1961	2010	15.5	26.59	VICTORIA INT'L A

Station ID	Province	RHBN	From	To	Drainage Area (km^2)	Distance (km)	IDF Station Name
08HB002	BC	Y	1913	2011	319	96.79	VICTORIA INT'L A
08MH016	BC	Y	1923	2011	335	152.18	VICTORIA INT'L A
08MH029	BC	N	1953	2011	144	96.04	VICTORIA INT'L A
08MH076	BC	N	1960	2011	47.7	89.97	VICTORIA INT'L A
02FF004	ON	N	1966	2010	41.4	140.20	WINDSOR A
02FF007	ON	N	1967	2010	466	180.10	WINDSOR A
02FF008	ON	N	1973	2010	110	146.43	WINDSOR A
02GC002	ON	N	1967	2010	329	153.40	WINDSOR A
02GC018	ON	N	1965	2010	287	164.36	WINDSOR A
02GD010	ON	N	1946	2010	150	175.30	WINDSOR A
02GE005	ON	N	1966	2010	146	150.41	WINDSOR A
02GG002	ON	N	1949	2010	730	109.51	WINDSOR A
02GG005	ON	N	1967	2010	172	132.63	WINDSOR A
02GG006	ON	N	1967	2010	267	97.88	WINDSOR A
02GH002	ON	N	1972	2010	125	28.28	WINDSOR A
02GH003	ON	N	1976	2010	159	14.31	WINDSOR A

4.2.2 Time Period Selection

To compare trends in streamflow to those found in the rainfall data, the duration selected for the streamflow data was chosen to be the same time period as the associated rainfall station. However, often the period of record of the streamflow data at a particular station is longer than that of the associated rainfall station. In these cases, using the rainfall duration would significantly reduce the length of streamflow data and ignore valuable long-term historical data. As such, trends in streamflow were also analyzed for two additional durations. These include both the full period of record available at each streamflow station, and a combined duration beginning at the same start year as the rainfall data record and ending at the end of streamflow period. Due to similarity in results, only the results from the latter are presented in Chapter 5.

4.2.3 Streamflow Data

Annual maximum and daily streamflow data were downloaded through the Water Survey of Canada's HYDAT Database (https://www.ec.gc.ca/rhc-wsc/). Daily data were utilized for construction of the peaks over threshold series. To deal with missing data when calculating the number of peaks per year, only years where an annual maximum streamflow was recorded were used in the analysis.

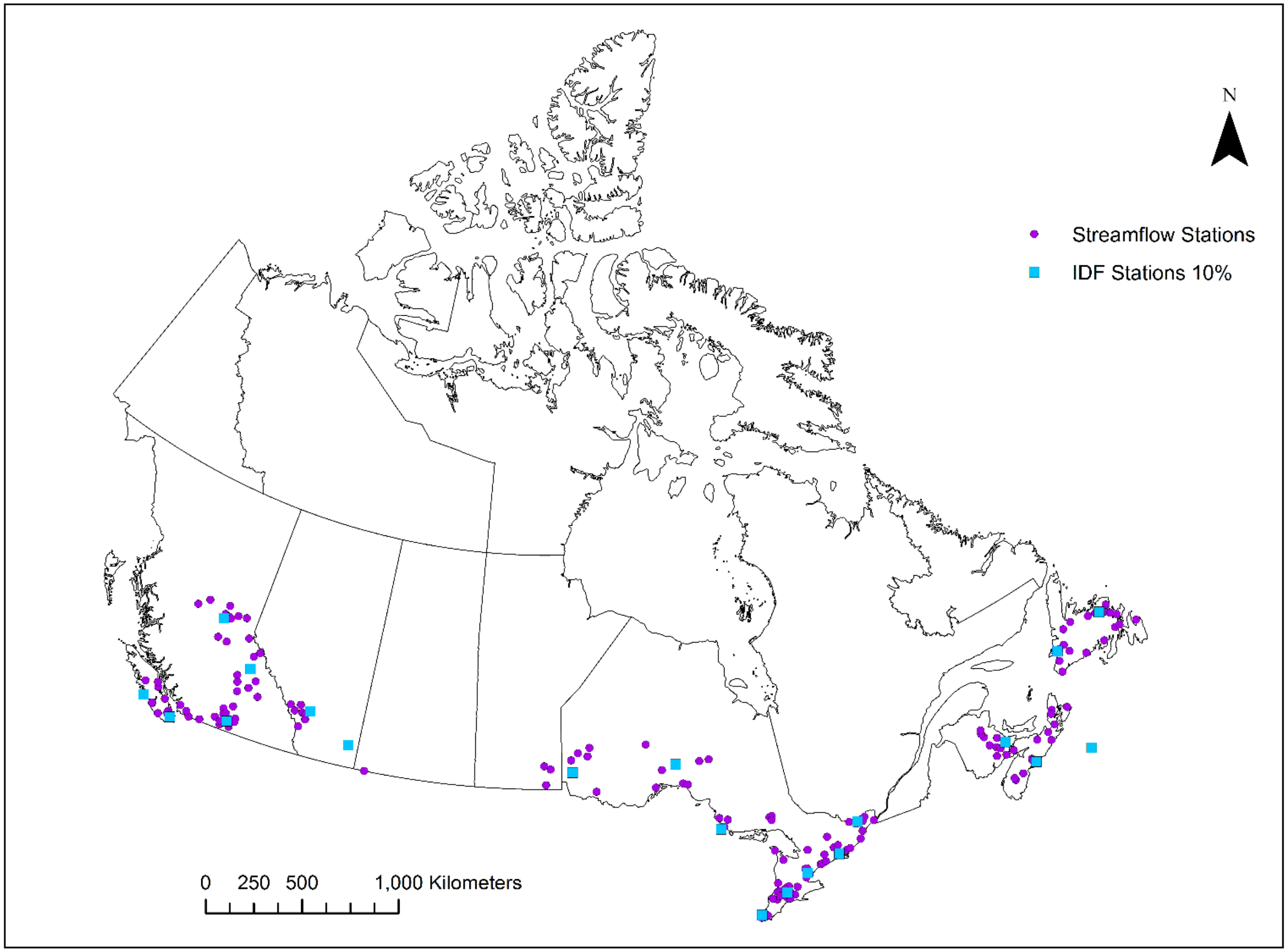

Figure 9. Location of IDF stations (blue) where a trend was found at the 10% significance level and the location of the associated streamflow stations (purple).

Chapter 5

Results

5.1 IDF Results

5.1.1 Mann-Kendall Trend Results

As discussed in Chapter 4, 51 climate stations across Canada were analyzed for trends in IDF rainfall data for nine storm durations (5, 10, 15, 30-minutes, 1, 2, 6, 12, and 24-hours). Of the 51 sites with IDF data, 20 were found to have a significant increasing or decreasing trend for at least one storm duration (Figure 10). More increasing trends than decreasing trends were found, with most decreasing trends occurring in southern Ontario. The lack of trends detected in the Prairies should also be noted.

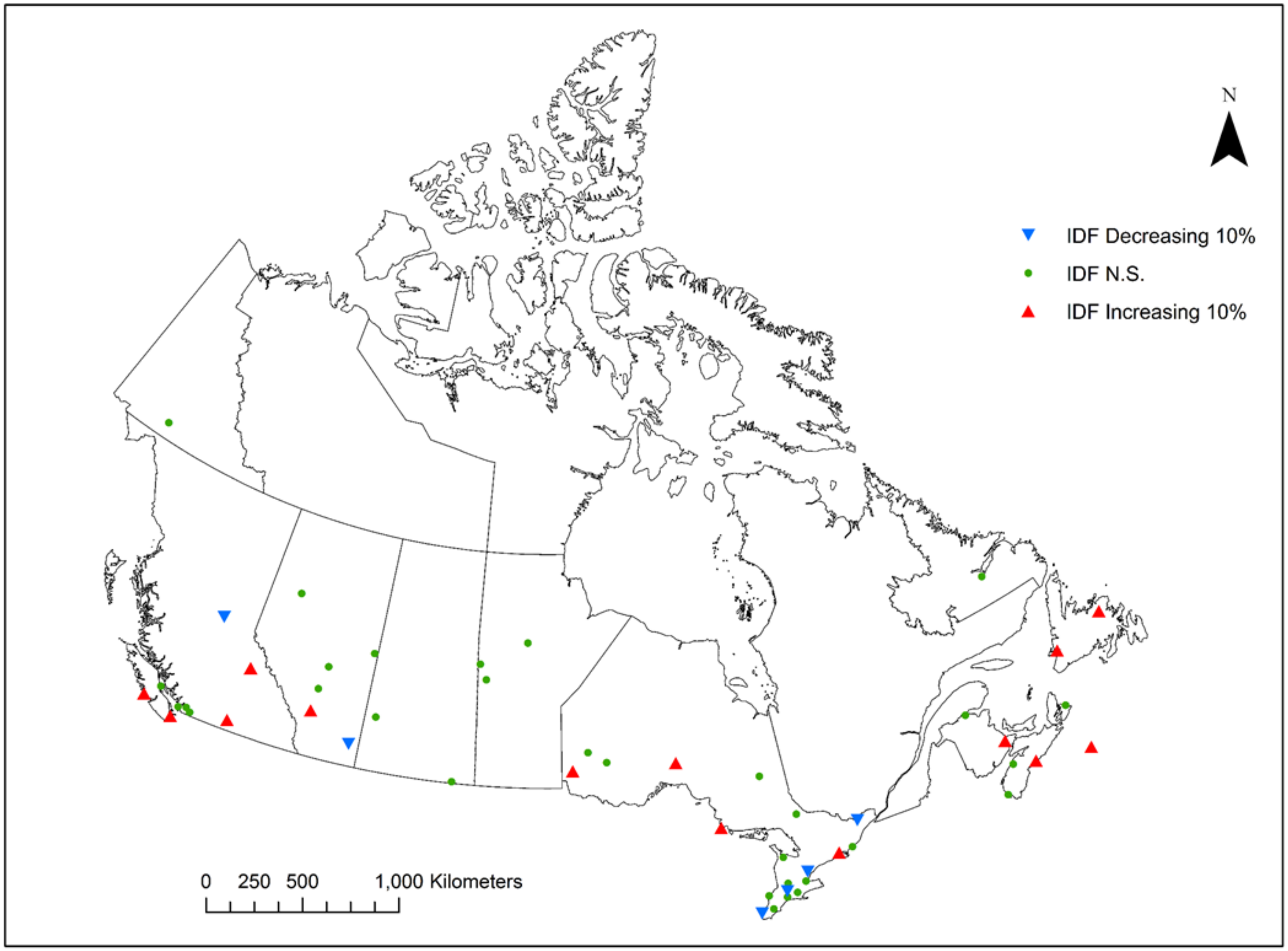

Figure 10. Location of IDF stations used in study and direction of trends. Trends found at the 10% significance level are indicated by a triangle (red = increasing; blue = decreasing). Stations with no trends found are indicated in green.

Table 3 presents the results of the trend test for each station where a trend was observed and for each storm duration. Stations are shown in order of west to east in order to compare trends regionally.

