Low-flow hydrology in low-order basins in Canada

by

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ABSTRACT

LOW-FLOW HYDROLOGY IN LOW-ORDER BASINS IN CANADA

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There is insufficient information about streamflow conditions in low-order, headwater streams in Canada despite being important hydrological and ecological features. A defining characteristic of many of these streams is that they experience intermittent flow during drier periods. As such, these streams are especially sensitive to change. There are numerous challenges with monitoring ephemeral streamflow activity, and the connectivity of these streams to both their hillslopes, and to downstream areas. The aim of this thesis was to quantify and describe the dynamics of low-flow conditions in temperate headwater streams.

Coupling an electrical resistance sensor with a new flow-detection sensor, a paired-sensor monitoring approach was used to monitor ephemeral activity in two small headwater catchments in southern Ontario. The timing of the transition between a continuously flowing stream to an intermittent stream differed between sites, with one site transitioning at the end of May, and the other at the end of August. These transition times were attributed to differences in precipitation during the field season, and compared to 40-year climate averages for each month. Predictors of flow were determined using monthly binary logistic regression models and found to vary monthly over the study period. Predictors such as maximum rainfall intensity were found to
be more seasonal, while others such as total rainfall, were more consistently identified.

An analysis of 40-year trends in discharge and low-flow indicators was conducted for unregulated streams in Canada. Annual discharge decreased widely across Canada with the timing of significant decreases occurring mainly during the summer months, and increases in the winter months. Significant decreases to the number of low-flow days were observed, however, regions with significant increases to both the number and length of low-flow events were also observed.

Changes to the frequency and timing of low-flow conditions in headwater streams can impact the hydrology and ecology of downstream waterways and the connectivity of hillslopes with fluvial systems. Long-term relationships between climate variables and low-flow conditions cannot be fully understood without adequate monitoring in headwater streams. Understanding the forms, processes, and functions of these critical, but vulnerable, temporary waterways has a long way to go in Canadian hydrology.
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1.1 Introduction

Catchments are composed of networks of branching streams varying in size, both in terms of physical size, as well as by other common metrics, such as discharge (Nadeau and Rains, 2007; Hansen, 2001). Another metric by which streams are classified is their permanence on the landscape. The most common terms for these streams are perennial, intermittent, and ephemeral, where they range from groundwater-based through to episodic. Though this discrete labelling system is ideal in briefly describing a type of stream, streams ultimately lie on a continuum of flow based on their properties (Uys and O’Keeffe, 1997). Uys and O’Keeffe (1997) describe this continuum based on flow permanence, where perennial streams are entirely permanent, being fed by groundwater between rainfall events, and are relatively the most predictable in terms of flow due to low variability (Figure 1.1). On the other end of the spectrum, Uys and O’Keeffe (1997) describe episodic streams as having predominantly event-driven flows and as such, being highly variable in their flow as well as the least predictable. Although extensive networks of intermittent and ephemeral streams are most commonly associated with arid and semi-arid regions, stream networks within humid temperate regions often exhibit ephemeral streamflow within their lowest-order reaches (Gomi et al., 2002a; Lowe and Likens, 2005; Uys and O’Keeffe, 1997; Bishop et al., 2008).
Low-order streams tend to be spatially extensive and can account for large proportions of a catchment’s network when flowing (Horton, 1945; Hansen, 2001; Blyth and Rodda, 1973; Day, 1978), however, are largely ignored in temperate environments (Bishop et al., 2008). Due to their small catchment sizes and extreme variability, studying these streams is not always a priority, however, they have been shown to be important hydrologically (Bishop et al., 2008; Wigington et al., 2005; Nadeau and Rains, 2007), ecologically (Labbe and Fausch, 2000; Meyer et al., 2007; Nadeau and Rains, 2007; Gomi et al., 2002a; Platts, 1979), and geomorphologically (Chin and Gregory, 2001; Gomi et al., 2002a; Bull, 1997), as well as being prone to disturbances from both anthropogenic and natural sources (Chin and Gregory, 2001; Bishop et al., 2008; Meyer et al., 2007; Covich et al., 1997; Brooks, 2009).
High-order streams tend to have low variability in flow, given their large catchment areas, and high volumetric discharge. These large catchment areas also provide a buffer from disturbance, or lengthen the time before any disturbance impacts the stream. However, anthropogenic risks from high-order streams are great, especially from flooding conditions. As such, studies of flooding conditions and risk management in Canadian perennial streams are numerous (e.g. Ward, 1989; Nirupama and Simonovic, 2007; Marsh and Hey, 1989; Peters et al., 2006; Wolfe et al., 2007). Low-flow considerations in these streams tends to be less studied, as the high levels of discharge and large catchment areas provide a sufficient buffer in most cases. In cases where stream regulation has been placed, this buffer from change is further increased. This relatively low variability in flow and buffering from disturbance has lead to high predictability of flow in many high-order streams. As a result of the great anthropogenic risks, and applications stemming from high-order streams, hydrological and ecological monitoring has focussed heavily on these streams.

Looking further upstream at medium and low-order perennial streams, flow variability tends to increase, as the smaller catchment areas provide less of a buffer. Monitoring in these streams uses the same techniques as higher-order streams, however tends to be done more sporadically than in the higher-order streams. The increase in flow variability, coupled with less monitoring in these streams, makes predicting discharge in these streams less reliable than in high-order streams, however, still sufficient. Anthropogenic risk from flooding tends to be minimal from these streams as the smaller floodplains associated with these smaller streams, tend not to impact large areas. Seasonal low-flow (Smakhtin, 2001) in these streams is more of a consideration, as during dry years, or during drought, the change in discharge can impact ecological (Smakhtin, 2001; Bunn and Arthington, 2002; Poff and Allan, 1995; Poff and Zimmerman, 2010) and geomorphological regimes Andrews (1979); Friedman et al.
In the furthest headwater areas, many of the lowest order streams exhibit periods of zero-flow, leading to high levels of variability in flow. This changes in discharge can range from seasonal, through to being episodic, only flowing when rain is occurring. The anthropogenic risk associated with these streams is largely non-existent, however, there are ecological and water quality factors that can be impacted by changes in these streams. Monitoring efforts in these streams is largely absent (Bishop et al., 2008), save for select studies in certain landscapes. As a result, current prediction in these streams in Canada is largely impossible, and most efforts tend to come from extrapolation of processes from downstream areas Buttle et al. (2012). The results of low-flow modelling methods from the Prediction in Ungauged Basins (PUB) literature point toward greater accuracy in humid areas, than arid areas, and larger catchment, than smaller catchments (Salinas et al., 2013). Given that one of the objectives of the PUB was to move away from models strongly based on calibration to models that had a stronger emphasis on increased levels of understanding (Hrachowitz et al., 2013), these results point to the continued need to further the understanding of processes in these smaller catchments. Given the sensitivity to change in these smallest streams, coupled with the lack of monitoring data, long-term prediction of the potential changes to these lowest-order streams is largely impossible. However, using active hydrometric stations in medium and low-order streams could help to shed light on these potential changes by capitalizing on the variability inherent in these monitored streams. If long-term changes in discharge are found, then the likelihood of change in the lowest-order streams is high. Given that these lowest-order streams are often sitting at a hydrological threshold, the impacts of crossing that threshold can be marked. To better understand the potential impacts, the forms, processes and functions of these lowest-order streams will be highlighted.
1.2 Form, process and functions of intermittent streams

1.2.1 Form

There is no universally accepted definition of intermittent streams (Uys and O’Keeffe, 1997). Instead, the terms gets used for streams where flow presence is variable throughout the year and is interspersed with other terms such as temporary, seasonal, interrupted, episodic or dryland streams (Uys and O’Keeffe, 1997). Some of these terms are also used to define streams not by their flow permanence, but by other characteristics such as periodicity, drying regime, and ecological structures (Meyer and Wallace, 2001; Uys and O’Keeffe, 1997). These inconsistencies largely stem from the variability in flow relative to what is expected in the given environment and Uys and O’Keeffe (1997) suggest that a strict semantic definition system is not ideal. Rather, they suggest that temporary streams can be placed along a continuum based on their flow duration (Figure 1.1), and the semantic characterization of the streams are not as important because of these blurred boundaries (Vannote et al., 1980; Uys and O’Keeffe, 1997; Hansen, 2001; Nadeau and Rains, 2007). Having blurred boundaries in defining the form and function of a catchment is not unique to temporary stream hydrology and is used widely in ecological research under the river continuum concept, suggesting that the stream network forms a gradient of conditions from the lowest-order areas to the mouth with regard to hydrology, geomorphology, and ecology (Vannote et al., 1980). The occurrence of intermittent channels on the landscape, regardless of where they lay on the continuum is largely driven by climate at the landscape scale, but can be influenced by geology and vegetation cover at the reach scale.

At the regional scale, climate is the biggest driver of intermittency where rainfall
and potential evapotranspiration (PET) are cited as being major controls on intermittency in arid and semi-arid regions (Levick et al., 2008). While these semi-arid areas do exist in Canada, mainly in the prairies, where snowmelt dominates flow regimes, there are humid areas within Canada where intermittent streams are found. The expectation in these streams is that they are dry during periods where PET is greater than rainfall inputs seasonally (Buttle et al., 2012). Exceptions to this can exist in soils that are fast draining or in areas with high-relief topography.

Hydrogeological conditions of a landscape, notably storage and hydraulic conductivity, can enhance or override the influence of climatic factors and can play a role in stream intermittency. Natural channels, such as those found in bedrock, may influence the spatial arrangement of streams (Winter, 2007). Even in less bedrock-dominated environments, the underlying material and depth to groundwater can greatly affect the prominence of intermittent streams. This is especially the case with channels with high infiltration material near the surface, but also a low-permeability layer near the surface to promote lateral movement of water during wet periods (Waddington et al., 1993). Finally, discontinuity from upstream water sources, coupled with deeper groundwater sources can lead to intermittent streams being present during specific seasons, or during specific climate conditions (Spence, 2006). For instance, a stream may be fed by an upstream wetland that provides water during normal and wet years, but during a drier year, the outlet of the wetland may be higher than the water level except during major rainfall events.

The occurrence of any one intermittent channel can be a result of many factors, but ultimately, it is the branching network of these individual channels and their interaction with the rest of the catchment, that are of the most interest. As most catchments tend to have a gradient of stream sizes, discharge rates, and other char-
acteristics, the extent of the flowing stream network can be highly variable and have highly variable consequences. How much of the stream network is flowing is dependant on the characteristics of any given location within the catchment.

1.2.2 Process

Hydrological processes

The active stream network is made up of channels that are experiencing flow at any given time in a watershed (Gurnell, 1978). The network is highly dynamic, responding to rainfall, climate, and landscape changes (Blyth and Rodda, 1973; Day, 1978; Gurnell, 1978). The extent, rate of expansion, and connectivity of the network over time is highly dependant on the processes that initiate flow in any given set of channels. As the network expands, the overall drainage density, and the connectivity in the catchment expand. The rate at which these occur is highly dependant on the how quickly each channel responds, and how long after a change in the system, the network is able to maintain that change in size. The flow, permanency and response rate of a stream network is often affected by the interactions with groundwater for each channel (Ward and Robinson, 2000).