Table 3 Significant trends in IDF data by storm duration

Station	5 min	10 min	15 min	30 min	1 hr	2 hr	6 Hr	12 hr	24 hr	Grand Total
Tofino						↑		↑		2
Victoria	↑						↑			2
Penticton	↑				↑			↑	↑	4
Prince George							↓			1
Blue River			↑				↑	↑	↑	4
Calgary						↑				1
Medicine Hat	↓									1
Kenora									↑	1
Geraldton					↑				↑	2
Sault Ste Marie		↑	↑	↑						3
Windsor	↓	↓			↓	↓	↓	↓		6
London							↓	↓		2
Toronto								↓		1
Belleville	↑	↑	↑	↑	↑	↑				6
Ottawa	↓	↓	↓	↓	↓	↓				6
Moncton								↑	↑	2
Shearwater				↑	↑				↑	3
Sable Island				↑						1
Stephenville	↑		↑			↑	↑			4
Gander						↑	↑	↑	↑	4
Grand Total	7	4	5	5	6	7	7	8	7	56

In British Columbia there are increasing trends for durations 6 hours and longer, as well as 5-minute duration. Only two significant trends were identified in the prairies with no consistent storm duration or direction. In northwestern Ontario there is an increasing trend for the 24-hour duration. In central Ontario increasing trends occur in short duration storms. In south central/western Ontario decreasing trends are observed, with trends in 6- and 12-hour rainfall occurring at more than one site. In south eastern Ontario there are trends in all 6 durations between 5-minute and 2-hours for two stations, however these trends are in opposite directions. Trends were found to be increasing in Belleville while decreasing ~200km away in Ottawa. Belleville was the only site in southern Ontario with increasing trends for any duration. All trends in the Maritimes are increasing, more commonly for the longer durations such as 30-minute, and 2-hour to 24-hour. The most common durations where trends were observed across Canada include the 5-minute, 2-hour, 6-hour, 12-hour, and 24-hour. Both significant increasing and decreasing trends were identified for each duration, with the exception of the 24-hour storm for which only significantly increasing trends were observed.

Where trends were found for more than one storm duration at a given location, all trends were found to agree on the direction of the trend. For example, a trend was found in annual maximum precipitation for each storm duration between the 5-minute and 2-hour storm length for the Belleville site, all of which were found to be increasing in magnitude. More increasing than decreasing trends were found, with decreasing trends observed in southern Ontario and central BC. Calgary, Kenora, Medicine Hat, Prince George and Sable Island had a trend for only one duration, while Belleville, Blue River, Gander, Ottawa, Penticton, Sault Ste Marie, Shearwater, Stephenville, and Windsor had trends for 3 or more durations. Windsor, Belleville and Ottawa had the most number of significant trends (6 durations).

The increases in the annual maximum daily (24-hour storm) precipitation is consistent with the findings of Mailhot *et al.* (2010), the findings of several large duration events (i.e., 12-hour) having decreasing trends is contrary to that observed by Burn and Taleghani (2013), who found mainly increasing trends for long duration storms. Adamowski and Bougadis found mainly decreasing trends in southwestern Ontario and the St. Lawrence region of Ontario, although few were significant and none were significant for large storm durations. Adamowski and Bougadis (2003) also identified positive trends in the central region, where Belleville and Toronto are located. With the exception of the direction of trend for Toronto, the findings of IDF trend directions in Ontario are consistent with the findings of Adamowski and Bougadis (2003). The significant trends identified by Adamowski and Bougadis were mainly for short durations, while the trends found in the study in Ontario are fairly evenly spread out among durations.

5.1.2 Change Point Analysis

The IDF rainfall data sets were analyzed for change points using the Pettit test. More change points were detected than trends. Of the 20 IDF sites, 75 change points were identified. This included 39 increasing and 17 decreasing change points. Of the 56 trends identified by the Mann-Kendall test, 40 were also found to have a change point by the Pettit test. The direction of change points and trends were always in agreement at a site.

To assess whether a step change was falsely identified as a trend, a visual inspection was conducted on a time series of the annual maximum precipitation series for each dataset where a change point and trend were observed. In addition to examining the pattern of the trend, the timing of the change point was also analyzed. Figure 11 shows a histogram of change points dates for the IDF data to compare when changes are occurring. The histogram shows that change points are different among sites and no systematic change (which may be more reflective of data collection than climate change) is occurring across sites.

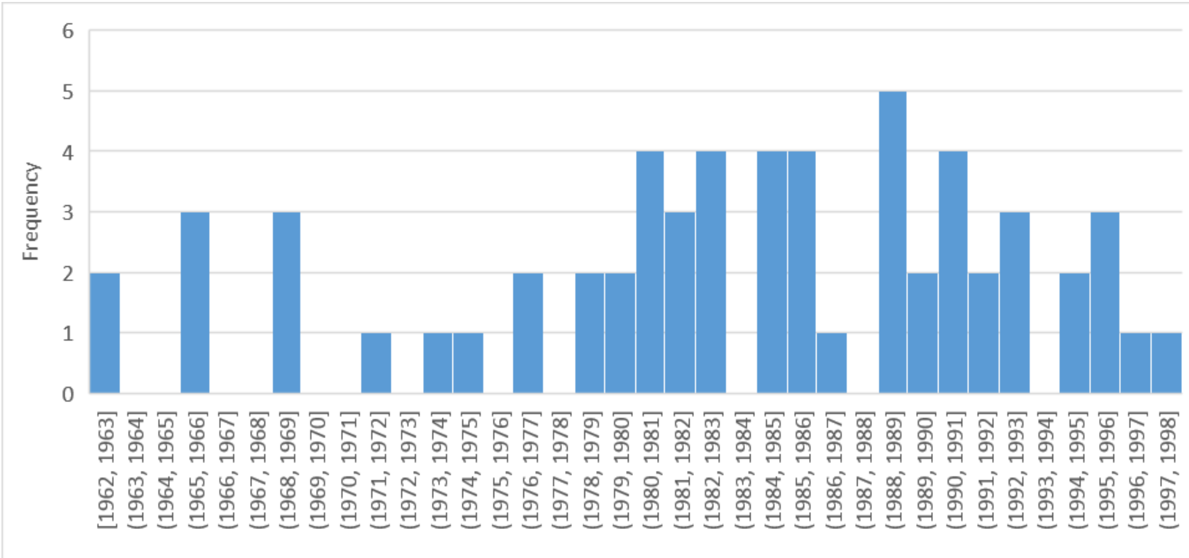

Figure 11. Histogram of IDF Change Points.

Some sites with more than one change point were in agreement about when the change point occurred (e.g., 5 durations in Ottawa had a change point around the 1981 +/- 1 year) while other sites had a different change point year for each duration such as Penticton with change points detected in 1963, 1969, 1979, and 1981 for various durations. There was not enough evidence from the change point analysis both on trend pattern and change timing to exclude any of the trends identified.

5.2 Annual Maximum Streamflow Results

5.2.1 Mann-Kendall Trend Results

The Annual Maximum Streamflow (AMQ) series were tested for trends using the Mann-Kendall trend test at each streamflow station for 3 durations. These durations were a) the full period of record at the streamflow station, b) the duration of the IDF station, c) from the start of the IDF data series period to the end of the streamflow record. Due to similarity in results, only the results for the combined duration, from the start of the IDF station to the end of the streamflow record, are presented in this thesis.

The trends in annual maximum streamflow are shown in Figure 12. The streamflow trends are mainly decreasing, which fits well with other studies. Other studies examining annual maximum streamflow trends in Canada observed spatial patterns of decreasing streamflow in the south due a shift to an earlier, more gradual snowmelt, resulting in reduced peak flows (Zhang *et al.*, 2001; Burn and Hag Elnur, 2002; Burn *et al.*, 2010). Most of the streamflow sites in this study are more southerly due to the limited number of IDF stations in the north with identified trends.

5.2.2 Change Point Analysis

The annual maximum streamflow series were analyzed for change points. Almost all annual maximum streamflow series with significant trends identified also had a change point. Only 4 sites that had a trend were not found to have a change point. Time series plots of each annual maximum streamflow series were reviewed where both trends and change points were observed to conclude if any change was falsely identified as a trend. No trends were found to be definitively step changes rather than trends and thus no trends were excluded in the analysis.

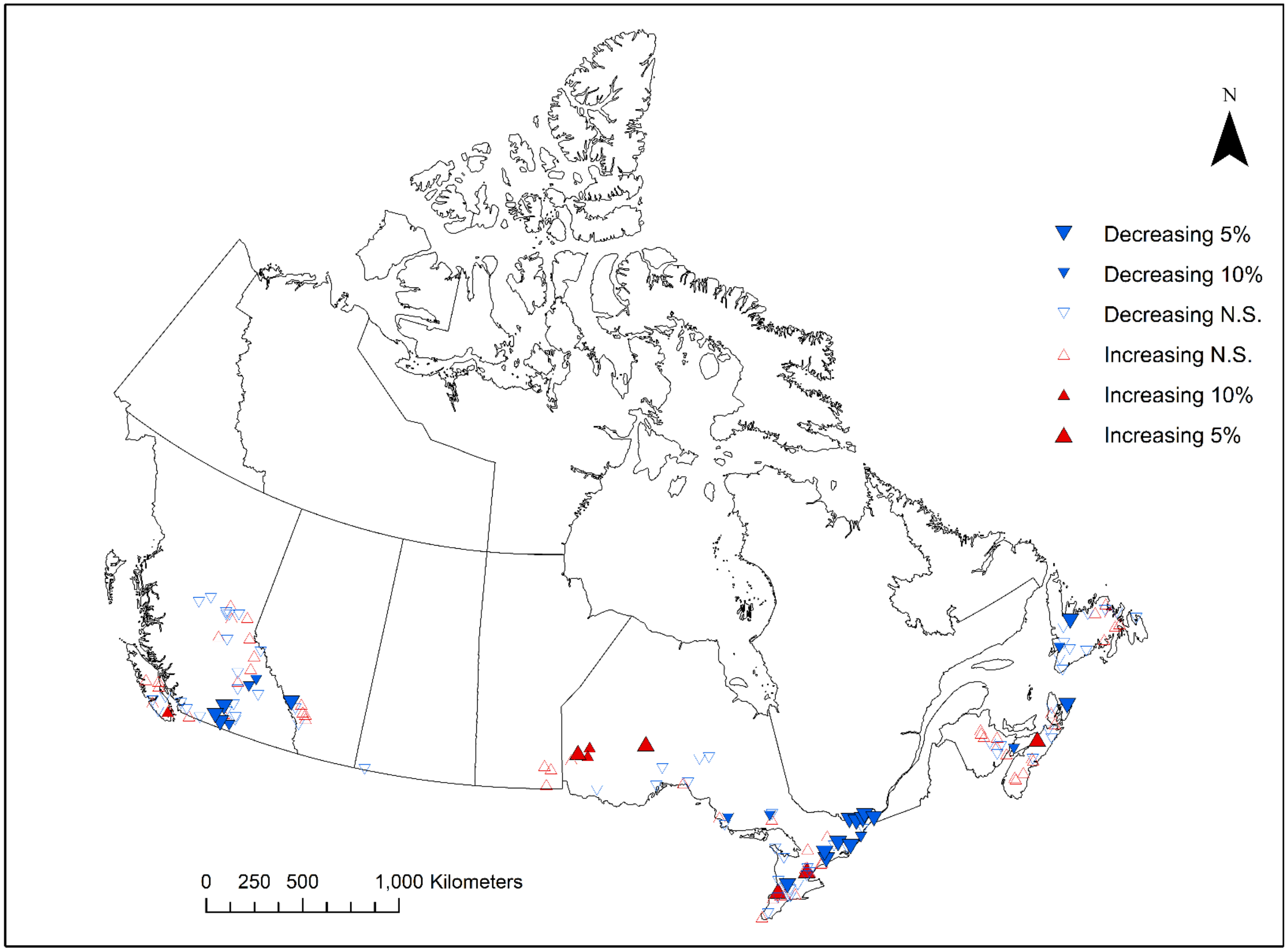

Figure 12. Streamflow trends in Annual Maximum Streamflow series.

A histogram showing the timing of the change points for the annual maximum streamflow series is shown in Figure 13. Since there was no consistent date for which the change points occurred, the change points do not provide enough evidence to discredit the trends.

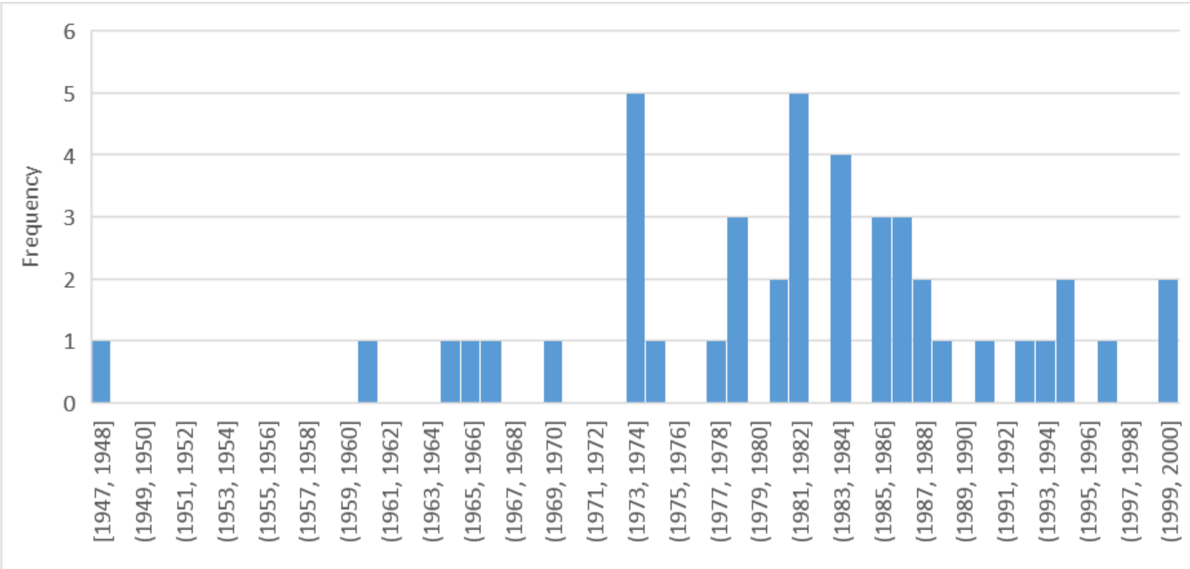

Figure 13 Change point for annual maximum streamflow.

5.2.3 Comparison of AMQ Trends to IDF Trends

Contrary to the trends in maximum rainfall, which were mostly increasing, the majority of trends found in annual maximum streamflow events were found to be decreasing. Only 9 increasing trends were identified while 25 streamflow stations saw decreasing trends.

The disagreement is strongest in western and eastern Canada, where the majority of streamflow trends identified in these areas are decreasing trends. There are some similarities to the annual maximum rainfall trends such as decreases in southern Ontario, increases in northern Ontario and an increase in coastal BC.

Each streamflow station was selected for comparison against at least one IDF station exhibiting a significant rainfall trend. The results of the significant streamflow trends are then related back to the specific duration for which the associated rainfall trend occurred. This allows for determining for which duration changes in rainfall events, if any, may be responsible for the changes in extreme streamflow. Each of the streamflow trends were compared to the trends at the IDF station they were paired with. This comparison is presented in Table 4. The direction of the trend was compared against that of the IDF site to assess agreement. The percentage of streamflow trends agreeing or disagreeing in trend direction to each IDF duration is also presented.

Table 4. Summary of Significant Trends in annual maximum streamflow compared to trends in IDF

IDF Trend	IDF Duration	Number of Increasing Streamflow Trends	% Streamflow Station with Increasing Streamflow Trend	Number of Decreasing Streamflow Trends	% Streamflow Station with Decreasing Streamflow Trend
Increasing	5	1	3%	9	25%
	10	0	0%	5	29%
	15	0	0%	7	26%
	30	2	5%	9	22%
	1	2	6%	8	23%
	2	0	0%	6	14%
	6	1	3%	4	11%
	12	0	0%	6	13%
	24	5	8%	7	11%
Decreasing	5	1	4%	8	35%
	10	1	5%	8	36%
	15	0	0%	8	80%
	30	0	0%	8	80%
	1	1	5%	8	36%
	2	1	5%	8	36%
	6	1	3%	1	3%
	12	2	6%	1	3%

	24	0	N/A	0	N/A

The 24-hour duration saw the most agreement for increasing rainfall trends. For the 24-hour storm duration, 7 IDF stations were found to have an increasing trend. Out of the 63 streamflow stations selected to represent these 7 IDF stations, 5 were found to have a trend, which resulted in 8% agreement between the streamflow and rainfall trend. For decreasing rainfall trends, the 15-minute and 30-minute duration were found to have the most agreement (80% each). Eight significant decreasing streamflow trends were found for all short and medium length durations associated with a decreasing extreme rainfall trend. There were numerous decreasing trends in annual maximum streamflow where increasing extreme rainfall trends were found. The most disagreement was found for the short durations, where between 25% and 29% of streamflow sites had a decreasing trend where an increasing rainfall trend was observed. This may imply that the shorter durations storms are not drivers in the annual maximum streamflow events for these streamflow sites.

5.2.4 Seasonality Analysis

To obtain an understanding about the timing of events, and the trend pattern amongst different hydrologic regimes, a seasonality analysis was conducted. The results of the seasonality analysis for annual maximum streamflow series are shown in Figure 14. The mean annual event timing and trend direction and significance is indicated in the figure. In general, there is a decreasing trend for nival (snowmelt driven) sites as the majority of significant trends identified as occurring in the spring with a high degree of regularity were decreasing. Exceptions to this are the four significant increasing trends which have mean event date occurring in June. These trends correspond to nival streamflow sites in northern Ontario associated with Geraldton and Kenora.

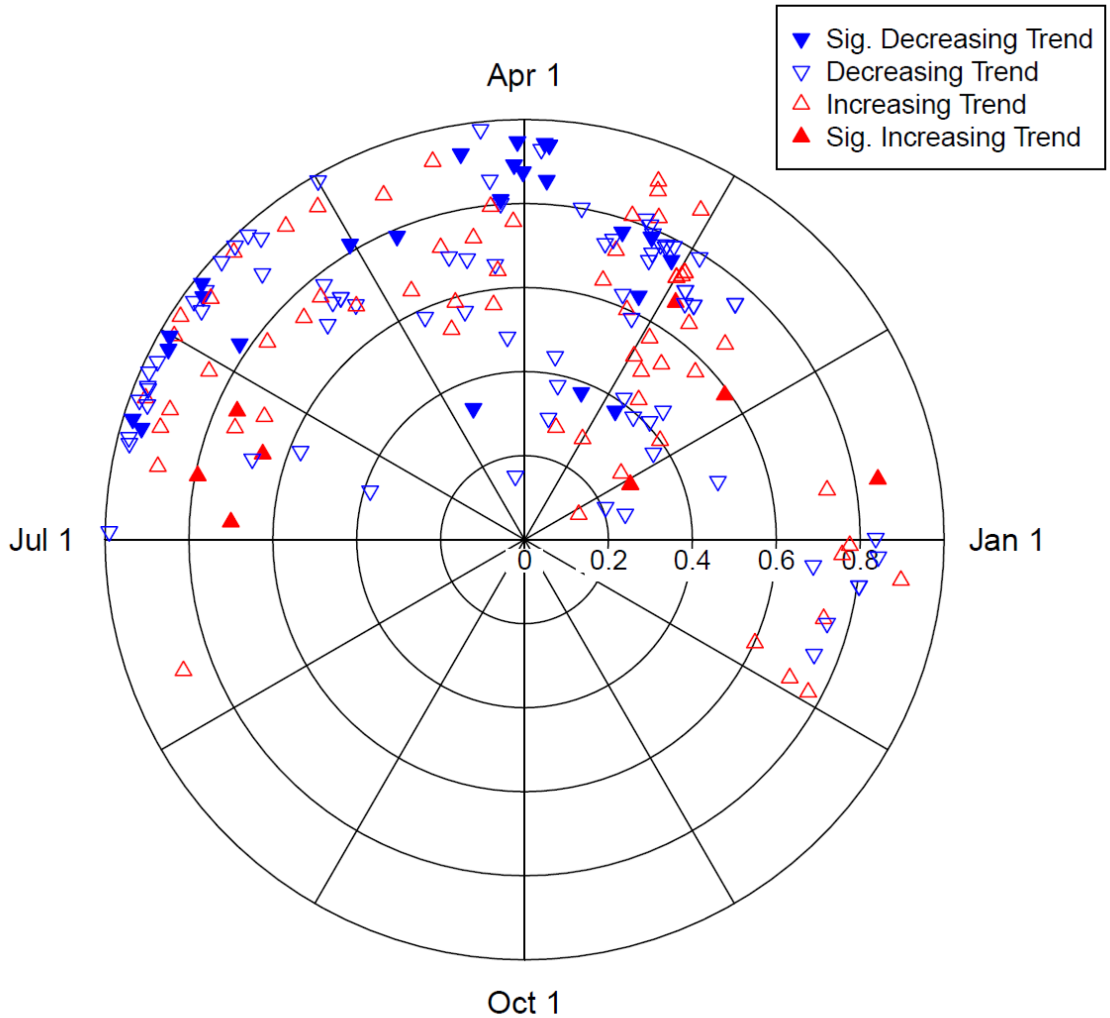

Figure 14. Seasonality and trends for Annual Maximum Streamflow.

To determine how seasonality may be changing over time, streamflow records were divided into two periods. The event timing of the first half of the record was compared to the event timing of the second half of the streamflow record. The results of this analysis are presented in Figure 15.

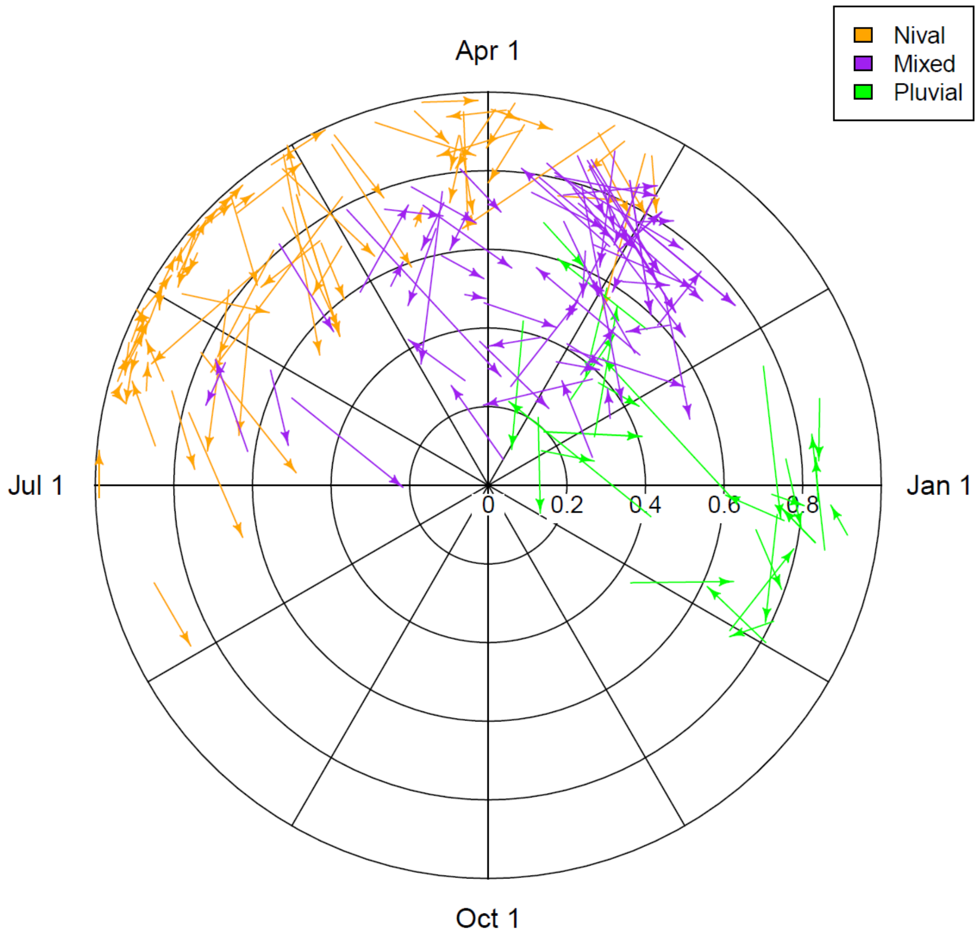

Figure 15. Change in Seasonality of AMQ from the first half of the streamflow record to the second half.