Relating to the Uys and O’Keeffe (1997) continuum, a primary control of the location of a stream on the continuum is its interaction with groundwater. Figure 1.2 the conceptual interaction with the groundwater table for the range of descriptors from Uys and O’Keeffe (1997). Perennial season streams are largely groundwater fed both during wet and dry seasons, affecting the amount of water in the channel. More intermittent streams tend to be groundwater fed during wetter parts of the year, or during wetter years, but as the groundwater table drops below the channel bed during
dry spells, the channel can become more episodic. Finally, on the other side of the continuum, episodic channels tend to be largely unaffected by groundwater sources even under wetter climates, but rather flow is initiated only during large rainfall events.

Figure 1.2 Groundwater interaction with streams along the continuum of flow. The dashed lines show the groundwater during typical maxima, while the dotted lines show the groundwater table during groundwater minima. (After Uys and O’Keeffe (1997) & Buttle et al. (2012))

In terms of the overall flowing network, the overall size will increase during rainfall events and eventually return to a stable state after the event has concluded (Blyth and Rodda, 1973; Day, 1978; Gurnell, 1978). The rate of expansion and contraction can range from very quick and highly variable on the landscape depending on the event and the conditions surrounding it (Morgan, 1972; Day, 1980; Gurnell, 1978). The way in which these streams expand and contract has been described in the literature Bhamjee and Lindsay (2011); Peirce and Lindsay (2014).

Three general models of expansion and two models of contraction have been described (Figure 1.3). Top-down expansion describes the flow of water from the surrounding hillslopes entering a dry channel and eventually connecting to the already flowing network (Bhamjee and Lindsay, 2011; Goulsbra et al., 2009; Day, 1978; Hewlett and Hibbert, 1967). This mode of expansion tends to happen the most during high intensity rainfall as well as in streams with headward wetlands exhibiting a fill-and-spill nature. The inverse of top-down expansion would be headward expansion,
where the normal flowing network expands headward as the ground saturates, increasing the size of the network (Bhamjee and Lindsay, 2011; Goulsbra et al., 2009). This mode of expansion is usually indicative of a groundwater table rising and contributing to stream flow. The final mode of expansion, coalescence, occurs when pools within the channel fill either from groundwater sources or from runoff from the surrounding hillslopes and eventually link to form a flowing network (Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014; Day, 1978, 1980). Coalescence can occur such that it is complete (i.e. connected to the downstream network) or incomplete (i.e. discontinuous to the downstream network) (Bhamjee and Lindsay, 2011). Complete and incomplete coalescence lay on a continuum, where streams tend to exhibit both depending on both rainfall characteristics as well as physical characteristics associated with them, such as infiltration rates.

Likewise, methods of stream network contraction are downstream contraction, where the flow ceases and the channel dries from the headwater areas toward the perennial reaches, and is generally associated with groundwater driven systems (Bhamjee and Lindsay, 2011; Goulsbra et al., 2009). Disintegration is the analogous method to coalescence, whereby the flowing network stops flowing by way of discontinuous reaches forming pools (Bhamjee and Lindsay, 2011). As with coalescence, this drying can be complete or incomplete and can have an affect on how the stream network expands during the next rainfall event.

The frequency, magnitude, intensity, and spatial extent of rainfall events have been identified as important to the understanding of stream network responses (Morgan, 1972; Gurnell, 1978; Gregory and Ovenden, 1979). Time since the last rainfall event has also been found to be important, though the amount of time varies in studies from
Figure 1.3 Models of stream network expansion. A) Downstream expansion refers to the movement of water from upstream, likely as a result of wetland-dominated channels; B) headward expansion describes the movement of the hydraulic head upstream as the ground saturates; C) coalescence describes the formation of pools that expand to create a continuous or discontinuous flowing network; D) disintegration describes the receding of the flowing network into isolated pools; and E) downstream contraction is the movement of the hydraulic head downstream. (Bhamjee and Lindsay, 2011)
two hours (Morgan, 1972) to longer periods ranging from 48 hours to ten days (Day, 1978; Morgan, 1972). In cases where groundwater was dominant, these longer periods were more prevalent as the response time of the system was slower and even small rainfall events could result in relatively large changes. The physical characteristics of the channels can influence the response both in terms of the rate of expansion and the extent. Since many intermittent streams expand once the underlying bed material is saturated or the infiltration rate is exceeded (Hewlett and Hibbert, 1967; Dunne and Black, 1970), the bed material plays a large role in the response (Dunne and Black, 1970; Gurnell, 1978; Day, 1980). Many of the same aspects that affect the surface saturated area, or variable source area (VSA), also affect intermittent streams. As such, the challenges associated with identifying the spatial and temporal variability of the VSA also apply to intermittent streams. However, relatively more research has gone into understanding the VSA and its responses to rainfall events, but less attention has gone into the link between the VSA and intermittent streams. The element threshold concept has also been identified as a driver for flow, where runoff is generated from a landscape element only when its storage threshold is exceeded (Spence, 2006). Under this concept, there is potential for several water reservoirs to exist within adjacent hillslopes, each with a different storage-discharge relationships. Identifying and monitoring these reservoirs is not always straightforward, but can be important to understanding flow in certain intermittent streams.

Geomorphic processes

Aside from the physical expansion and contraction of the stream network within the catchment, intermittent streams can provide key linkages between the hillslopes and the downstream reaches (Gomi et al., 2002a). The hydrological links formed during
periods of flow can be responsible for transportation of water, sediment, nutrients, organic matter, and other pollutants downstream (Vannote et al., 1980; Gomi et al., 2002a; Wigington et al., 2005; Freeman et al., 2007). The movement of sediment downstream can have both stream-health related, as well as channel morphology effects. Compared to the relatively stable, progressive change seen in perennial streams, intermittent streams can show large changes to channel morphology during large rainfall events, but be relatively dormant otherwise (Chin and Gregory, 2001). In arid intermittent streams, it has been shown that up to 65% of total sediment transport can occur when only 5% of rainfall is accounted for (Chin and Gregory, 2001), however, in humid regions, this is less likely to occur and the low stream-power associated with most flows mean that many channels can be quite stable (Chin and Gregory, 2001; Gomi et al., 2002a; Richardson and Danehy, 2007). Channels exhibiting long-term stability are prone to sediment and organic matter build-up from debris that has fallen into the channel and this increase in debris can serve as aquatic habitat (Richardson and Danehy, 2007).

1.2.3 Function

intermittent streams can have many functions on the landscape, including being conduits of water, sediment, nutrients and pollutants, affecting downstream water quality, as well as providing ecological habitats for various types of flora and fauna. Considering the function of intermittent streams, it is important to note the variable nature of flow in the channels. This variability makes intermittent streams hot-spots on the landscape (McClain et al., 2003) only truly ‘appearing’, hydrologically speaking, during periods of rainfall or moist climatic conditions. These periods where the stream network is highly active can be considered hot-moments, describing the high
temporal variability associated with the streams. While considered hot-spots during flow, the streams are still active in other ways during non-flowing or disconnected flow periods, and can have major consequences during periods of flow. During dry periods, intermittent channels accumulate organic matter, increasing levels of carbon and nitrogen, leading to hot-moments of biogeochemical transport (McClain et al., 2003) during periods of flow, which can be highly concentrated (Vannote et al., 1980; Elmore and Kaushal, 2008; Wipfli et al., 2007). Sitting at the nexus of the hillslopes and the flowing stream network, intermittent streams can play an important role in downstream water quality (Lowe and Likens, 2005; Likens and Bormann, 1974). Water quantity in these stream ultimately balances on stream network density, connectivity to VSAs in the hillslopes, as well as connectivity to downstream reaches (Bull, 1997). During periods of high connectivity to both the hillslopes and downstream reaches, the potential for water to be transported downstream is high, and increases potential high-flow periods in these areas. However, during periods of flow where there is little connectivity to downstream reaches, these lowest-order streams can contribute to groundwater recharge (Bull, 1997).

Intermittent streams can have a variety of ecological roles depending on their temperature, water availability, and light regimes, which can affect vegetation, water chemistry, and potential food resources (Meyer et al., 2007; Richardson and Danehy, 2007). These differences are what allow for high biodiversity in intermittent streams themselves and the areas immediately surrounding them (Meyer et al., 2007). Five characteristic groups of species were identified by Meyer et al. (2007) as relying on intermittent streams: 1) endemic species adapted to these lowest-order streams, 2) species found in both low-order areas and larger streams, 3) migratory species that use these streams seasonally, 4) species that use low-order streams for life-cycle stages, and 5) species that do not live in the streams, but require resources provided by
those streams. The most common organisms found in low-order streams are algae, mosses, bacteria, fungi, and insects, however certain species of fish do utilize them at specific life-cycle stages (Meyer et al., 2007; Meyer and Wallace, 2001; Richardson and Danehy, 2007; Clarke et al., 2008; Freeman et al., 2007). The specific adaptations needed to survive in the lowest-order streams has removed many predators common in downstream reaches allowing for success in many species of insect, amphibian, and salamanders (Richardson and Danehy, 2007). Discontinuous reaches of streams make ideal fish breeding areas as the low stream-power, combined with a lack of predators, allow fish to lay eggs in pools with plenty of nutrients for their roe (Labbe and Fausch, 2000). Once the fish grow to an acceptable size, they are able to re-enter the main stream network during periods of higher connectivity. Because of the small size of low-order streams, they are prone to disturbance, both natural and anthropogenic, which has potential to eliminate local populations of species, even with small changes to the hydrological regime.

1.3 Disturbance

Due to their small size and impermanence of flow, many of these low-order streams are prone to high-levels of anthropogenic modification or extermination by way of land-use change, channelization, urbanization and damming (Chin and Gregory, 2001; Meyer and Wallace, 2001; Elmore and Kaushal, 2008). Burial of intermittent streams, especially in urbanized areas is common and depending on size, they will either be paved-over or redirected into culverts Paul and Meyer (2001). Burial has major impacts on the connectivity between hillslopes and downstream reaches, as well as changes to water quality and ecological functionality of the streams (Paul and Meyer, 2001). In areas where streams have been redirected into culverts, the ecological suitability
is very low, and the changes in hydrological pathways generally lead to highly flashy streams due to the impermeable nature of the land-cover above (Levick et al., 2008). Water quality in these cases is often compromised as runoff from paved surfaces carries various pollutants downstream with no riparian buffers (Elmore and Kaushal, 2008). Chin and Gregory (2001) found that changes to intermittent streams can have varying effects depending on the stage of development. During early development, there were high influxes of sediment into the streams however, after construction ended, sources of sediment were reduced, leading to less sediment delivery downstream (Chin and Gregory, 2001; Paul and Meyer, 2001). Water extraction and diversion have been identified as being potential causes of intermittency in streams that were historically perennial especially where groundwater depletion is occurring (Winter, 2007; Uys and O’Keeffe, 1997; Constantz and Essaid, 2007). The inverse has also been documented, where once intermittent streams become perennial after urbanization due to leakages from water supply networks (Welty et al., 2007). Human and natural fire disturbances and clearing of land for forestry and agriculture also has implications for intermittent stream water quantity and quality such as increased streamflow due to reduced interception, and more direct pathways from point and non-point source pollution Buttle and Metcalfe (2000); Malmqvist and Rundle (2002).

Agricultural modification of streams, by way of channelization, deepening, and covering leads to changes that can have significant implications for water quality and quantity (Buttle et al., 2012). Agricultural activities have been shown to increase salinity by clearing native vegetation and raising the groundwater table, reduced flows from groundwater pumping or irrigation diversion, increased nutrients and turbidity in streams from runoff originating in fields, and ecological devastation from pesticide run-off from fields into streams and groundwater sources. In addition, the use of temporary streams for livestock watering in arid areas, or simply the presence
of intermittent streams in livestock enclosures, can lead to both the widening and compacting of channels and the degradation of downstream water quality (Levick et al., 2008)

Given the high degree of coupling between rainfall and snowmelt, and flow in intermittent streams, even small changes in the former can result in large changes to the hydrological regime (Bishop et al., 2008; Brooks, 2009). Changes in the global, national and regional climate have been studied and the overall hydrological responses have been modelled. Changes in both temperature and rainfall frequency, timing and duration could have adverse responses in many low-order streams both hydrologically (Brooks, 2009; Bull, 1997) and ecologically (Johansson et al., 2010; Blaustein et al., 2010). Schindler (2001) notes that one of the potential impacts of climate change could be the movement of first-order streams toward greater intermittency and longer durations in the dry state due to increases in evapotranspiration. Along the same lines, Brooks (2009) observed that flashier flow patterns may be more prominent and would lead to longer periods of isolation for statics pools in the north-eastern United States, however, Buttle et al. (2012) state that these alterations are likely in various regions in Canada as well. Studies of the responses in specific Canadian regions have been undertaken, with varying results. In permafrost dominated areas, studies have shown that reduced permafrost may increase storage and decrease flows, leading to greater intermittent flow (Jones and Rinehart, 2010), but others have shown that a deeper active layer may provide more storage in current zero-flow basins, allowing for a more sustained flow over the summer months (Buttle et al., 2012; Newbury, 1974). In western Canada, changes in snow accumulation and snowmelt rates are expected to affect intermittent streams the greatest, where decreased snowpack or increased snowmelt rate will result in perennial streams become more ephemeral (Hauer et al., 1997). Relating the work of Covich et al. (1997) in the Great Plains,
Buttle et al. (2012) hypothesizes that the high low topographic complexity, and high hydrological diversity, of the prairie regions in Canada, will be highly responsive to climate variability and change. Specifically, Buttle et al. (2012) observed that there are a large number of intermittent streams in this region and the expected reductions in rainfall and evapotranspiration will shift all streams toward more episodic flow regimes. Extending on this, Buttle et al. (2012) notes that extreme rainfall events are expected to increase in frequency (Kharin and Zwiers, 2005) and may result in current episodic streams to become less episodic and more intermittent. Ultimately, the variability in conditions is expected to change the nature of the hydrology and ecology of these streams, but the scarcity of studies looking at the direct implications make the regional outcomes hard to predict. Much of this understanding has stemmed from inadequate monitoring over long periods.

1.4 Monitoring

As stated above, monitoring efforts tend to concentrate on high-order streams, as they have high degrees of risk associated with flooding, as well as water resource implications. However, monitoring does occur in medium and low-order streams, though more infrequently. As pointed out, these stations can be useful in determining the long-term trends in streamflow in lower-order streams, and assessing the potential for change. Within the lowest-order streams, monitoring is largely absent, and numerous studies recognize that there is a dearth of data relating to intermittent stream flow regimes (Bishop et al., 2008; Uys and O’Keeffe, 1997; Freeman et al., 2007; Buttle et al., 2012; Peirce and Lindsay, 2014; Elmore and Kaushal, 2008; Jaeger et al., 2007). The lack of monitoring data is largely attributed to the highly dynamic nature of intermittent streams, both spatially and temporally (Bishop et al., 2008). Stream
network expansion is a highly distributed phenomenon and traditional methods of hydrological monitoring are largely unsuited in these environments. This lack of data has consequences both in terms of water resource management and conservation, and without it, understanding of long-term changes in these systems is severely diminished, leading to poor policy and strategic planning (Elmore and Kaushal, 2008). Studies have monitored stream network expansion using a variety of specialized techniques.

1.4.1 Observation techniques

Observational studies have been conducted in an attempt to quantify stream network expansion (Morgan, 1972; Blyth and Rodda, 1973; Day, 1978). These pioneering studies in quantifying stream network expansion were based on field observations identifying the flowing stream head. The use of evenly spaced pegs or markers in the stream allowed for accurate positioning during storms and allowed for expansion rates to be calculated (Day, 1978). Some studies considered network expansion on an event-basis (Day, 1978; Morgan, 1972) while other observed at equal intervals, tracking seasonal changes as well as specific rainfall events (Blyth and Rodda, 1973). While successful at producing preliminary data on stream network expansion, observational studies had a unique set of challenges associated with them.

The number of streams being studied in the network were quite large and trying to observe large areas of a catchment to gather a snapshot in time was highly dependent on the number of observers available (Morgan, 1972). The result was a very coarse spatial and temporal resolution of data, which, as Morgan (1972) established, can be detrimental to studying this phenomenon because streams could dry up in as little as 30 minutes after the end of rainfall. Rapid changes in stream length, combined
with discontinuity between stream reaches made this task more daunting still (Day, 1978, 1980). These discontinuities resulted in false recordings of the true extent of connected flow and had implications for source areas of runoff (Day, 1978; Blyth and Rodda, 1973). Ultimately, the sole use of direct observation techniques was not adequate to understanding the complexities of dynamic low-order streams and common hydrological monitoring tools were ill-suited for the task.

Due to the high spatial and temporal resolutions needed for monitoring stream network expansion, automated monitoring tools are an ideal approach to address some of the issues with observational techniques. However, the erosive nature of many of these streams made certain methods unsuitable, such as velocity meters, crest-stage gauges, and stream gauges (Constantz et al., 2001). These tools can provide the high temporal resolution needed for monitoring even the fastest changes in flow, but are highly limited spatially due to their high costs and setup effort (Constantz et al., 2001; Blasch et al., 2002; Bhamjee and Lindsay, 2011). The ineffectiveness of these types of methods led to specialized sensors for monitoring distributed phenomenon such as stream network expansion.

### 1.4.2 Sensors for monitoring intermittent flow

Specialized sensors were developed in response to the demands of monitoring stream network expansion with the general goals of minimizing cost to increase spatial resolution. In doing so, iterative designs have been put forth and tested in attempts at increasing the reliability, accuracy, and temporal resolution of the data. Initial tests with sensors began with the use of temperature sensors buried beneath the bed of the stream, measuring the pronounced change in temperature when water was present or absent (Constantz et al., 2001). The major issues with using this type of sensor
surrounded the actual interpretation of the data, where trying to distinguish between flowing and stagnant water, or ice or snow required much experience (Constantz et al., 2001). Complications also arose with rapid changes in atmospheric conditions, such as when a storm front passed over the field site. Constantz et al. (2001) found that burying the sensor under the bed mitigated some of this response. The next step in the progression of specialized network expansion sensors came when Blasch et al. (2002) removed the thermistor from the temperature sensors, thereby creating an electrical resistance (ER) sensor.

By using two electrodes, the sensor was essentially an open circuit that could be closed by water covering both electrodes. The response would be recorded on the data logger as a drop in electrical resistance. A threshold of resistance was selected to represent when water was present or not in the channel by the researcher. While quite successful, a few issues still surrounded the use of ER sensors in this state. Adams et al. (2006) noted that the sensor electrodes were prone to corrosion and variability between sensor responses was high, and Blasch et al. (2002) noted that the placement of the electrodes in the channel could affect the output response. Notably, Blasch et al. (2002) showed that placement below the bed could lead to interference and recording of moisture conditions rather than flow in the channel, but that placing the electrodes too high above the bed could have consequences for the size of flows that could be measured. Another issue was in the data recording and interpretation, where interval data loggers were used, much of the data recorded was redundant, and during dry-spells, the loggers could fill up before actually recording any network expansion. Iterative improvements to both the structural and logistical issues came in following years.

The structural issues of previous designs were mitigated through the use of exter-

20
nal sensor-heads specifically designed for the environments in which monitoring was taking place (Goulsbra et al., 2009; Bhamjee and Lindsay, 2011; Jaeger and Olden, 2012; Peirce and Lindsay, 2014). In doing so, sediment build-up around the sensors was minimized resulting in more accurate data. To address issues of data interpretation and redundant data recording, Bhamjee and Lindsay (2011) introduced the use of inexpensive state-loggers coupled with specialized sensor heads. The use of state-loggers allowed for longer recording periods, as the data loggers would not fill up during dry periods, not record redundant data about when the stream was flowing. In addition, this increase in efficiency allowed for a greater temporal resolution of one second. The increase in temporal resolution proved to record a lot of noise in the data, especially during the long cessation period after a rainfall event due to the water fluctuating around the level of the electrodes. All of the aforementioned sensor designs were recording the presence and absence of water, and using that data to infer flow. However, discontinuous connectivity has been seen in studies using similar sensor designs (Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014) where coalescence was mainly shown to be the method by which the stream network expanded. By only having water presence data, it was possible to detect the formation of pools, but without actual flow data being collected, the inference of flow could only be made, with no data to back it up.

While momentum has been building on the technical front, the use of water presence as a proxy for flow has consequences in understanding the processes and the contributions of low-order streams. Overall, the monitoring effort in low-order basins is relatively poor with few studies having monitored intermittent flow over relatively large spatial scales as well as over long periods of time. The high variability of flow in these streams, and their sensitivity to climatic inputs means that they are likely going to be the first to respond to changes in climate. With little-to-no baseline data
at present in these areas, there is no way to directly assess the changes in flow regimes or even in which direction they are moving. However, using the available data from hydrometric stations in medium and low-order streams can potentially shed light on what is occurring upstream. Ultimately, the shifts in streams along the continuum of flow will occur, but without adequate data to show how they change under both natural and anthropogenic change, the amount of uncertainty surrounding these areas will be high.

1.5 Aim and objectives

The aim of this thesis was to quantify and describe the dynamics of low-flow conditions in temperate low-order streams. Therefore, the objectives are to:

1. Explore the long-term trends of low-flow events in Canada and relate those trends to future flow scenarios in temporary stream networks,

2. Identify the limitations in current intermittent stream monitoring approaches and contribute methodological solutions to those challenges, and

3. Describe the flow timing, duration, and patterns of flow processes in agricultural low-order streams in southern Ontario using a novel sensor network.

1.6 Thesis outline

Chapter 2 describes 40-year trends in discharge and low-flow indicators across Canada relates these results to intermittent low-order basins that are rarely monitored. Chapter 3 describes the current limitations in intermittent stream network activity monitoring, introduces a new flow detections sensor, and novel multi-sensor monitoring
approach that addresses the limitations of previous monitoring efforts. An analysis of intermittent stream activity is presented from data collected using the multi-sensor network in two southern Ontario catchments in Chapter 4. Finally, Chapter 5 contextualizes the implications of this research and provides insight into the future of intermittent stream monitoring.
CHAPTER 2

LOW-FLOW TRENDS IN UNREGULATED CANADIAN STREAMS

40 years (1970-2010) of daily discharge data at unregulated stations across Canada were analysed for trends in annual and monthly discharge, and three low-flow indicators. The $Q_{95}(7)$ method was used to determine the annual low-flow threshold, and trends in the number of days, the number of events, and the length of low-flow events were analysed. Trend analysis was completed using the nonparametric Mann-Kendall test, and results are reported for stations with statistically significant changes, and summarized by major river basins. Overall, annual discharge decreased widely across Canada, however, some regions experienced increases in annual discharge. The timing of the trends in discharge occurred mainly during the winter and summer months, with increases during the winter likely because of changes in snowmelt timing, and decreases in discharge during the summer months. The majority of stations had significant decreasing trends in the number of low-flow days, however, stations in some regions were found with increasing trends. The timing of changes to low-flow days was also explored, and showed decreasing trends in many basins during the spring and autumn. Low-flow events, where multiple days of low-flow conditions persist, also showed strong regional clusters of low-flow events. The west coast of Canada saw more significant increases in the number and length of low-flow events, while the central and eastern prairies exhibited fewer and shorter events. Finally, the dearth of monitoring in intermittent low-order streams is discussed in light of these results. These low-order basins are more sensitive to changes from climate and anthropogenic changes as they exist at a threshold on the landscape. As such, they are more likely to be impacted both earlier, and in a greater way, than the downstream areas where monitoring is more prevalent.