Although several nival sites with a high level of regularity experience no change in regularity, those that do experience a change in regularity generally demonstrate a decrease that could indicate a shift from a nival towards a mixed regime. Many mixed sites experience a shift in mean event timing to an earlier date. This could be due to an earlier spring melt, or to the occurrence of more annual maximum flow dates occurring in the fall or winter, rather than in the spring as a result of snowmelt.

5.3 Peaks over Threshold Results

5.3.1 Mann-Kendall Trend Results

The results of the trend analysis on the peaks over threshold series are similar to the annual maximum streamflow series but with even fewer increasing trends identified. Only 4 increasing trends were identified while 25 streamflow stations saw decreasing trends. The locations of the increasing and decreasing trends are very similar to the annual maximum flow series. The results of the peaks over threshold trend analysis are shown in Figure 16.

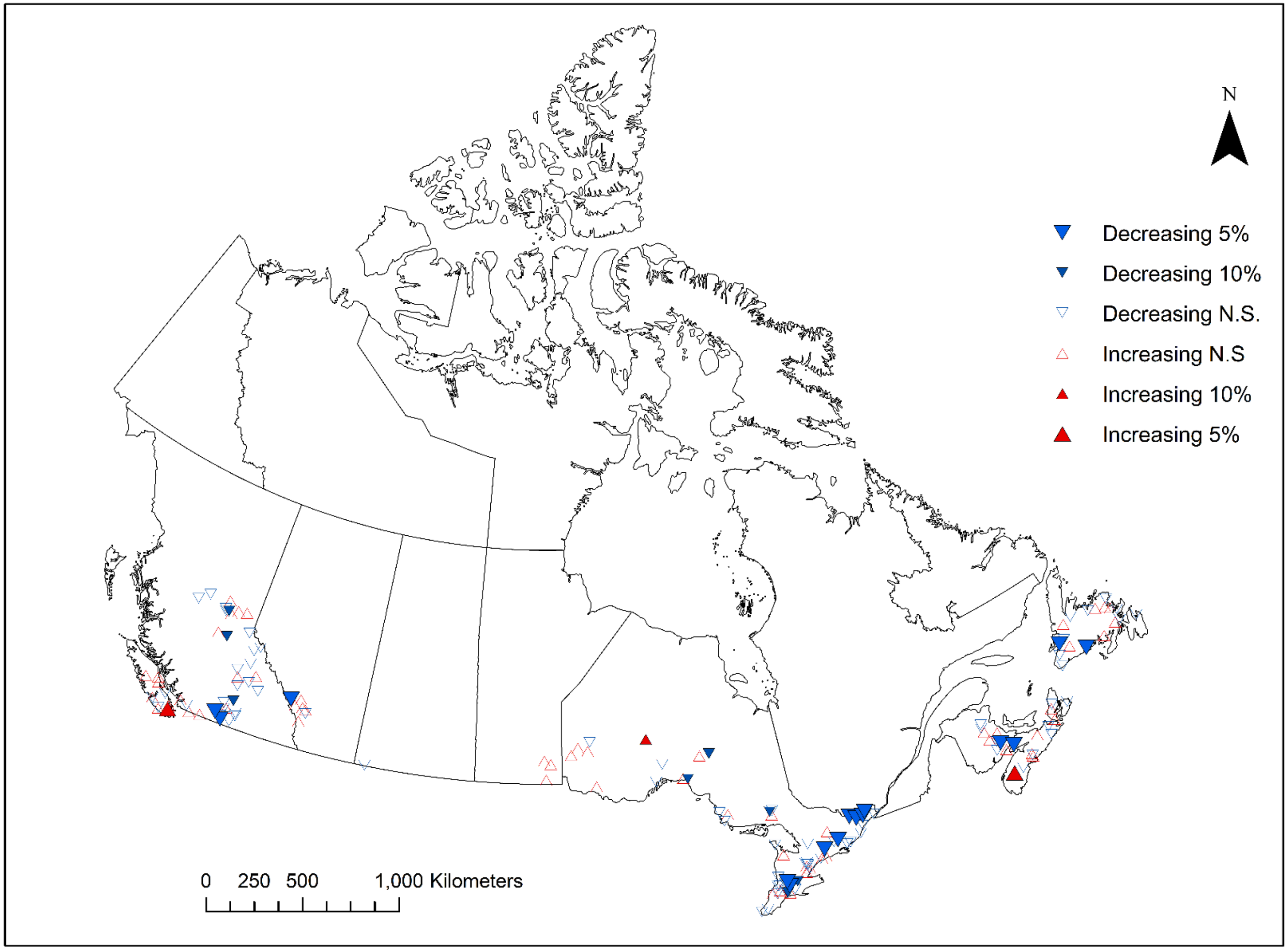

Figure 16. Streamflow trends in Peaks over Threshold series (POT).

Significant increasing trends are observed near Victoria, Geraldton and Shearwater. The remainder of the significant trends identified were decreasing.

5.3.2 Change Point Results

A change point analysis was conducted for all the peaks over threshold series. A summary of the resulting change point dates is identified in Figure 17. The histogram shows a wide spread of change point date. There is no strong evidence from the change point analysis to refute any trends identified.

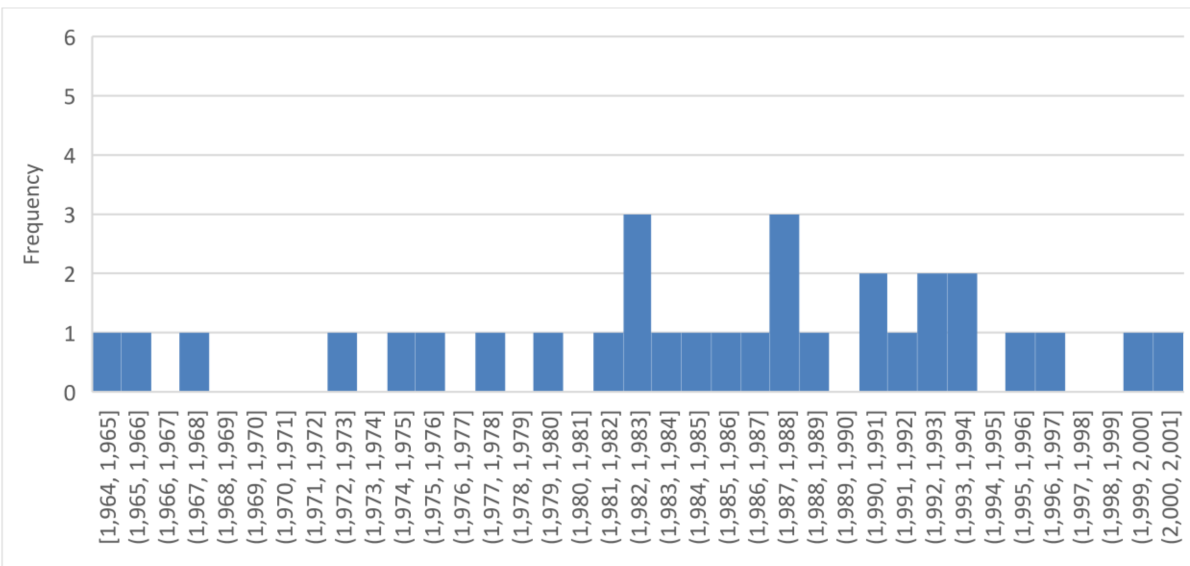

Figure 17 Change point histogram for peaks over threshold series.

5.3.3 Comparison to POT Streamflow Trends to IDF Trends

Table 5 summarizes the number of increasing and decreasing streamflow trends and how they correspond to the trends for their associated rainfall trend. Streamflow sites with decreasing rainfall trends were in agreement and saw a corresponding decrease in peak streamflow. No streamflow sites associated with a decreasing IDF trend were found to have an increasing trend. The greatest agreement in decreasing rainfall and streamflow trends occurred for the 15 and 30-minute storm duration (50%). Between 5-7 significant decreasing streamflow trends were identified in relation to decreasing IDF trends for all durations, except the 24-hour storm where no decreasing rainfall trend was observed.

Table 5. Summary of Significant Trends in POT streamflow compared to trends in IDF

IDF Trend	IDF Duration	Number of Increasing Streamflow Trends	% Streamflow Station with in creasing Streamflow Trend	Number of Decreasing Streamflow Trends	% Streamflow Station with Decreasing Streamflow Trend
Increasing	5	1	3%	6	17%
	10	0	0%	3	18%
	15	0	0%	3	11%
	30	2	5%	6	15%
	1	3	9%	7	20%
	2	0	0%	4	10%
	6	1	3%	2	5%
	12	0	0%	4	9%
	24	3	5%	7	11%
Decreasing	5	0	0%	6	26%
	10	0	0%	6	27%
	15	0	0%	5	50%
	30	0	0%	5	50%
	1	0	0%	6	27%
	2	0	0%	6	27%
	6	0	0%	7	21%
	12	0	0%	5	15%
	24	0	N/A	0	N/A

The majority of peak streamflow series were identified as having a decreasing trend. Streamflow sites corresponding to an increasing IDF trend had both increasing and decreasing trends in the peaks over threshold series. In relation to increasing rainfall trends, there were more streams with disagreeing trends (decreasing) than agreeing trends (increasing) and a disagreeing trend occurred for each rainfall duration. No durations had more than 20% of sites in disagreement. The increasing rainfall does not appear to cause any increases in peak streamflow, suggesting the peak streamflow may be due to other factors, such as snowmelt, geology, land use.

5.3.4 Seasonality Analysis

The results of the seasonality analysis are shown in Figure 18. Almost all significant trends are decreasing, most of which are of nival or mixed regime. The four significant increasing trends are scattered and are driven by different processes.