2.1 Introduction

Understanding trends in streamflow variability is meaningful for long-term water resource management. To be able to account for future long-term changes, such as changes in landuse and climate, the baseline variability in streams should be established. Trends in both annual temperature and precipitation in Canada have shown
increases over the past century (Zhang et al., 2000). The seasonality of these changes has not been uniform, with spring temperatures showing greater increases over the latter part of the 20th century (Bonsal et al., 2001). Changes to precipitation type, from snow to rain, affect the timing and quantity of water available in areas where snowmelt is the primary driver of spring and summer discharge (Stewart et al., 2005). These changes in precipitation and temperature have impacted the hydrological characteristics of many Canadian river systems. Studies in Canada have looked at how changes in climate affect trends in discharge (Zhang et al., 2001), ice conditions (Latifovic and Pouliot, 2007; Gagnon and Gough, 2005; Bonsal et al., 2006; Zhang et al., 2001), and extreme precipitation events and the resulting flood-timing and magnitude (Milly et al., 2002; Kunkel et al., 1999). However, little research has focussed on the long-term trends in low-flow indicators.

Low-flow hydrology refers to the seasonal minima of flow for a station without the resource implications that are associated with drought conditions, though some researchers refer to continuous seasonal low-flow periods as annual droughts (Smakhtin, 2001). Specifically, the changes to the magnitude, timing and persistence of these events are important, as they can affect both water resource availability and ecosystem dynamics. Studies have looked at low-flow indicators using hydrometric data, but often using only a subset of stations in reference basins (Stahl et al., 2010; Hannaford and Marsh, 2006), specifically the Reference Hydrometric Basin Network (RHBN) in Canada (Burn et al., 2010; Khaliq et al., 2008; Douglas et al., 2000; Harvey et al., 1999). Using hydrometric records from only ‘pristine’ reference basins is useful for examining how trends in low-flow indicators are related to climate, with no effects from direct anthropogenic influences, however, trends in reference basins are also less pronounced than those those not in reference basins (Bawden et al., 2014). Unregulated rivers, by comparison, are influenced by changes to climate, natural, and
anthropogenic changes in their catchments, however, the trends in these basins still affect water resources, and should not be ignored (Foley et al., 2005; Costa et al., 2003; Allan, 2004). Regardless of whether the changes to low-flow anthropogenic or not, trends are still meaningful, as they hint at what future hydrological conditions might look like in different regions of Canada.

Low-flow trends can be described using hydrometric data, however, are only representative of the areas hydrometric stations are located. Low-order basins, where many streams are seasonally intermittent or ephemeral (Uys and O’Keeffe, 1997) have highly variable flow regimes. The high variability of discharge (or lack thereof) in these streams means they are especially sensitive to changes in climate and landcover, with both water resource and ecological implications (Brooks, 2009; Chin and Gregory, 2001; Lowe and Likens, 2005; Brooks, 2009; Bishop et al., 2008; Schindler, 2001). This sensitivity means that even small changes to discharge could be more pronounced in these smaller streams than in the traditionally gauged streams. The timing of changes to discharge can also play a role in water resource availability, as the flow timing and hydrological connectivity in these streams change. Despite this, there is a shortage in the monitoring effort in these areas (Bishop et al., 2008). Schindler (2001) noted that first-order streams in Canada could become intermittent or may remain dry for longer periods because of increased evapotranspiration. Understanding how low-flow conditions are changing in Canada using the current hydrometric network can allow for a better understanding of what the changes in low-order basins might look like.

This study describes the trends in Canadian annual and monthly total discharge, and trends in three low-flow indicators in unregulated rivers. These results are presented in terms of the spatial distributions and clusters, as well as the temporal
patterns found in the trends. Given the trends found in many of the unregulated rivers in the Canadian hydrometric network, and the sensitivity of low-order streams to changes in climate and land-use, this paper argues that increased monitoring efforts in low-order catchments is important for understanding the dynamics of low-flow in Canada.

2.2 Methods

2.2.1 Data

The data used in this study were obtained from Environment Canada’s hydrometric database (HYDAT). The database contains daily measures of discharge and/or level for 7,654 stations that have operated between 1813 and present. A 40-year period between 1970 and 2010 was selected for this study as this time-frame had a large number of active stations in the database (Figure 2.1). From this set of stations, unregulated stations were selected using the respective variable in the database. Furthermore, only stations with continuous datasets between 1970 and 2010 were selected. This reduction of the data resulted in a total of 500 stations that met each of these criteria. However, stations in the Mississippi basin were omitted as it is not a major basin in Canada. As well, after filtering the data, only one station was present in the Northern Quebec and Labrador basin, and since this is not representative of this basin, it was also excluded. After this final reduction of data, 493 stations remained.

2.2.2 Variables

Six variables were analysed for temporal trends in streamflow, two total discharge variables, and three low-flow indices. Total annual discharge was calculated by summing
each daily discharge record for each station. Total monthly discharge was calculated by summing each month of discharge for each year, at each station. Each month was analysed separately for trends over time, giving a better idea of seasonal shifts to discharge. The number of low-flow days was calculated for each month using the mean $Q_{95}(7)$ value for the 40-year study period as the threshold for low-flow. The number of low-flow events considered a low-flow event to be one or more consecutive low-flow days. The beginning of an event occurred where a low-flow day was preceded by a non-low-flow day, and the end was a non-low-flow day following a low-flow day. Finally, using for each event, the number of days the event persisted were calculated. For each variable, trend analysis was completed using the non-parametric Mann-Kendall
test, often used for the detection of trends in hydrological and climatological data (Zhang et al., 2001; Smakhtin, 2001; Stewart et al., 2005; Peterson et al., 2002). To avoid false-positives created by positive serial correlation (Kulkarni and von Storch, 1995), the commonly-used ‘pre-whitening’ technique suggested by Kulkarni and von Storch (1995), and von Storch and Navarra (1999), was applied to the dataset. The trend for the time series is identified using the following procedure:

1. The lag-1 serial correlation ($c$) is computed,

2. if $c < 0.1$, Mann-Kendall test is applied to the original time series ($y_1, y_2, \ldots, y_n$), otherwise,

3. Mann-Kendall test is applied to the pre-whitened time series ($y_2 - cy_1, y_3 - cy_2, \ldots, y_n - cy_{n-1}$).

Each variable was calculated using the programming language R and sub-divided into the Water Survey of Canada’s major river basins (Figure 2.2). Grouping the stations by major basin provided a standardized approach to summarizing the data.

2.3 Results

2.3.1 Total annual discharge

Across Canada, the trend in annual discharge was mainly decreasing (Figure 2.3). 71 of the 99 stations had significantly decreasing trends, and 28 showed significant increases. The greatest proportion of stations with significant trends were located in the Great Slave Lake basin, where 38% of stations in the basin showed a significant
Figure 2.2 Major river basins of Canada and station locations. The inset table indicates the number of stations used in the study found in each river basin.
A decrease in total annual discharge. Basins with relatively high proportions of stations with decreasing trends were Western Hudson Bay, and Southern Hudson Bay with 38% and 35% respectively. The Arctic basin had the largest proportion of increasing trends with 18% of stations exhibiting significant increases in annual discharge.

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<tr>
<th>Basin</th>
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<td>Maritime</td>
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**Figure 2.3** Stations with significant (p <0.05) changes in total annual discharge trends for unregulated stations in Canada.
2.3.2 Total monthly discharge

The proportion of stations showing significant increases in total monthly discharge occurred predominantly during the winter months (Figure 2.4). Between 10% and 17% of all stations showed significant increases in monthly discharge during the period between November and April. However, during the spring and summer months, significant decreasing trends occurred in 15-20% of stations. The monthly trends in discharge for each major river basin demonstrated distinctive regional variation (Figure 2.5). In the Arctic basin, more than half of the stations had significant increasing trends during the winter months. A similar pattern was observed in the Yukon basin. However, in the Yukon basin, a higher proportion of stations had decreasing discharge trends during the summer months, peaking in July and August. The Pacific, Great Slave Lake, Nelson, Mississipipi, Western & Southern Hudson Bay, and Maritime basins all showed peaks in the number of stations with increasing trends in March or April, and again at the start of the new hydrological year in October and November.

There was more variability in the patterns between basins observed in the proportion of stations with decreasing monthly discharge trends. Peaks in the proportion of stations with significant decreasing trends in discharge were observed in almost all the basins, however the timing of those peaks varied in each basin. The Arctic, Yukon, Pacific, St. Lawrence, and Maritime basins showed marked peaks, whereas the other basins had stations with sustained decreases in discharge over the year, with smaller peaks during certain months. The Arctic, Yukon and Pacific basins showed an increase in the proportion of stations with significant decreases in discharge during the summer months, peaking in July or August. Similar peaks were observed in the Great Slave Lake, and Nelson basins, however, they were less pronounced. The
Southern Hudson Bay, St. Lawrence, and Maritime basins showed higher proportions of stations during the spring, peaking in April or May.

Figure 2.4 Percent of all stations with significant trends in total monthly discharge.

2.3.3 Number of low-flow days

More stations had significant decreasing trends in the number of low-flow days per year, than increasing trends (Figure 2.6). Across all basins, 40% of stations had decreasing trends, while 28% of stations had increasing trends. The Arctic and Yukon basins had more than half of the study stations with significant decreasing trends. On the contrary, the Western Hudson Bay, and Great Slave Lake basins had the highest proportion of stations with increasing trends at 29.4% and 27.3% respectively. There was high intra-basin variability within some basins. For example, the Great Slave
Figure 2.5 Proportion of stations with significant trends in total monthly discharge, by basin.
Lake basin had 27% of stations with increasing trends and 20% of stations with decreasing trends, but the increasing trends were clustered in the southern region of the basin. These stations formed a spatial cluster that was also present in the Nelson and Western Hudson Bay basins.

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Figure 2.6 Stations with significant (p < 0.05) trends in the number of low flow days per year.
The timing of low-flow days can impact water resources. Significant decreases in the number of low-flow days peaked in the spring and autumn months for the Arctic, Pacific, Great Slave Lake, and both the Southern and Western Hudson Bay basins (Figure 2.7). The Yukon basin had a relatively high proportion of stations with significant decreasing trends during the spring months, but not during any other months. The Nelson basin had fewer peaks, but overall, the proportion of stations with significant decreases reached a maximum during the summer months. The St. Lawrence basin had two peaks in decreasing trends, one during the winter months, and another during the early summer months. The patterns in the proportion of stations with significant increasing trends was more dampened than the patterns in decreasing trends. Peaks during the summer months occurred in the Yukon, Pacific, and Great Slave Lake basins, while the Arctic, Maritime, and Western Hudson Bay basins had peaks earlier in the year. The Pacific, Great Slave Lake, Nelson, Western Hudson Bay, Maritime, and St. Lawrence basins had a small proportion of stations with increasing trends throughout the year.

2.3.4 Number and persistence of low-flow events

Across Canada, the proportion of stations with significant decreasing trends in the number and mean length of low-flow events (i.e. consecutive days of low-flow) was greater than significant increasing trends in the same variables (Figures 2.8 & 2.9). 17.8% of the stations had significant decreasing trends, while 5.4% of the study stations had significant increasing trends in the number of low-flow events per year. The Arctic and Yukon basins had the highest proportion of stations with decreasing trends at 50% and 40% respectively, followed by the Nelson, Western Hudson Bay,
Figure 2.7 Stations with significant \((p < 0.05)\) trends in the number of low flow days per month, by basin.
and St. Lawerence basins having between 20-30% of stations with significant decreasing trends. Western Hudson Bay had the greatest proportion of stations (17.6%) exhibiting significant increasing trends, followed by the Great Slave Lake basin with 12.7%. The remaining basins had less than 10% of stations with significant increasing trends. Clusters of stations with increasing trends were present in the Nelson, Great Slave Lake, Pacific, and Western Hudson Bay basins.

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**Figure 2.8** Number of stations with significant (p < 0.05) trends in the number of continuous low flow days per year.
Canada-wide, under 9% of station showed significant decreasing trends in the mean length of low-flow events, while 3% showed increases in event length (Figure 2.9). Increases in discharge should lead to a decrease in the average length of low-flow events, and the data in Figure 2.3 demonstrates that this relation exists. However, the inverse was observed, where stations with significant decreases in annual discharge had significant increase in the average length of low-flow events. There were also stations that had significant increases in discharge and significant increases in the length of the average low-flow event, and vice-versa.

2.4 Discussion

2.4.1 Trends in discharge

Significant trends in discharge were mainly decreasing, with 14% of all stations having decreases in discharge and just over 5% having significant increases. The spatial distribution of these increasing trends was greater in the Arctic basin, where over 18% of stations showed a significant trend. This increase in overall discharge has been documented in North America (Lammers et al., 2001) and Eurasia (Peterson et al., 2002). Bawden et al. (2014) found that trends in precipitation were the greatest control on trends in discharge, and that significant decreases in discharged occurred during the summer months in the Athabasca River. This trend toward decreases in summer discharge were observed in this analysis, with around 20% of stations nationwide showing significant decreases in discharge in August. Comparing these results to the 49-year precipitation and temperature trends from Zhang et al. (2000), significant increases in both temperature and total annual precipitation were observed,
Figure 2.9 Number of stations with significant (p < 0.05) trends in the mean length of continuous low flow days per year.
particularly in western Canada. The areas with the greatest increases in tempera-
ture corresponded with many of the stations that observed significant decreases in
annual discharge. The temporal trends observed in discharge for each basin also
align well with the temporal trends in both precipitation and temperature in the
Zhang et al. (2000) study, in particular the reduction of winter precipitation in the
southern portions of the Great Slave Lake basin, where the majority of the stations
with decreasing trends were located. Similarly, where decreasing discharge trends in
the summer months were observed in the Great Slave Lake, Western and Southern
Hudson Bay, and Maritime basins, decreases in winter precipitation, and increases in
summer temperature, were observed by Zhang et al. (2000). However, some of the
stations that do not follow this pattern may also be affected by changes to land-use
over the study period. Annual precipitation projections for Canada show increases
between 5% and 50% (IPCC, 2007), however, the timing of this precipitation is ex-
cept to occur during the winter months. Winter precipitation increases could result in
greater winter discharge as precipitation is likely to occur as rain, rather than snow.
This shift in winter precipitation would mean that areas relying on spring snow-pack
for discharge would have earlier timing of low-flow events, and possibly, longer events.
Summer precipitation (June, July, and August), is predicted to increase marginally
in most of Canada, up to 10%, with potential decreases in southern British Columbia
up to 10% (IPCC, 2007). Coupled with increases in summer temperature, this could
result in longer dry periods, as well as shifts in the timing of those dry periods later
into the autumn. In addition, near-term predictions (2016-2035) of evaporation for
southern Canada are around 5% with a potential maximum 10% decrease in runoff
(IPCC, 2013). Predicting the trends in discharge, and the timing of those trends,
allows for a better understanding of overall water resource availability, however, may
not accurately describe the response of low-order basins, as they exist at a threshold.
2.4.2 Relationship between discharge and low-flow

Changes in the low-flow indicators were expected to be negatively correlated to discharge trends. Where increases in discharge were observed, it was expected that the number, severity, and timing of low-flow days and events would decrease, and vice-versa. This relationship was evident at many stations, however, there were stations with significant changes in low-flow indicators (Figures 2.6, 2.8 & 2.9), but not in annual discharge (Figure 2.3). Some stations had significant trends in discharge, but not significant trends in low-flow indicators and vice-versa. In most of these cases, if the non-significant trends were analysed, the expected relationship between discharge and low-flow indicators was still present. Significant changes to annual discharge did not always translate to significant changes in low-flow indicators, nor did significant changes to low-flow indicators imply significant changes to annual discharge.

Number of low-flow days

Comparing the number of annual low-flow days to the significant trends in discharge, 20% of stations showed significant trends in discharge, while just over 40% showed significant trends in the number of low-flow days. This showed that statistically less significant trends in annual discharge still lead to significant trends in low-flow days at many stations. Given that anthropogenic responses can be stronger than climate responses (Bawden et al., 2014) landuse changes may be the control in this instance. Changes to the timing of low-flow days can have more pronounced impacts on water resources, especially during periods where water is scarce.
Timing of low-flow days

There was an inverse relationship between total monthly discharge (Figure 2.5) and the number of low-flow days per month (Figure 2.7). However, the number of stations that had significant trends in discharge and monthly low-flow days was not equal. There were more stations with significant trends in discharge than there were stations with significant trends in monthly low-flow days (Table 2.1). Significant trends in discharge were not always found in stations with significant trends in the number of low-flow days per month. In basins with high proportions of stations with increasing trends in the number of low-flow days per month during the summer months, water resources could be strained, particularly during the key agricultural growing season. Significant increases in the number of monthly low-flow days occurring during the winter months was less prevalent. To significantly increase the number of low-flow days during the winter months more freezing would need to occur, thus lowering discharge enough to exceed the $Q_{95}(7)$ threshold.

Timing of the significant decreases in the number of low-flow days per month could mean that water is more readily available in these catchments, and could have potential implications on flooding and high-water levels. Where significant decreases in the number of low-flow days are occurring during the winter months, this could be explained by warmer winter temperatures, and thus, more discharge entering river networks that were typically frozen for much of the winter (Zhang et al., 2000). Many peaks in decreasing numbers of low-flow days tended to occur during the spring and autumn months (Figure 2.7). Regional changes to the start of spring streamflow timing are leading to earlier snowmelt and thus earlier periods of high discharge (Stewart et al., 2005). Earlier periods of high-discharge would be reflected as decreasing trends in the number of low-flow days during these transition months. The persistence of
Table 2.1 Comparison of the number of stations with significant trends in monthly discharge & monthly low flow days.

<table>
<thead>
<tr>
<th></th>
<th>Stations with sig. discharge trends</th>
<th>Stations with sig. low flow trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>133</td>
<td>92</td>
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<tr>
<td>February</td>
<td>107</td>
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<td>March</td>
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</tr>
<tr>
<td>December</td>
<td>98</td>
<td>63</td>
</tr>
</tbody>
</table>

low-flow event are important to consider, alongside the number of low-flow days, as there are water resource implications.

Number and length of low-flow events

A single low-flow day, when surrounded by periods of normal flow, has little impact on water resources, however, multi-day low-flow events can have lasting effects on water resources. The impact on water resource from low-flow events can persist beyond the actual event. Where trends are seasonal, the compounding of either a water deficit or surplus can have inter-annual effects. Further compounding this with extremes in precipitation and temperature, can lead to extreme departures from normal conditions. There were strong regional trends in the number of low-flow events, especially
in western Canada (Figure 2.8. Increases in discharge, should result in decreases in the number of low-flow days per year, and an increase in the number of low-flow events annually. Likewise, decreases in discharge should result in more low-flow days annually, and fewer low-flow events annually. The inverse relationship between the number of low-flow days and the number of low-flow events occurs because individual days begin to overlap, creating longer, but fewer low-flow events. However, for most stations in this study, this inverse relationship between low-flow days and events did not occur. Many stations with significant decreases in the number of low-flow days also had decreases in the number of events annually. There were more decreases in the number of low-flow days during the winter months likely due to an increase in snowmelt or a greater presence of rainfall instead of snow (Hodgkins and Dudley, 2006; Arora and Boer, 2001). The variability and timing changes of snowmelt might have contributed to a decrease in the number of low-flow events during the winter months. Trends in the mean length of events (Figure 2.9) decreased consistently with the trends in the number of low-flow days and events. Decreases in the number of days and events, and the length of those events, leads to longer periods of flow above the $Q_{95}$ threshold, punctuated by short periods of low-flow translating to more variability in the timing of these low-flow periods. On the contrary, increases in the number of low-flow days and events, and increases in the length of those events, leads to more consistent periods of low-flow, punctuated by shorter periods of flow above the $Q_{95}$ threshold (Figures 2.6, 2.8 & 2.9).

2.4.3 Mechanisms for change

While change is occurring in the various basins, the mechanisms driving those changes are not consistent across the country. The primary mechanisms were either climate,
in less populated areas, land use change, especially in southern Canada, and changes to local discharge regimes such as permafrost and glacial melting. In the Arctic basins, there is evidence that increases to discharge are occurring from factors such as permafrost thaw (St Jacques and Sauchyn, 2009). In the Pacific basin, increases to discharge can be attributed to climatic changes (Shrestha et al., 2012), while decreases, especially during the summer months, have to do with changes to glacial meltwater timing (Stahl and Moore, 2006). In the western prairies, changes to both climate and land-use change have affected discharge, especially through the change to storage areas (Conly and Van der Kamp, 2001). Discharge trends in the southern areas of the St. Lawrence basin are largely attributed to land use change stemming from intense development. Finally, in the Maritimes, shifts in climate account for much of the change (Whitfield and Cannon, 2000).

2.4.4 Implications for low-order streams

This study analysed trends in discharge and low-flow indicators for a subset of monitored, unregulated rivers with at least 40 years of data. Typically, hydrological monitoring stations are not set up in areas that are near the boundary of perennial and intermittent reaches. These areas are usually located in the headwaters of catchments and means areas upstream of the most headward station are hydrologically poorly understood. These temporary low-order streams have important hydrological (Bishop et al., 2008) and ecological (Gomi et al., 2002a) roles, and have been shown to be susceptible to changes in climate (Schindler, 2001). Relating this to the results of this study, changes to discharge and low-flow indicators will most likely be evident in these upper reaches before they are noticed downstream, because they are highly responsive to changes in precipitation, snow melt, and evapotranspiration. In addition, the changes in these streams are likely to be more extreme, as small changes
to water input, can result in large changes to downstream connectivity (Bull, 1997). Low-order streams make up a large portion of a catchments hillslopes, and affect the storage capacity and connectivity to the catchment as a whole, providing water to downstream areas only during the wettest parts of the year, or during periods of rainfall. Increased disconnectivity between these streams and downstream reaches could affect water quantity, and water quality in downstream areas. With little monitoring occurring in these upper reaches, the connectivity of these streams and the magnitude of their role on water resources is poorly understood (Bishop et al., 2008). In areas identified in this study as showing decreases to discharge, or increases to the number, length, and timing of low-flow events, the result in intermittent low-order streams will be realized as greater disconnectivity, and more episodic flow regimes (Uys and O’Keeffe, 1997). This decreased flow means that a shift in water resources downstream will occur, with less water availability. In areas with trends indicating more discharge, and less low-flow, this will increase connectivity and streams will shift toward a more perennial regime. Given that few intermittent streams are protected to the same degree as perennial streams by means of riparian buffers, these streams will become ideal conduits for sediment and pollutant transport directly into downstream waterways. Without adequate monitoring, the degree of change to both the hydrology and ecology in low-order basins, whether from anthropogenic or climate impacts, is purely speculative. However, given the importance of these streams, this data gap needs to be filled to better understand, and manage these water resources.