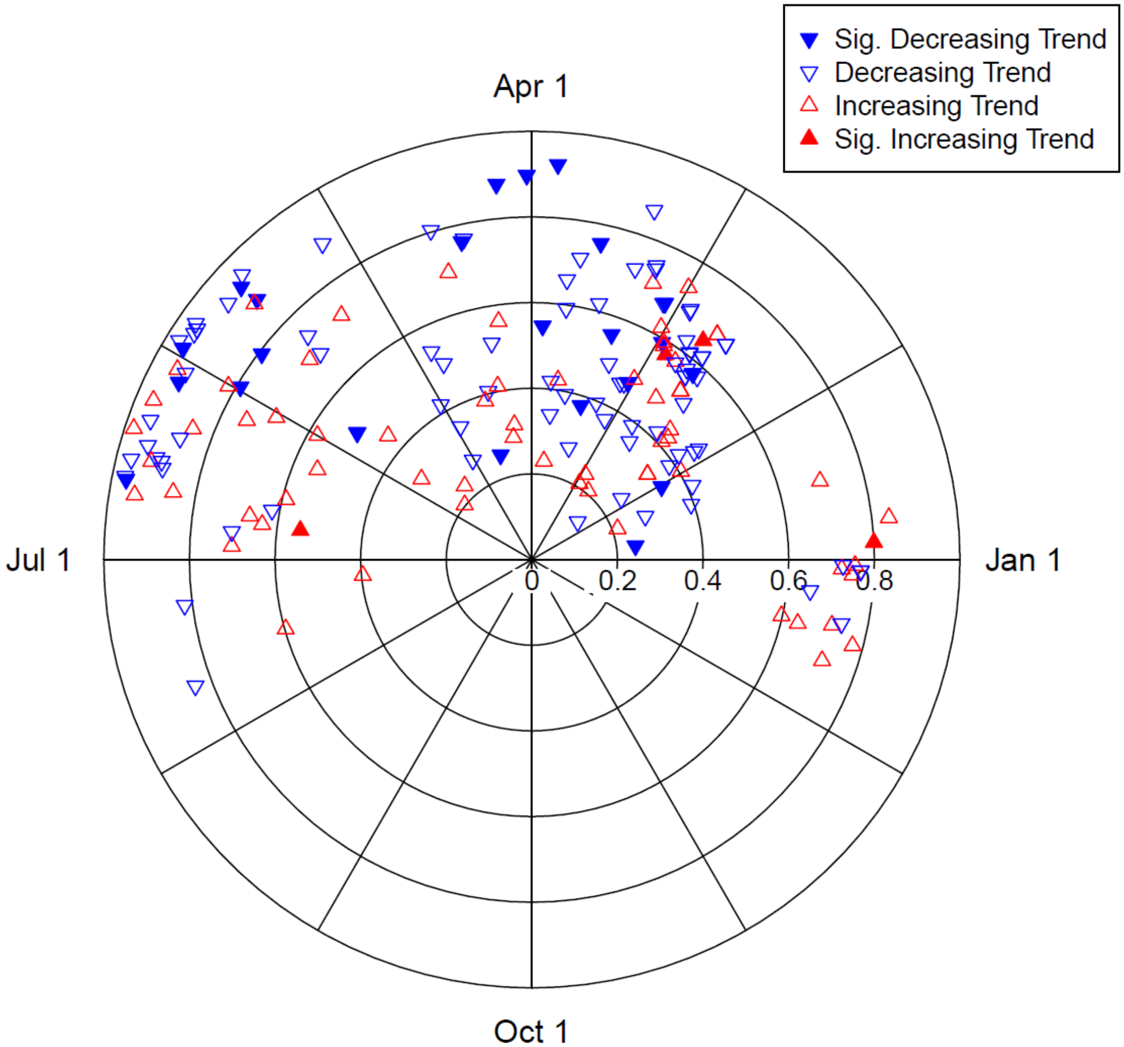

Figure 18. Seasonality and trends for Peaks Over Threshold Streamflow series.

To determine how seasonality may be changing over time, streamflow records were divided into two periods, such that the event timing of the first half of the record was compared to the event timing of the second half of the record. Results of this analysis are presented in Figure 19.

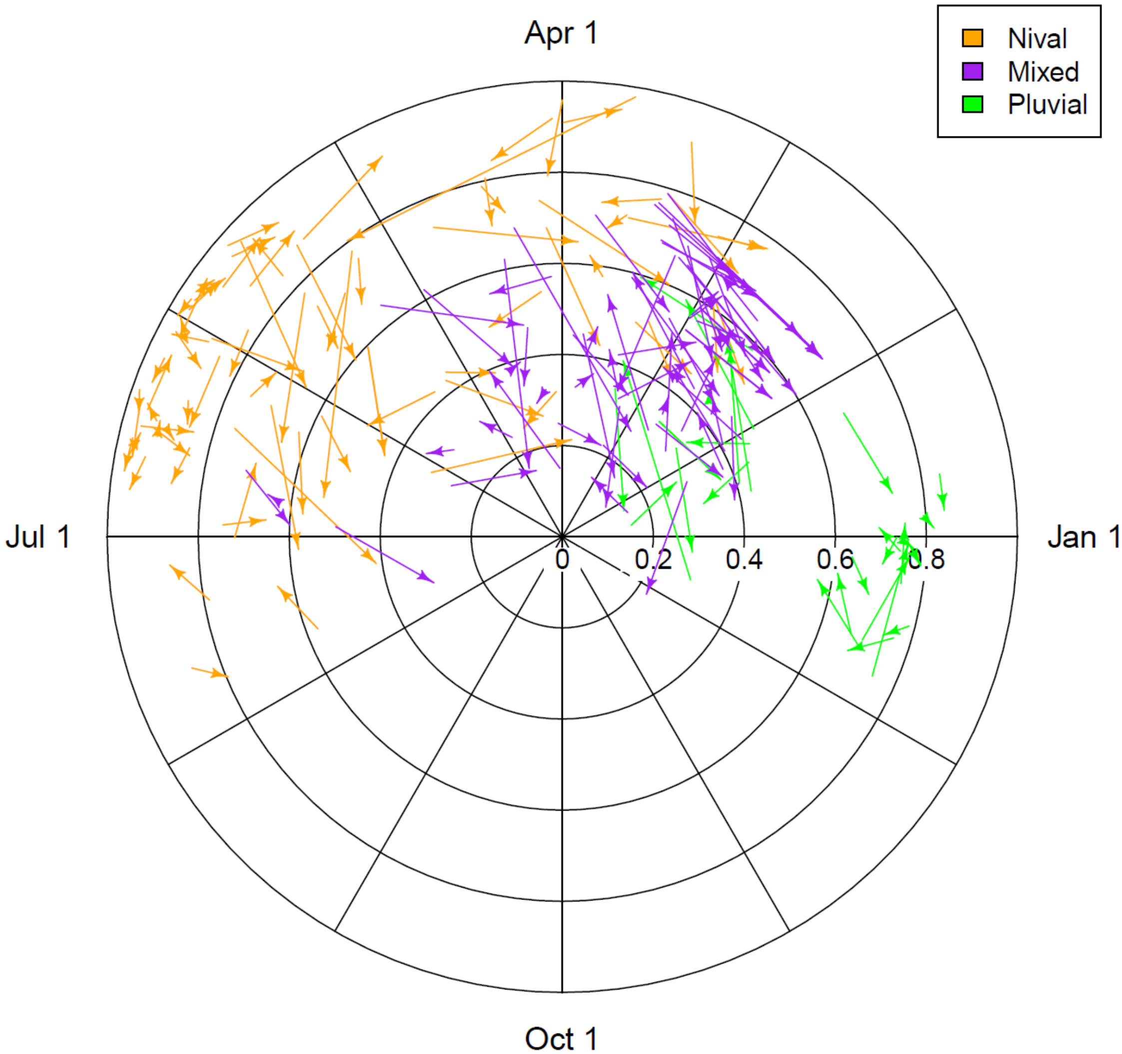

Figure 19. Change in Seasonality of POT streamflow series from the first half of the streamflow record to the second half.

Changes in seasonality observed in the POT series are similar to those from the annual maximum series.

5.3.5 Number of Peaks per Year Results

Trends in the number of peaks per year series were identified and are presented in Figure 20. 23 sites were found to have an increase in the number of peaks per year, while 7 other sites have a decrease in the number of peaks per year. The increases occur in southern BC, northwestern Ontario, southern Ontario, and the Maritimes, while there are decreasing trends in central BC and a few other locations.

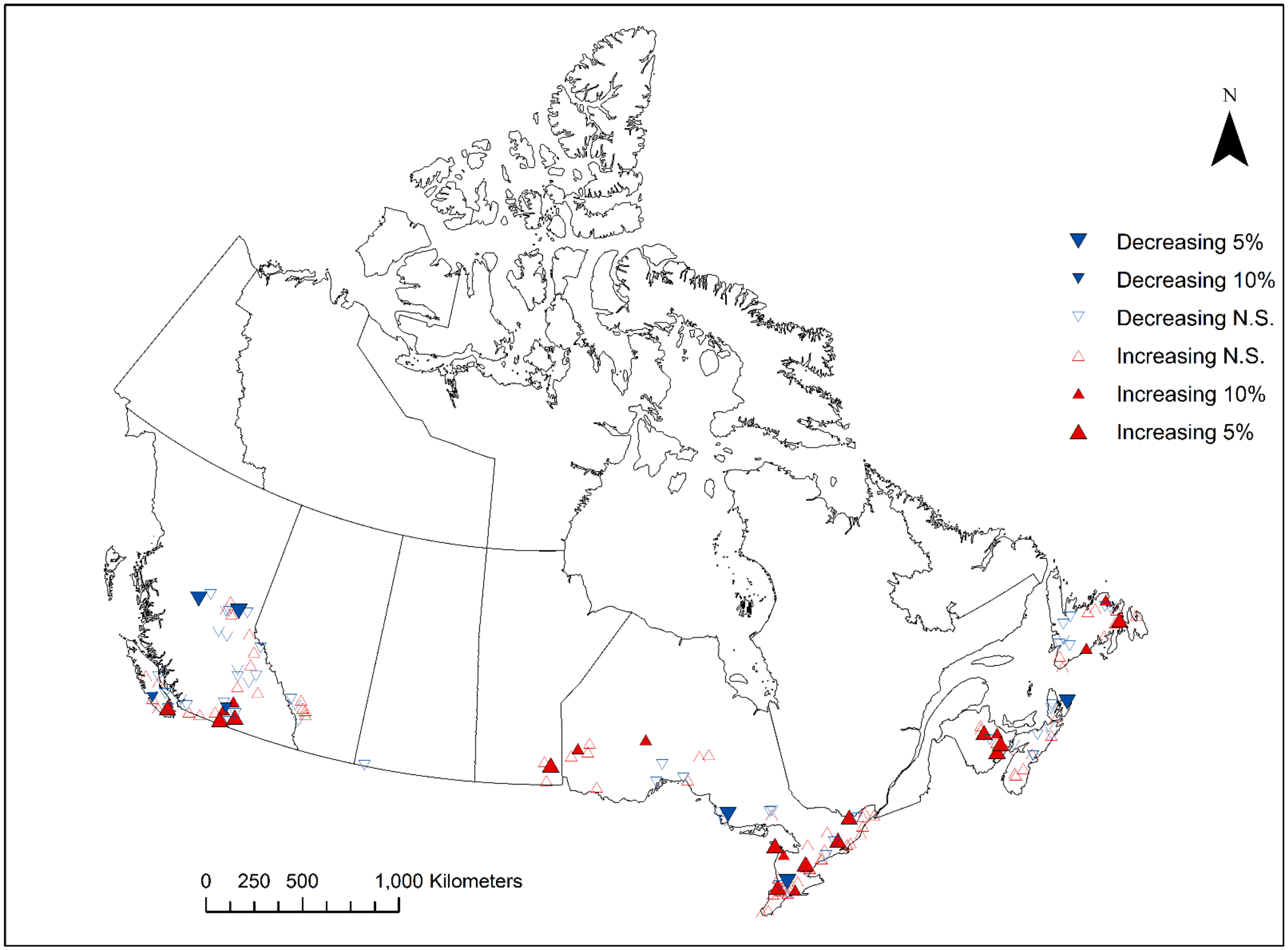

Figure 20. Streamflow trends in Number of Peaks per Year series (NPY).

Table 6 compares how many trends were identified for the npy series, and how that relates to the trends found at their associated IDF station. The number of streamflow peaks per year is increasing at locations that correspond with both increasing and decreasing rainfall events for all storm durations. The highest number of increases in the number of peaks per year correspond to sites near rainfall stations with increasing trends in the magnitude of 12 and 24-hour storms. Extreme streamflow events are increasing in frequency as a result of changes in extreme rainfall from long duration events.