2.5 Conclusions

An analysis of 40-year trends in discharge and low-flow conditions at Canadian hydrometric stations revealed the following:
This study described the trends in Canadian annual and monthly total discharge, and trends in three low-flow indicators in unregulated rivers. Spatial distributions and temporal patterns were found in the stations exhibiting significant trends. The conclusions of this paper are:

1. A large proportion of stations showed significant decreasing trends in annual discharge, however, there was variability in the monthly timing of those changes. As well, there were spatial clusters of similar trends found across the basins.

2. The annual number of low-flow days and events, as well as the length of low-flow events, showed significant decreases in much of Canada, however parts of the western prairies showed some significant increases. These changes are likely due to a redistribution of water through the hydrological year.

3. Significant changes in discharge generally resulted in the expected change in low-flow indicators at most stations, however, there were cases where the expected relationship was not found. In these cases, it was likely that other local or regional controls were at play. In addition, significant changes in annual discharge did not always result in significant changes in low-flow indicators, nor are significant changes in low-flow indicators predicated on significant changes in annual discharge.

4. The current monitoring network, while dense in some areas, but sparse in others, tends to ignore low-order, highly variable intermittent streams. These low-order basins may experience changes to climate and landuse at different rates, however, without any baseline data, the rates of changes in areas like the headwaters of catchments are poorly understood.
CHAPTER 3

MONITORING INTERMITTENT LOW-ORDER STREAMS: A PAIRED-SENSOR APPROACH

This paper introduces a paired-sensor approach to monitoring intermittent streamflow. Part of this approach includes the design of a new flow detection sensor. This flow detection sensor addresses the limitation of previous electronic resistance (ER) sensors that use water presence as a proxy for flow for assessing hydrological connectivity, by explicitly measuring flow presence. Using paired ER and flow detection sensors, this paper evaluates the performance of each sensor individually, and as a pair. Individually, the sensors were tested for the amount of noise they contain and the types of errors they were prone to committing. As a paired set, the sensors were analysed by the percent of time they were in valid states versus invalid states. Valid states included when water was present, but flow was absent, when water and flow were both present, and when water and flow were both absent during a storm. One invalid case existed, where the sensors recorded flow presence, but not water presence. These valid and invalid cases were assessed using data collected from sensor networks established at two study sites in southern Ontario. This analysis was completed for the overall corroboration at each site, for each storm at each site, and based on the relative position of the sensors in the channel at each site. The sensors were in valid states 83% and 94% of the time at each respective study site. Differences in local site conditions were found to affect the performance of the sensor network, however, no significant correlation was found between storm characteristics and sensor performance. Particularly, bed roughness was found to be a factor as it restricted the placement of the sensors. Despite this, the paired-sensor network helps to increase the understanding of the flow dynamics within low-order streams by explicitly separating the two hydrological characteristics. A discussion of the the challenges, limitations, and opportunities of monitoring intermittent flow is presented and insights into how to address those limitations are provided.

3.1 Introduction

Studies have assessed changes to discharge in perennial streams under different meteorological and climate conditions (e.g. Peterjohn and Correll, 1984; Hill, 1996; Mayer,
The headward expansion of stream networks during periods of rainfall are less well studied, as are the implications of networks expanding into channels with no riparian buffers (Wigington et al., 2005). Expansion of intermittent streams occurs during the wet-seasons and periods of intense rainfall during the dry season. Ephemeral streams tend to be through-flow and surface-flow dominated, compared to largely groundwater controlled perennial streams (Nadeau and Rains, 2007; Adams et al., 2006). Low-order streams are relatively small, yet numerous, on the landscape. These streams can account for a large proportion of the flowing network when fully expanded and can be a significant source of water in a catchment (Horton, 1945; Lowe and Likens, 2005). Ephemeral and intermittent streams are important hydrologically (Wigington et al., 2005; Gomi et al., 2002a), geomorphologically (Chin and Gregory, 2001; Gomi et al., 2002b), and ecologically (Labbe and Fausch, 2000; Meyer et al., 2007; Gomi et al., 2002a). The increase in drainage density of the network can affect downstream water quantity and quality, by increasing hillslope connectivity (Arnell, 2002; Burt and Butcher, 1985; Quinn et al., 1991; Day, 1978; Goulsbra et al., 2014).

All streams exist on a continuum of flow, ranging from perennial to episodic (Uys and O’Keeffe, 1997). Uys and O’Keeffe (1997) designated two thresholds along the continuum where streams are no longer considered perennial, but rather intermittent or ephemeral: where surface water is present, but not flowing (i.e. contain stagnant water), and where surface water is not present (i.e. completely dry). The position of a stream on the continuum of flow can vary seasonally and inter-annually, where streams can be perennially aseasonal during the spring and autumn months, but episodic during the dry summer months (Blyth and Rodda, 1973; Gurnell, 1978; Day, 1978). The ability to predict flow in streams decreases as streams become more episodic, while the variability in flow increases (Uys and O’Keeffe, 1997). This decrease in prediction is attributed to a low degree of monitoring in low-order basins,
especially in temporary streams (Bishop et al., 2008).

Bishop et al. (2008) highlighted the dearth of data pertaining to low-order streams; the further upstream from the mouth of a river you travel, the less data that exists. Bishop et al. (2008) was referring to all types of data, including ecological data, however, with regard to hydrology this has resulted from a lack of monitoring in these zero and first-order streams. The scarcity of monitoring data has to do in part with the technical challenges of monitoring a spatially distributed, highly variable phenomenon like stream network expansion and contraction. Some studies have attempted to monitor these landscape hot-spots (McClain et al., 2003) using a variety of techniques. Observation-based monitoring methods have been used in the past to determine the extent of the flowing network (Day, 1978; Blyth and Rodda, 1973) however, the major shortcoming was poor spatial and temporal resolution. The use of inexpensive sensors and data loggers allowed for significant improvements in both spatial and temporal resolution. Temperature sensors buried under the bed have been used, but the complexity associated with interpreting the results reduced the effectiveness (Constantz et al., 2001). Blasch et al. (2002) created an electronic resistance (ER) sensor by removing the thermistor from the temperature sensors. Over time, refinements of the ER sensor design improved the accuracy and interpretation of the data (Blasch et al., 2002; Goulsbra et al., 2009; Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014). Later, Bhamjee and Lindsay (2011) found that state loggers further simplified the interpretation of intermittent streamflow monitoring records, while reducing data volume and increasing the temporal resolution of observations. The primary limitation of using bed temperature sensors (Constantz et al., 2001) or electrical resistance sensors (Blasch et al., 2002; Goulsbra et al., 2009; Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014) has been that they monitor the presence or absence of water within the channel, and are unable to detect whether that water
is flowing. Bhamjee and Lindsay (2011) found that persistent standing water within pools can occur commonly within low-order channels.

This paper introduces a new paired-sensor intermittent stream monitoring approach. This includes a new flow detection sensor that addresses the limitation of previous sensor designs to distinguish between periods where the channel is wet (i.e. stagnant water) and periods of flow (i.e. moving water). An evaluation of individual sensors, as well as the pairs are evaluated to understand the advantages and limitations of this approach. This paper evaluates how a paired-sensor network, consisting of both water-presence and flow-presence sensors, can enhance intermittent flow monitoring efforts.

3.2 Methods

3.2.1 Sensor design and materials

The ER sensor was based on the design of Bhamjee and Lindsay (2011), and constructed from the same acrylic thermoplastic, bonded with marine glue. The flow detection sensor (Figure 3.1) is based around a vane design that closes a circuit when water is flowing, while opening the circuit when water is not flowing, regardless of whether stagnant water is present. The ability to distinguish between the presence of water and the presence of flowing water is how the flow detection sensor improves upon previous sensor designs. As water passes through the mouth of the sensor it forces the vane to open. When the vane opens, the magnet on the end of the vane moves away from a normally-closed reed switch, opening the circuit and triggering a logger reading. Using a normally-closed reed switch on the main sensor body, with the magnet on the vane, allows for an open circuit when there is no water (i.e. the
vane is closed and the magnet has opened the circuit) and a closed circuit when the magnet moves away from the reed switch, thus leaving it in the normally-closed position. This characteristic allows for better battery life for the loggers, as the sensors tend to be in the no-flow state for longer periods of time over a given season.

The sensors were constructed from 3 mm acrylic thermoplastic. The material was chosen because it was easy to work with, lightweight and strong. In addition, it is not susceptible to corrosion, and is relatively inexpensive, thus keeping costs to a minimum and ensuring the sensors can endure many deployments. The hinge for the vane was made from stainless-steel welding rod as it is rigid but easy to cut to size. The reed switches used for the design were single-pole, double-throw, normally-open/normally-closed (part #: GC Electronics 35-752), though a single-pole, single-throw, normally-closed reed switch would also work effectively. The reed switches were soldered to the provided TRS connectors supplied with the HOBO U-11 data loggers using 22-gauge solid-core wire. The magnets used to trigger the reed switches were small cylindrical rare-earth magnets. These were used because of their strength, small footprint and weight, allowing them to be attached to the end of the vane without interfering with the closure of the vane, nor adding too much additional weight. The various parts of the sensor were bonded using marine glue.

### 3.2.2 Sensor setup

Setting up the two types of sensors in the field required a mounting system to be added to the sensor. For this study, a base-plate with holes for pins, or a strap over the top were used, as well as using heavy weights on-top of the sensor. This latter configuration was especially useful in rock-bed streams where pinning the sensor to
Figure 3.1 Flow presence sensor design. a) shows a single-pole, double-throw normally closed reed switch. b) represents the rare-earth, cylindrical magnet used to activate the switch.
the bed was difficult. Ultimately, there are numerous methods of anchoring available to match the channel characteristics and ensure the sensors stay stationary (e.g. Isaak et al., 2013).

Sensor siting within the cross-section of the channel was within the thalweg to maximize the probability of water flowing through the sensor even during the lowest flows. Areas with substantial debris (e.g. leaves, twigs, etc.) were avoided during installation as these could have potentially blocked the opening of the flow detection sensor, keeping the vane in the open position, or inundating the ER sensor. Proper installation of the flow detection sensor required angling it on the bed so the vane remained closed during periods of no-flow, but took minimal effort to open when flow was initiated. This was tested during installation by opening the vane and releasing it. The vane should close completely. Placing the sensor on too steep of an angle may have resulted in missed flow events, as more energy is needed to open the vane. The ER sensors were placed so the electrodes were level with each other. Each sensor was plugged into a state-port on the data logger. Each sensor in the pair was positioned ahead of the other, trying to place them as close together as the site would allow, while leaving enough space to reduce flow interference between sensors. The spacing of sensor pairs was far enough apart so as to decrease redundancy, but close enough to capture variability in expansion and contraction. A spacing of approximately 10 m was chosen for this study, although appropriate spacing will depend on the environment and the application.