Table 6. Summary of Significant Trends in NPY streamflow compared to trends in IDF

IDF Trend	IDF Duration	Number of Increasing Trends in the NPY	% Streamflow Station with Increasing Streamflow Trend	Number of Decreasing Trends in the NPY	% Streamflow Station with Decreasing Streamflow Trend
Increasing	5	7	19%	1	3%
	10	2	12%	1	6%
	15	2	7%	1	4%
	30	3	7%	2	5%
	1	6	17%	1	3%
	2	4	10%	1	2%
	6	4	11%	0	0%
	12	10	21%	2	4%
	24	13	21%	1	2%
Decreasing	5	3	13%	0	0%
	10	3	14%	0	0%
	15	2	20%	0	0%
	30	2	20%	0	0%
	1	3	14%	0	0%
	2	3	14%	0	0%
	6	3	9%	3	9%
	12	4	12%	1	3%
	24	0	N/A	0	N/A

The trends in the number of peaks per year are illustrated on a seasonality plot in Figure 21. The mean event timing corresponds to the peaks over threshold series. While most of the increasing and decreasing trends are spread out, there is a notable cluster of mixed regime sites occurring in March with an increase in the number of peaks per year. The three decreasing trends for nival sites with a mean event date in June are located in BC.

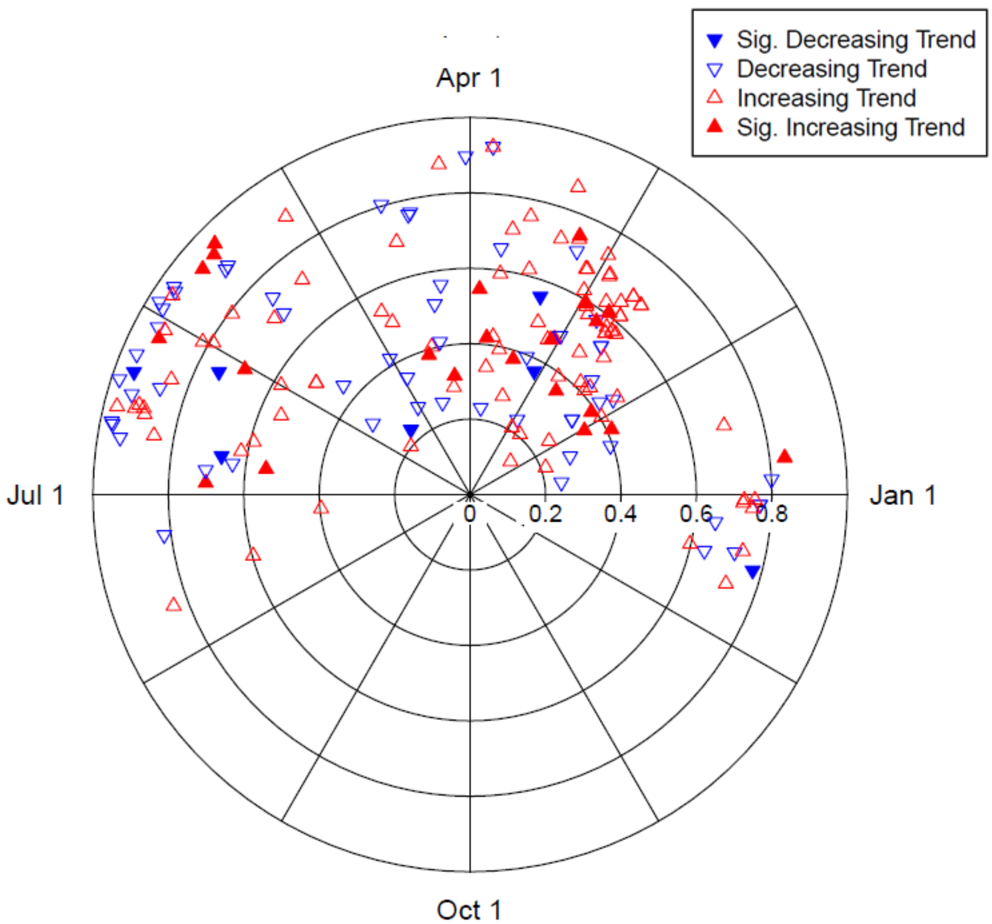

Figure 21. Seasonality and trends for number of peaks per year streamflow series.

5.4 Removing Snowmelt Period (Exclusively rainfall driven flood events results)

To assess exclusively rainfall driven events, the snowmelt period of streamflow was removed from nival and mixed sites as outlined in Section 3.5. After removing the snowmelt period, annual maximums were recalculated based on the daily data for the remaining portion of the year. Therefore, the magnitudes of the annual maximums differ from those presented in Section 5.2. Due to the amount of effort involved in the peaks over threshold selection process, thresholds were not recomputed after removing the snowmelt. The removal of the snowmelt period resulted in fewer peak events. To retain more sites, sites were included in the trend analysis if 20 or more peaks were retained.

5.4.1 Annual Maximum Streamflow Results

5.4.1.1 Mann-Kendall Trend Results

The majority of annual maximum streamflow series are found to have increasing trends. This reverse in trend confirms the decreasing annual maximum flow observed in section 5.2 was due to decreasing spring freshet. The trends shown in Figure 22 however, are exclusively rainfall driven. Most streamflow sites have increasing trends, with the exception of those located in British Columbia and Nova Scotia. While more increasing than decreasing trends is more consistent with the extreme rainfall trends, the spatial location of these trends differs. Disagreement with the extreme rainfall trends occurs in Nova Scotia and most of southern Ontario. It is interesting to note that all significant trends in rainfall driven streamflow events in Ontario are increasing, contrary to mainly decreasing extreme rainfall trends in this area.

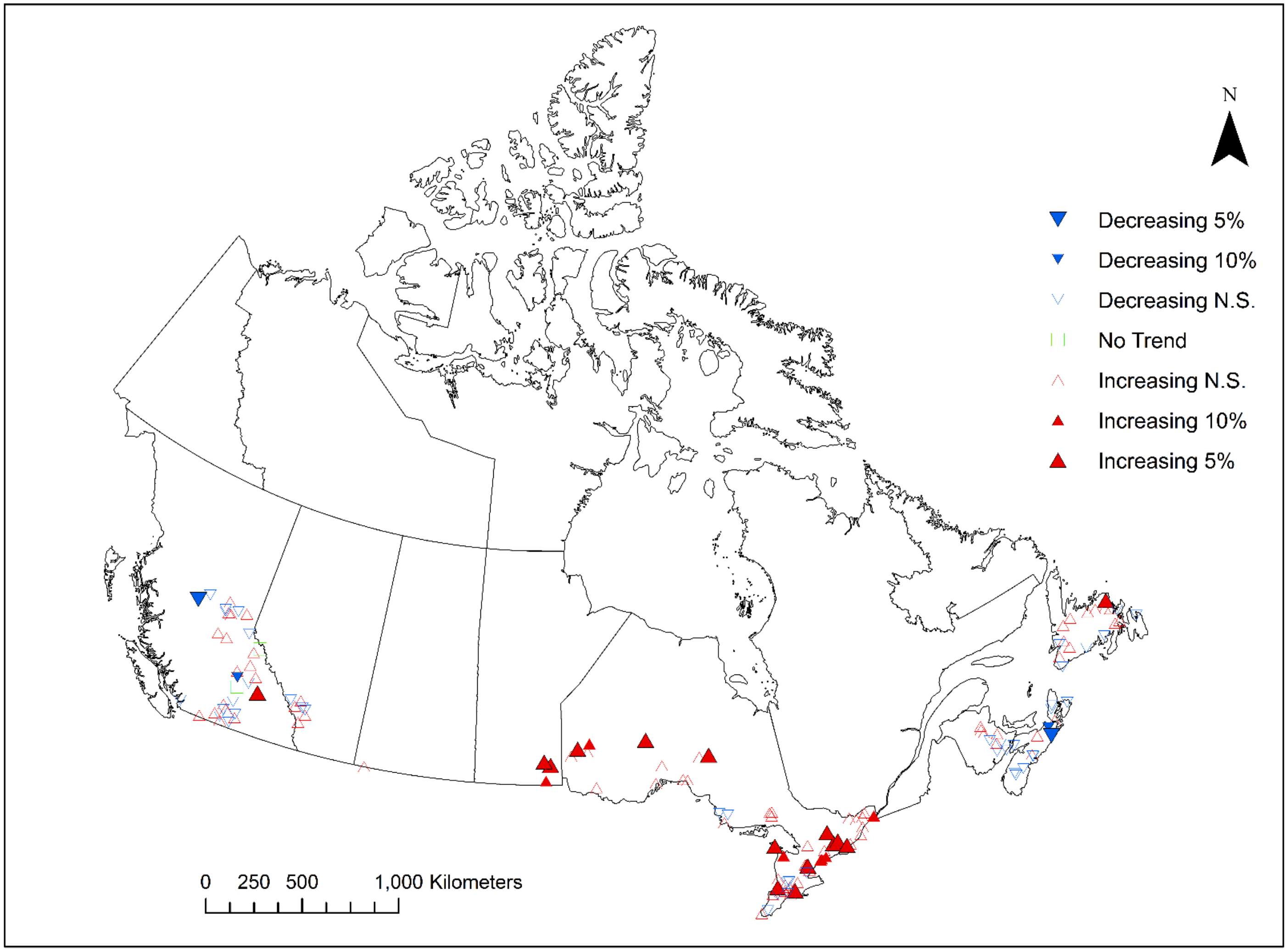

Figure 22. Streamflow trends in exclusively rainfall driven Annual Maximum Streamflow series (AMF)

5.4.1.2 Change Point Analysis

A change point analysis was conducted for all the exclusively rainfall driven annual maximum streamflow series. A summary of the resulting change point dates is shown in Figure 23. The histogram shows a wide spread of change point date. There is no strong evidence from the change point analysis to refute any trends identified.

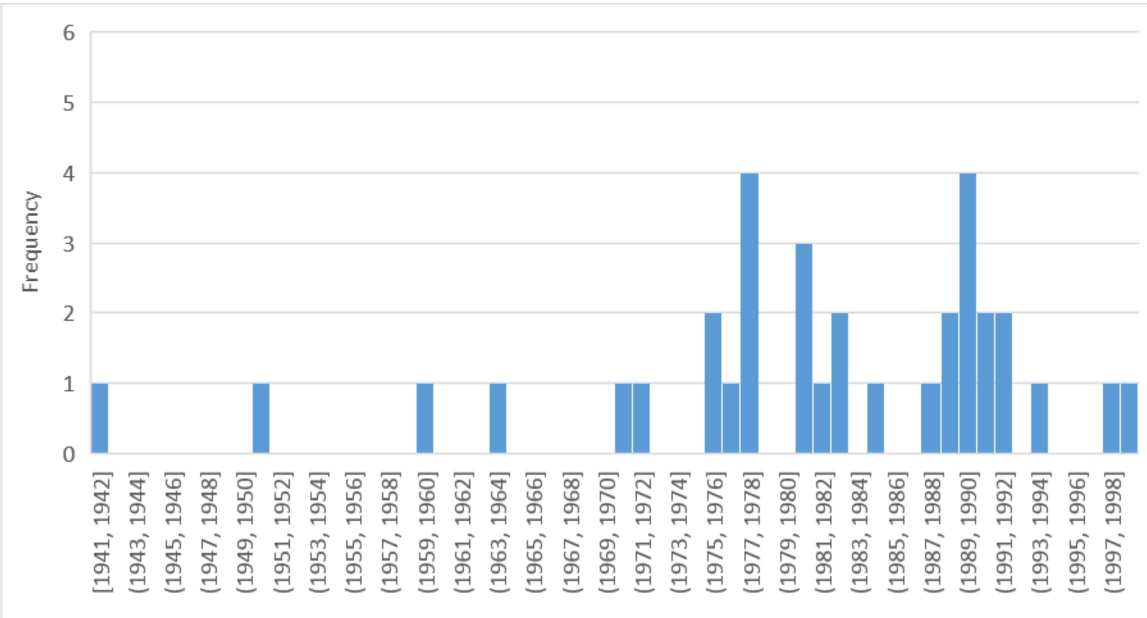

Figure 23 Change point histogram for rainfall driven annual maximum streamflow series

5.4.1.3 Comparison of AMQ Trends to IDF Trends

As shown in Table 7, with the exception of the 6 and 12-hour storm, between 8 and 9 increasing streamflow trends were identified for all other storm durations resulting in 14-47% agreement with increasing IDF trends. Despite fewer increasing streamflow trends for decreasing IDF trends, a similar level of disagreement was obtained (9-30%) as there are fewer decreasing IDF trends as well.

Table 7. Summary of Significant Trends in exclusively rainfall driven annual maximum streamflow compared to trends in IDF

IDF Trend	IDF Duration	Number of Increasing Streamflow Trends	% Streamflow Station with Increasing Streamflow Trend	Number of Decreasing Streamflow Trends	% Streamflow Station with Decreasing Streamflow Trend
Increasing	5	8	28%	0	0%
	10	8	47%	0	0%
	15	9	33%	1	4%
	30	8	20%	3	7%
	1	9	26%	1	3%
	2	8	24%	0	0%
	6	3	10%	1	3%
	12	2	5%	1	3%
	24	9	14%	2	3%
Decreasing	5	4	17%	0	0%
	10	4	18%	0	0%
	15	3	30%	0	0%
	30	3	30%	0	0%
	1	4	18%	0	0%
	2	4	18%	0	0%
	6	3	9%	1	3%
	12	7	21%	0	0%
	24	0	N/A	0	N/A

5.4.2 Peaks over Threshold Results

5.4.2.1 Mann-Kendall Trend Results

The results of the peaks over threshold trend analysis after removing the snowmelt period are shown in Figure 24. Removing the snowmelt period resulted in fewer above threshold events. Fewer stations were included in order to retain at least 20 threshold exceedances at each site. The trend analysis on the peaks over threshold streamflow series results in significant trends in southern Ontario and eastern Canada only. Many sites further north and in the West did not have enough events to analyse after the removal of the snowmelt period. Only 5 increasing trends and 5 decreasing streamflow trends were identified. All five decreasing trends are significant at the 5% significance level.

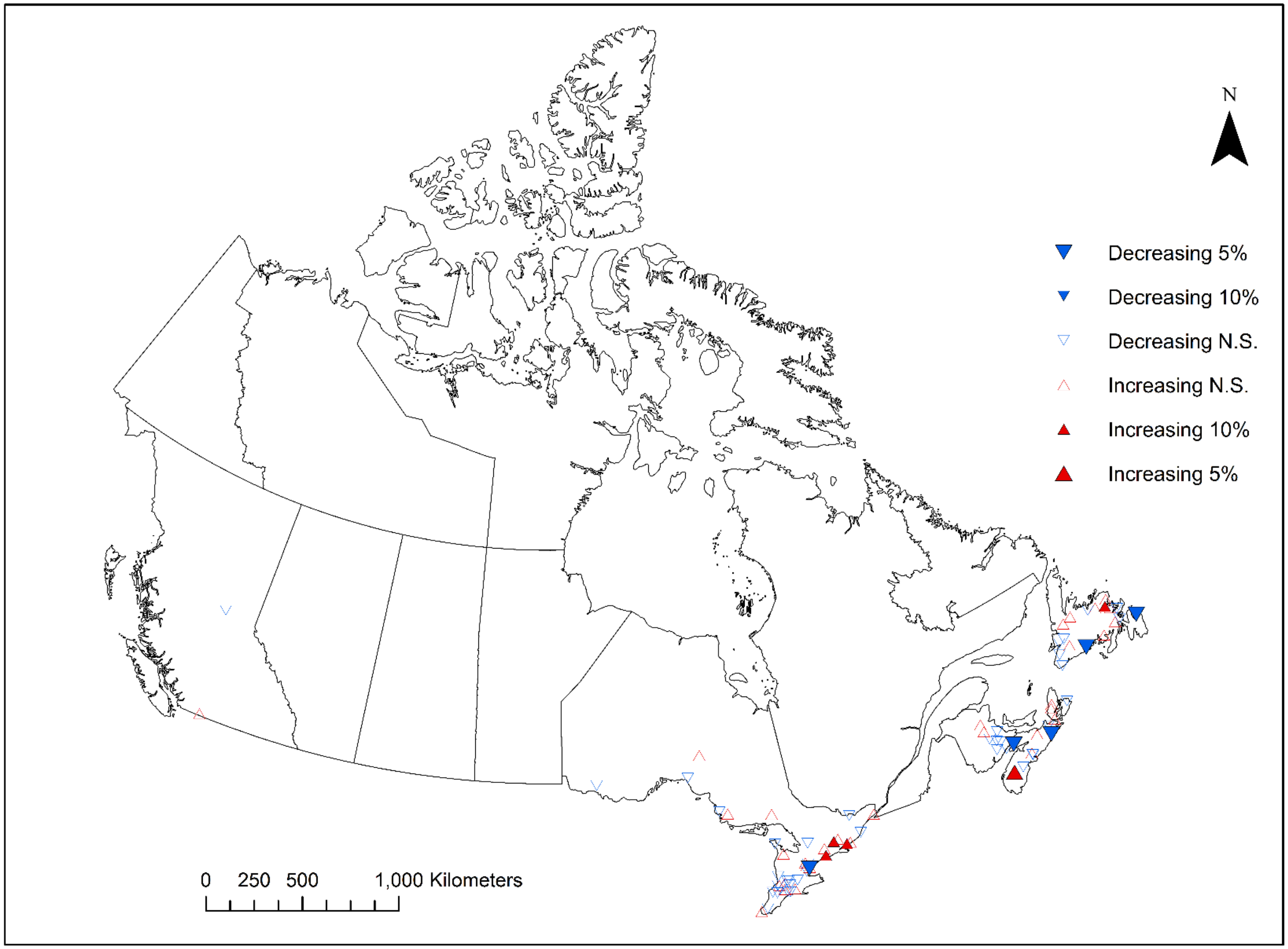

Figure 24. Peaks Over Threshold (No Snowmelt)

5.4.2.2 Change Point Analysis

A change point analysis was conducted for all the no snowmelt peaks over threshold series. A summary of the resulting change point dates is shown in Figure 25. The histogram shows a wide spread in the timing of change points. There is no strong evidence from the change point analysis to refute any trends identified.

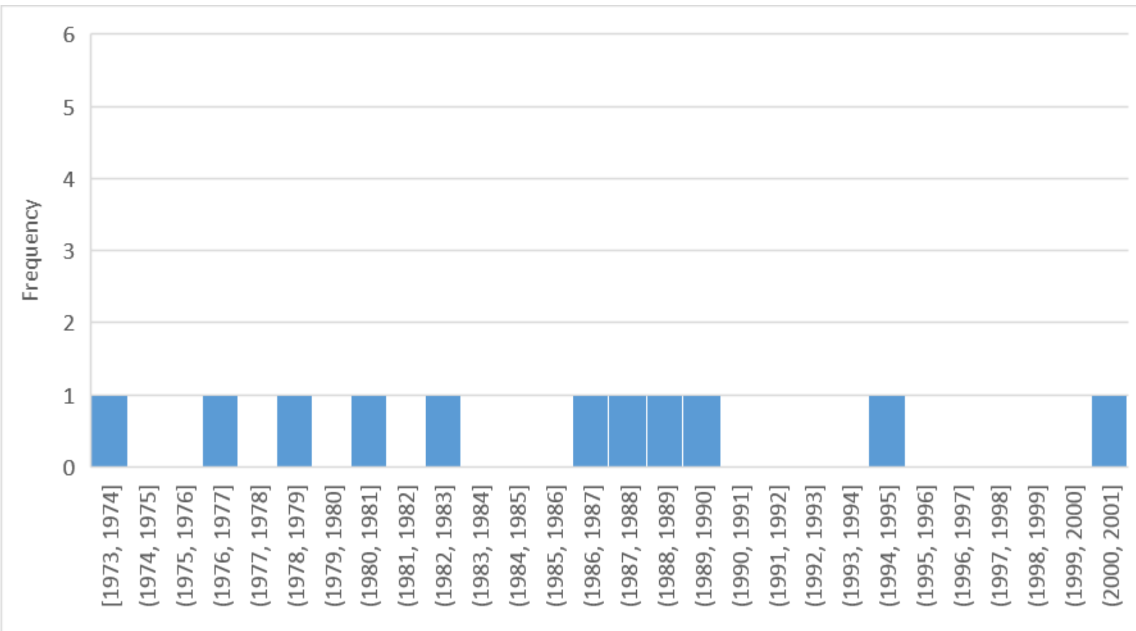

Figure 25 Change point histogram for rainfall driven peaks over threshold streamflow series

5.4.2.3 Comparison of POT Streamflow Trends to IDF Trends

Comparing the streamflow trends to IDF trends shows more agreement in southern Ontario than in eastern Canada. The decreasing streamflow trends observed in Eastern Canada are contrary to the only increasing rainfall trends identified there.

Table 8 relates the identified streamflow trends with corresponding rainfall trends. As illustrated in Figure 24, a cluster of three of the increasing trends were identified associated with Belleville, which had increasing rainfall trends for all durations between 5 min – 2 hour. There were not enough other trends identified to assess relationships.

Table 8. Summary of Significant Trends in exclusively rainfall driven peaks over threshold streamflow compared to trends in IDF

IDF Trend	IDF Duration	Number of Increasing Streamflow Trends	% Streamflow Station with Increasing Streamflow Trend	Number of Decreasing Streamflow Trends	% Streamflow Station with Decreasing Streamflow Trend
Increasing	5	3	20%	1	7%
	10	3	27%	0	0%
	15	3	27%	0	0%
	30	4	12%	3	9%
	1	4	25%	2	13%
	2	4	17%	2	8%
	6	1	5%	2	11%
	12	1	6%	1	6%
	24	2	7%	3	10%
Decreasing	5	1	6%	0	0%
	10	1	6%	0	0%
	15	1	17%	0	0%
	30	1	17%	0	0%
	1	1	6%	0	0%
	2	1	6%	0	0%
	6	0	0%	0	0%
	12	0	0%	1	3%
	24	0	N/A	0	N/A

5.4.3 Number of Peaks per Year Results

Trends in the number of peaks per year series were identified and are presented in Figure 26. 14 sites were found to have an increase in the number of peaks per year, while 5 other sites have a decrease in the number of peaks per year. The increases occur in Ontario and Newfoundland, while there are decreasing trends in Penticton, British Columbia and Nova Scotia. This is fairly similar to the findings of Burn *et al.* (2010) which found the number of rainfall driven events to generally be increasing in eastern and central Canada, with some decreasing trends occurring in western Canada.