3.2.3 Field sites

Field-based sensor performance and evaluation was undertaken at two field sites in southern Ontario. Each site contained at least one intermittent channel.
Site 1 (43.7580 N, 79.9392 W) was located in a predominantly agricultural area in southern Ontario, west of the town of Cheltenham (Figure 3.2). The study-reach of intermittent channel was located in a forest adjacent to active corn fields and an apple orchard. The stream originates in the surrounding fields and is bounded by a riparian buffer where it bisects the field. In the forested section, the active stream is greatly incised in the banks and has a mix of bed-surface sediment conditions. At the head of the study-reach there were large cobbles and boulders across the width of the channel, however the bed-surface exhibited noticeable sediment fining downstream. The lower reaches of the channel had less rocks on the bed-surface and appeared sandier. Grain-size analysis showed that in the 30 cm below the bed, there was more longitudinal consistency along the study-reach. The channel was on average 53.7% sand, 12.1% silt and clay, with the remainder being grains larger than sand. The site had an average organic matter content of about 5.1% with a standard deviation of 1.3% along the entire study reach. The channel flattens and widens toward the mouth, with an approximate average channel width of 2.5 m, however, flow tends to be concentrated in a far narrower area. The forest is composed of large, mainly deciduous, trees with minimal understory. This lack of understory resulted in leaf litter accumulation in the autumn months and increased the debris load in the channel. The channel empties into the Credit River near Cheltenham, Ontario.

Site 2 (43.3798 N, 80.3433 W) was located in a conservation area with a wetland feeding into the intermittent stream during the spring and autumn months (Figure 3.3). The catchment is long and narrow in the study reaches, and the stream is bounded by rock cliffs approximately 15 m away from each bank. The channel has an average width of 1.5 m. Similar to Site 1, Site 2 has marked changes with regard to substrate on the channel surface. The channel surface was less rocky near the
head of the study-reach than closer to the mouth. Based on grain-size analysis, the upper 30 cm section of the bed averaged 64.7% sand, 19.4% silt and clay, and 15.9% pebbles. In terms of organic matter, Site 2 had an average of 8.6% and a standard deviation of 2.7%. The forest surrounding the study reach is composed of predominantly deciduous trees but has a dense understory, protecting the channel from leaf litter. The upper contributing hillslopes include forest, as well as active and fallow agricultural fields. The channel flows into the Grand River near the confluence with the Speed River, in Cambridge, Ontario.

3.2.4 Data collection

Stream network expansion data was collected at both sites utilizing paired ER and flow detection sensors along the study reaches with 14 sensor pairs at Site 1, and
12 sensor pairs at Site 2 (Figures 3.2 and 3.3). Simple meteorological stations were setup at each site to capture rainfall, temperature, and wind speed using HOBO tipping bucket raingauges with integrated temperature sensors in Stevenson screens, and 3-cup anemometers. Meteorological data was collected close to each site because localized rainfall events are common in both areas.

3.2.5 Sensor-data processing

Data processing for the sensors was completed to reduce the noise found during the onset and cessation of flow. Noise occurred in both sensors when the sensor was at the threshold for measurement. In the flow detection sensor, this was when the water was flowing just enough to turn it on, but any perturbations, or drops in flow velocity below the threshold caused the sensor to close momentarily. In the ER sensor, this noise occurred when the water was at the height of the electrodes and opening
and closing the circuit if one electrode was removed from the water. This noise was expressed as high-frequency noise, and was easy to distinguish from lower frequency events. To reduce this noise, the same 30-second filter used by (Bhamjee and Lindsay, 2011) was applied to the collected data. The filter first determined the previous state of the sensor. If it was reporting water or flow presence, and less than 30 seconds had elapsed before it reported water or flow absence, the state was changed to show that water or flow was present. If the change from water or flow presence to absence had occurred outside of the 30-second buffer, then no change was made. Water and flow presence were prioritized over water and flow absence because if there was enough water in the channel to turn on either sensor, even for a few seconds, then it was likely that water or flow was present during brief moments of the sensor not reporting the variable. The percent of records changed for each sensor is presented in Table 3.1. At both sites, ER 2 showed no changes in the data as this sensor was plugged into an event channel on the logger and only recorded the initial presence of water, not the cessation of water (Figure 3.4). This meant that only every other sensor pair in the network could be used for corroborating invalid cases (i.e. cases where the flow detection sensor records flow, but the ER sensor does not detect water). Despite this limitation of using the event-port on the HOBO U-11 logger, the valid cases were assessed and the data were still considered.

### 3.2.6 Sensor performance

The performance of the flow detection sensor design was analysed by direct comparison to the ER sensor from Bhamjee and Lindsay (2011). The Bhamjee and Lindsay (2011) ER sensor was more likely to commit errors of omission (i.e. under-report water) than it was to commit errors of commission (i.e. report water presence when
Table 3.1 Percent of records changed from no-flow to flow based on a 30-second filter for noise. Sensor pairs are sorted by location in channel from the most upstream to most downstream. Some water presence sensors have no records changed because they were plugged into the event port of the data logger (see 3.2.5)

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there is none present), as the water needs to be at the level of the electrodes to record a state change. The exception to this robustness against errors of commission regarding water presence is if the sensor became buried under sediment and was then measuring the moisture rather than channelized flow. However, the ER sensor was likely to commit errors of commission when recording whether the water is flowing or stagnant.

Since the ER sensors determined the presence and absence of water, while the flow detection sensors determined the presence of flowing water, corroboration was sought for valid recorded periods. The valid periods included water presence with no flow, water presence with flow, and complete absence of water and flow during the storm periods. In addition, invalid cases were identified, where flow was recorded, but water presence was not (Figure 3.5). To determine a valid presence of water, the ER sensor
needed to be reporting water, while the flow detection sensor needed to be reporting no-flow. For valid flow presence, both sensors needed to be reporting water and flow respectively. For a valid dry channel, both sensors needed to be reporting no-water and no-flow respectively. Finally, any other combination was recorded as being an invalid occurrence (i.e. cannot have flow without water present in the channel). These occurrences were recorded both as a function of how much time elapsed in the state, as well as the number of changes to a particular state. The valid cases were compared at both the site-level, on a per-storm basis, and by the relative position of the pairs in the channel. Site level data were combined to show the overall corroboration between the ER and flow detection sensors for each of the four cases as a percent of time spent in a particular state. For overall sensor corroboration, only data during storm periods was included, as water and flow absence dominates these intermittent streams, and would inflate the degree of corroboration. Reporting of storm-level results was done for each site individually, as a percent of the storm time in a given state. A single storm event was defined as the period where rainfall events recorded by a tipping-bucket rain gauge were less than 24 hours apart. Once the 24 hour threshold was overcome, a new storm event was created at the beginning of the next record. This allowed for long, less intense storms with breaks in rainfall to be better classified. Last, the percent of time spent in a valid or invalid state for each sensor was completed and analysed by their relative location in the study-reach.

3.3 Results

The sensor pairs were tested over 14 and 28 storms respectively at Sites 1 and 2 (Table 3.2). Site 1 had fewer storms over the testing period because the stream
Figure 3.5 Valid and invalid cases between sensors. a) represents the ER sensor, describing the presence and absence of water in the channel, while b) represents the flow detection sensor, describing the presence and absence of flow in the channel. i) is the valid case of both water and flow being present. ii) is the valid case of water present, but flow absent. iii) is the valid case of neither water, nor flow, being present. iv) is the invalid case where there is flow present, but no water in the channel.

entered an ephemeral regime later in the season. Both sites experienced similar median rainfall amounts over the study period.

3.3.1 Sensor performance

Overall sensor performance at Site 1 resulted in the ER and flow detection sensor being in valid states 83.26% of the time during storm periods. At Site 2, the sensors were in valid cases 94.86% of the time during storm periods. Both sites had sensors recording the presence of water and flow in the channel (‘case i’ in Figure 3.5) for more than half of the storm time (Table 3.3). Case ii was the next most prevalent case at both sites, where standing water was present in the channel, but not flow. Case iii, when the channel was dry, was minimal with regard to storm duration percentage. However, Case iii would be very prevalent in the overall season statistics, as the
Table 3.2 Storm details.

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Table 3.3 Overall corroboration between ER and flow detection sensors during storm events at both sites, by time (in percent).

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channels were dry between storms. Finally, case iv, the invalid cases, showed that overall, Site 2 performed better than Site 1. Site 1 was in an invalid case 16.74% of the storm time, while Site 2 was in an invalid case 5.14% of the storm time. The valid and non-valid cases were parsed by storm to better examine the differences for each site.

Examining the valid/invalid cases on a per storm basis, there was more variability in invalid cases at Site 1 than at Site 2, where Site 2 was less variable over the season (Table 3.4). The sensors performed better at Site 2, with higher levels of corroboration overall. The sensor performance was not related to the duration or intensity of the storm itself. Sensor-pairing agreement was further analysed based on siting position along the study reach.

Performance of sensor pairs by location within the study reach, can be observed in Table 3.5. Only every second sensor-pair is presented as the pair with the ER sensor connected to the event-port (ER 2 in Table 3.1) could not be tested for invalid cases (see Section 3.2.6). Upstream sensor pairs were in an invalid state more often than those downstream at Site 1. However, at Site 2, the furthest downstream sensor pair (Pair ID 11) was in an invalid state the most, over 20% of the time. The sensor pairs with the poorest performance were in areas that were rockiest at both sites. At Site 2, where the worst performing sensor pair was located (Pair ID 11), the sensor
pair upstream of it performed notably better. Given that it was around 20 metres upstream and out of the rocky terrain, this difference is understandable.

3.4 Discussion

3.4.1 Sensor performance

The ER sensors contained more noise than the flow detection sensors at both sites (Table 3.1). However, at both sites, some flow detection sensors had orders of magnitude more noise than others, even those sensors immediately upstream or downstream. Examining Site 1, Vane 1 on Logger 1, 42.96% of the records were altered by the noise-reduction algorithm, while the flow detection sensor 10 m away, Vane 2, Logger 1, showed a low degree of noise reduction, at just under 6%. Comparing the flow detection sensors with high noise levels (>40%) with their corresponding ER sensor in the pair, the ER sensors were some of the least noisy sensors in the dataset. Examining the sensors with high ER noise, and comparing them to their paired flow detection sensors, the opposite was observed in most cases. This inverse relationship between the amount of noise for each sensor type in the pair may result from the physical placement of each sensor and/or the physical characteristics of the channel. The channel at Site 1 contains larger rocks in the headward portions than in the downstream areas where it was flatter, wider, and sandier (Figure 3.6). At Site 2, the lower portion of the reach had larger rocks, while the upstream area had a relatively sandier bed. The rockier areas generally resulted in better noise performance from the ER sensors than from the flow detection design. Because the flow detection design relies on careful setup to ensure that the vane can open and close freely, in areas with a high density of larger rocks this became problematic, as individual rocks influenced where the sensor actually got positioned to avoid contact with rocks. Rocks
Table 3.4 Corroboration between ER and flow detection sensors at both sites for each storm, by time (as a percent of the storm time).

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<td>1.70</td>
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<td>99.83</td>
<td>0.00</td>
<td>0.00</td>
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</table>
Table 3.5 Percent corroboration between ER and flow detection sensors at the sensor-pair level, for all storms, by time. This includes only the upper pair of each logger due to the event-logging constraint. The data for each site are sorted from the most upstream sensor pair to the most downstream pair.