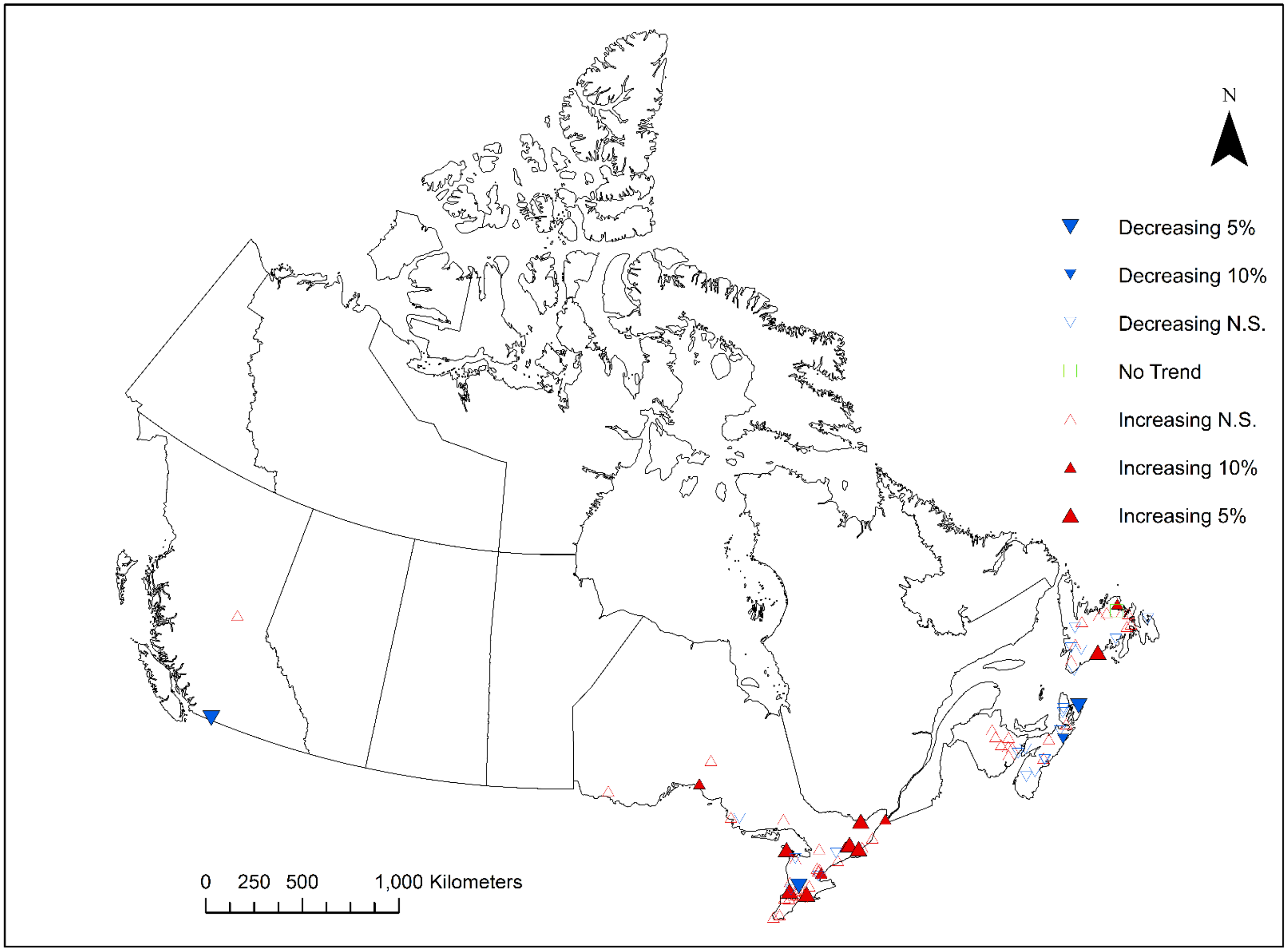

Figure 26. Streamflow trends in number of peaks per year (NPY), excluding the snowmelt period

Table 9 illustrates that the frequency of streamflow events is increasing for all storm durations, regardless of whether the magnitudes of the rainfall events are increasing or decreasing.

Table 9. Summary of Significant Trends in the number of peaks per year for exclusively rainfall driven streamflow compared to trends in IDF

IDF Trend	IDF Duration	Number of Increasing Streamflow Trends	% Streamflow Station with Increasing Streamflow Trend	Number of Decreasing Streamflow Trends	% Streamflow Station with Decreasing Streamflow Trend
Increasing	5	4	27%	1	7%
	10	5	45%	0	0%
	15	5	45%	0	0%
	30	6	18%	2	6%
	1	6	38%	0	0%
	2	5	21%	0	0%
	6	2	11%	1	5%
	12	1	6%	0	0%
	24	5	17%	0	0%
Decreasing	5	7	39%	0	0%
	10	6	33%	0	0%
	15	5	83%	0	0%
	30	5	83%	0	0%
	1	6	33%	0	0%
	2	6	33%	0	0%
	6	2	8%	1	4%
	12	4	13%	1	3%
	24	0	N/A	0	N/A

5.5 Discussion

Despite mostly decreasing trends observed in extreme rainfall in Ontario, most maximum annual rainfall driven streamflow events were found to be increasing. This suggests there may be other factors or multiday rainfall events contributing to the non-snowmelt streamflow events. Renard *et al.* (2008) state "there is no reason to believe that a trend in annual maxima of rainfall will result in an identical trend in annual maxima of discharge." This study was limited to single event storms for durations under 24 hours. The most intense storms may not directly cause a comparatively large streamflow event as the peak discharge depends on a number of factors. Factors such as the antecedent conditions, multiple consecutive wet days, and rain on snow will influence the response of the streamflow event.

To separate other impacts on streamflow from climate change impacts (such as urbanization, dams, etc.), only streamflow sites classified as "natural" as opposed to "regulated" were selected and preference was given to RHBN sites where possible. As climate stations are located at urban centers, this may result in streamflow stations meeting this criteria being further from rain gauge and watersheds selected which may not be receiving the same precipitation. While all stations selected for inclusion are classified as natural, a few are still located in urban areas. The urbanization over time may be partially responsible for trends as reduced perviousness will result in peakier events. For these reasons the change point analysis was completed on the datasets, however it was difficult to discern change points from trends without further investigation into each site.

Streamflow stations selected for this study were within 200 km from the rainfall stations found to be exhibiting trends. Due to the variability of rainfall patterns and spatial coverage of storms, it is not certain that the gauges selected to be associated with a given climate station will experience similar extreme precipitation events. If the extreme rainfall falls outside of the catchment or within a fraction of the catchment, the streamflow events may not correspond to that precipitation. This can be especially true for thunderstorms which can be very localized. In some locations, such as southern Ontario where rainfall gauges are more densely located, streamflow sites selected to be associated with an IDF station with a trend may have been more closely located to other IDF stations which in the analysis were found to not have a significant trend. Other factors like elevation may influence whether the selected climate data are actually representative of the selected watersheds. This was not assessed in the process of selecting comparison streamflow sites. Comparing the timing of rainfall to streamflow on an annual or peak basis may help verify if the selected streamflow site is representative of the climate station.

The snowmelt period for some sites was obviously shifting (in many sites becoming earlier). However, to be consistent and simplify/standardize the approach only one overall time period was classified as the snowmelt period and removed. This could result in some rain events being excluded due to a wider snowmelt period as opposed to a shifting snowmelt period. This is also true for sites that do not have a defined snowmelt period in certain warmer years.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The Mann-Kendall non-parametric trend test was used to identify trends in IDF data for various rainfall durations at stations across Canada. Nearby streamflow sites were examined for trends in annual maximum flow and peak streamflow as defined using a peaks over threshold analysis, as well as in the number of peaks per year exceeding the threshold.

Of the 51 IDF stations analyzed for trend 20 were found to have a significant trend for at least one duration. While the majority of trends were increasing, a significant decreasing trend was identified in Prince George and four significant decreasing trends were identified in southern Ontario. Although most of the IDF sites found with a significant trend were showing signs of increasing rainfall amounts, more streamflow sites were found to have a decreasing trend for both trends in the annual maximum and peaks over threshold streamflow event series.

The trend for each streamflow station was compared to the trends in the IDF durations for the IDF station it was associated with. For increasing annual maximum streamflow trends, the highest level of agreement was with the 24-hour storm duration (8%), while for decreasing trends, the highest level of agreement was for 15-minute and 30-minute storms (80%). Overall for the annual maximum analysis there was nearly an equal amount of agreement to disagreement in trend direction. The most disagreement was found for the short durations, where between 25% and 29% of streamflow sites had a decreasing trend where an increasing rainfall trend was observed. Trends on the peaks over threshold streamflow series were similar to the annual maximum streamflow with a higher level of agreement obtained. No increasing streamflow trends were found where a decreasing IDF trend was identified, however a decreasing streamflow trend was identified for increasing IDF trends of all duration lengths. Reviewing the seasonality of the sites supports that many of the streamflow sites that are decreasing in trend are from a nival snowmelt regime, and may be changing towards a mixed regime, making rainfall driven events more important. The number of peak streamflow events per year also was generally increasing across the country (except for a few areas such as more northern BC sites). The majority of decreasing streamflow trends were a result of decrease in the spring freshet. After removing the snowmelt period, rainfall driven streamflow events were evaluated for trend and found to be mainly increasing. While the overall agreement in trend direction between the extreme rainfall and streamflow events increased, disagreement still occurred in the East Coast sites and much of southern Ontario, where unlike the rest of the country, a cluster of IDF stations experienced decreasing trends in extreme rainfall. After removing the snowmelt period annual maximum streamflow only experienced increasing trends in Ontario sites. While annual maximum events were resampled from the dataset after removing the snowmelt period, thresholds were not re-evaluated for peaks over threshold series. As the shift to rainfall driven events is more recent, few sites had greater than 20 peak events when the snowmelt was excluded and some sites were lost in the analysis due to insufficient number of peaks. The peaks over threshold resulted in fewer significant trends due to the smaller dataset. While Ontario sites were in agreement, there were more disagreeing trends on the east coast than agreeing and no significant trends were identified in western Canada. The increases in the number of peaks per year occur in Ontario and Newfoundland, while there are decreasing trends in BC and Nova Scotia where sites are more pluvial than nival, and rainfall events occurring in the winter may have been removed during the removal of the snowmelt period.

6.2 Recommendations for future work

A limitation of trend tests is that they are retrospective and can only show what has happened in the past and not indicate directly what will happen in the future (Burn et al. 2010). In order to better assess whether the historical observed trends would continue in the future, downscaled results from a Global Climate Model should be fed into a hydrologic model for analysis (Burn et al., 2010).

Evaluating trends in multiple locations within close proximity can increase the likelihood of Type I error resulting in more trends identified than likely to be occurring. Therefore, it is suggested that in future analysis a field significance analysis be conducted. This could be conducted using a bootstrap analysis.

This analysis was conducted with the latest data at the time. It is likely that more data will be available. The extension of period of record would allow both for a more up to date analysis of trends and potentially the inclusion of more locations that previously did not meet the minimum length of record to be included in this study. The inclusion of more stations, particularly in the north and in Quebec where no stations were available, would allow for a more holistic view of changes in Canada. As most of the hydrologic regime changes were occurring more recently, an extended series may allow for the inclusion of more rainfall driven events.

A uniform snowmelt period was identified for sites, however this can vary year to year, and with changing climate, the timing of snowmelt will shift. In order to truly represent exclusively rainfall driven events, without excluding any by choosing a snowmelt period that is too wide, a different type of analysis would need to be conducted. A hydrologic model could be used to separate which events are a result of snowmelt, or examination of temperature for the same locations may provide some insight. While this would provide more valuable insight on a case by case basis, it would be considerably more work to assess multiple locations such as in a study like this.

Many of the peak events were lost after removing the snowmelt period, shortening the series resulting in some sites being excluded in the trend analysis. After removing the snowmelt period, the peaks over threshold analysis should be repeated on the remaining dataset. With the exclusion of the snowmelt events, lower thresholds may be selected at some sites and more peak events will be retained.

A further recommendation is to look at other metrics of extreme rainfall. This could include a peaks over threshold analysis on rainfall or consider a duration longer than 24 hours to consider the impact of multiple consecutive wet days.

Further examination into watershed characteristics and IDF durations and their effect on changes in streamflow are suggested.

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