<table>
<thead>
<tr>
<th>Site 1</th>
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<th>Site 2</th>
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<td></td>
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<td>iii</td>
<td>iv</td>
<td>Pair ID</td>
<td>i</td>
<td>ii</td>
<td>iii</td>
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<tr>
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<td>5</td>
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<td>7.46</td>
<td>25.61</td>
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<td>13</td>
<td>91.26</td>
<td>0.03</td>
<td>8.68</td>
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</tbody>
</table>

were removed from in front, and behind, the flow detection sensor in some cases to avoid contact with the sensor while still allowing it to be sited in the thalweg. Where the flow detection sensor outperformed the ER sensors was generally in areas with shallower gradients and wider channels, resulting in flow depths at, or just below, the level of the ER electrodes. Bhamjee and Lindsay (2011) described this scenario as being the likely cause of noise in the sensor data. Examining the data, these constant on-to-off and off-to-on state changes were prevalent at the start and end of periods of activity within the channel.

Noise in the data was the main contributor to invalid cases between the two sensors at each location. These invalid cases occur mostly during the onset and cessation of flow, when the water level was around the level of the electrode for the ER sensor, and around the threshold for opening the vane on the flow detection sensor. Using
Figure 3.6 Photos of channel surface characteristics at Site 1. a) the upper parts of the channel were deeply incised and contain lots of pebble-sized grains on the bed-surface. b) the lower reaches of the channel had a relative absence of larger grains on the surface. c) in the mid-to-upper reaches, there was a mix of pebbles, cobbles, and boulder sized grains on the bed-surface, which lead to potential siting issues. Photos taken June 26, 2012.
a 30-second filter on both datasets helped to reduce, but not eliminate, this noise. Where sensor pairs were set up slightly further apart, the local site conditions affected how quickly the sensors reacted to changes in flow within the channel. This lag period lead to invalid cases, though usually for short periods of time.

Generally, the ER sensors were more likely to under-report flow, committing errors of omission, than they were to over-report flow, committing errors of commission. The flow detection sensor design, when setup correctly, should result in the same types of errors. However, possible errors of commission were committed when the vane was held open during dry periods as a result of improper setup, or in areas with high debris load. Errors of commission can be compounded storm-to-storm if the vane is not closed. To reduce such errors, initial placement of the sensor was important, trying to choose locations that were minimally impacted by debris and large sediment during flow periods. However, these areas were not always avoidable, and in these cases it was important to take other actions, such as frequent site visits, to ensure the vane was closed after periods of flow. Other possible actions that can be taken include trying to deflect debris and sediment around the sensor, though this can be often be impractical without disrupting the flow through the sensor. Large-aperture screening could be used in front of the sensor if very large debris is an issue, but must be done only to the degree that the debris is diverted, but the flow is not altered in any major way.

3.4.2 Sensor size and customization

A possible explanation for the variation in the performance of the flow detection sensor is the ability for the water to physically open the vane. The flow detection sensor was bench-tested in a stream table with relatively low flows, at various angles.
to see if the flow detection sensor vane would open and close. However, observations
during field visits showed that the flow detection sensors perform especially well when
the channel was full and the water level was at, or near, the top of the sensor head.
This flow depth also helped to reduce some of the noise associated with the vane
opening and closing over short periods. Knowledge of typical flow depths in the
channel would be useful to help customize the physical size of the sensor to keep flow
at the sensor height. However, excessive flow, coupled with large debris, resulted in
some sensors becoming unmounted and destroyed, particularly during the early part
of the season when flow was continuous. Scaling-down the size of the sensor allows
for a greater percent of surface area contact between the water and the vane allowing
it to be opened more easily. Smaller sensors could be more prone to sediment settling
and debris-jamming however, resulting in potential errors of commission when the
vane is stuck open.

3.4.3 Challenges of monitoring intermittent streams

The variation of channel and flow characteristics along a reach can complicate lon-
gitudinal spacing of sensor pairs. If the sensor spacing is too sparse, some of the
expansion and contraction patterns will be missed and very little redundancy will
be built into the network. However, if they are too densely spaced, then there will
be too much redundancy or autocorrelation between sensors. This autocorrelation
can be good for verifying if sensors are working correctly by comparing them to their
neighbours, however, in terms of resources, it is less efficient. For example at Site 2,
sensor pairs 9 and 11 (Table 3.5) performed quite differently, with the latter having a
high degree of invalid cases. By examining these two pairs, indications of the problem
in one pair can be sought out by looking for differences in the adjacent pairs. A bet-
ter approach would be variable spacing depending on the reach characteristics. The
most efficient technique would be to site sensor-pairs more densely in areas that are prone to errors (e.g. rocky beds, like at Site 1, pairs 1, 3, and 5) or where the active channel is more mobile within the banks, while setting them up further apart in areas where there is little change to channel morphology, or bed material differences. This variable spacing should capture any features in the channel, such as confluences (e.g. Site 1, pairs 8 and 9), and changes to the morphology of the channel. Ultimately, the purpose of the monitoring study should be considered so as to select an appropriate scale. Scaling-up of monitoring data can be complicated by the dynamic nature of intermittent channels, especially those that are more episodic. These paired sensors are point measurements that are being used to represent connectivity of a linear feature, and while inferences can be made about the dynamics, they must be framed within the context of the spatial scale being measured. Compared to testing in the lab, field tests resulted in a higher rate of failure, likely due to both scaling factors, as well as debris in the channel. The former can easily be addressed, by enlarging or minimizing the scale of the sensors, while the latter can only be addressed through the use of customized diversion and stronger anchoring techniques [e.g.] (Isaak et al., 2013).

Many of the technical limitations in previous intermittent stream monitoring studies can be improved by using a paired-sensor approach. Previous studies have used a single sensor to detect water presence and infer that the water was flowing (Constantz et al., 2001; Blasch et al., 2002; Adams et al., 2006; Goulsbra et al., 2009; Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014; Goulsbra et al., 2014). However, the assumptions that once water is present in the channel it is immediately flowing, or will flow at all, can be misleading. Just over 27% and 20% of the storm times, there was water present in the channel, but no flow at the study sites (Table 3.3). Bhamjee and Lindsay (2011) showed that there are three main types of channel expansion. The
most dominant expansion regime, coalescence, resulted from pools of water within the channel joining and forming a flowing network. However, the study also concluded that there was no practical way to distinguish the difference between discontinuous flow and this pooling effect in the data. This uncertainty would be minimized with the paired-sensor network introduced here. However, simply replacing the ER sensor with the flow detection sensor is not advised, as there is no way to know when the pooling begins to occur. Having a pair of sensors, each with a dedicated purpose, ensures both of these characteristics are being captured. In addition, being able to determine what is occurring below the bed would be useful in studies where groundwater interaction with the bed are needed. If a paired-sensor approach is sought, either a two-channel state logger should be used for each pair to minimize wiring, or a four-channel state logger could be used to marginally reduce costs. In either case, a paired-sensor approach would benefit from having all sensors connected to state-ports unlike the one ER sensor that was connected to an event-port on each logger in this study due to logger availability. Doing so allows recording not only the onset and cessation of both water and flow for all sensor pairs, but also for testing for the three valid cases and one invalid case, and can help to minimize setup problems early in a monitoring effort.

3.5 Conclusions

This study introduced a new paired-sensor approach to monitoring connectivity in intermittent streams. This included the design of a flow detection sensor to be used alongside an ER water presence sensor. As well, the setup and considerations required to successfully deploy this type of network were presented, and the merits of a paired-sensor approach. Finally, customizations and considerations that could help improve
the performance of the sensors in certain environments were discussed. The major conclusions of the paper are:

1. Pairing ER sensors with the flow detection sensor design provides a means of assessing the performance of individual sensors within a sensor network. This paired approach can also be used as a means of optimizing sensor configuration as well increasing the types of information that can be derived from the monitoring data.

2. The overall performance of the flow detection sensor design was good, with residual noise in the ER sensor accounting for many of the invalid cases. Customizations such as altering the size of the sensors could allow for better performance by ensuring the water levels are not at the critical thresholds required to activate the sensors.

3. Care needs to be taken in rocky beds as the location of the sensors can greatly degrade performance. Other potential considerations with siting include ensuring debris does not keep the vane open, and the spacing of each sensor pair. The former problem can be alleviated in many cases by diverting debris around the sensor, or using large-aperture screening to stop debris ahead of the sensor. Increasing the density of sensor pairs in rocky beds would give a better idea of whether sensors are performing correctly. Regardless, frequent site visits will ensure that sensors are working as expected.
CHAPTER 4

INTERMITTENT STREAMFLOW ACTIVITY IN SOUTHERN ONTARIO

Streams are often classified by their flow duration. A large proportion of streams in a catchment are low-order streams, and are often seasonally intermittent. In southern areas of Canada, these streams tend to display intermittent flow during the driest, warmest months of the year. More specifically, in southern Ontario, where agriculture dominates these low-order catchments, there are implications for water quality concerns. Responses to rainfall during these intermittent periods vary by stream, and can often exhibit water present in the channel, but not flow. Water presence has different hydrological and ecological implications than flow presence, and separating the two states is important. Using a novel paired-sensor approach, this study monitored two southern Ontario intermittent streams for both the presence of water, and the presence of flow. Using the resulting intermittent stream activity data from two southern Ontario catchments, characteristics of flow timing and duration were explored, as well as the predictors of intermittent stream activity. The timing of the transition from a continuously flowing to intermittent stream occurred in late-August at Site 1 and late-May at Site 2. The differences were largely attributed to antecedent conditions in the catchment. The channels had flow in them during 95.5% and 59.5% of the periods between May 1 and November 1. Using the 40-year monthly averages for rainfall and temperature, the results from the study period were contextualized to long-term meteorological conditions. Predictors of water presence and flow presence were analysed using binary logistic regression models for each month of the study season. Site 1 had less variability overall in the predictors of both water presence and flow presence, than Site 2. Predictors such as total rainfall, and local site roughness were more consistently significant predictors over the study season, while maximum rainfall intensity was more seasonal. Controls on intermittent behaviour showed seasonal variation in predictability. The study also complements the idea that with more long-term monitoring in these low-order streams, the dynamics of flow would be better understood in relation to changes in climate and land-use.

4.1 Introduction

Streams can be classified based on the intermittency of their flow such that perennial streams exhibit continuous flow throughout the year, and intermittent streams
exhibit periods of no flow annually (Hansen, 2001; Nadeau and Rains, 2007; Uys and O’Keeffe, 1997). Within the category of intermittent streams, there is variability in the duration of discontinuous flow, where the flow can be seasonally intermittent, ceasing flow for only a short period each year, right through to episodic, where flow is largely controlled by precipitation events (Uys and O’Keeffe, 1997). Many of these intermittent streams are found in the lowest-order catchments (Vannote et al., 1980) and contribute to the majority of the total stream network length in many catchments (Gomi et al., 2002a; Lowe and Likens, 2005). Despite a reduction to the permanency, these intermittent segments can still contribute significantly to downstream discharge, sediment, organic matter, and nutrients during periods of flow (Brooks, 2009; Gomi et al., 2002a; Meyer et al., 2007). Intermittent streams play an important ecological role (Brooks, 2009; Labbe and Fausch, 2000; Meyer et al., 2007; Nadeau and Rains, 2007; Gomi et al., 2002a; Platts, 1979), and the timing of intermittent flow can be more important to macroinvertebrate productivity than habitat suitability (Chadwick and Huryn, 2007).

Knowing the controls on intermittent flow allows for a better understanding of the timing and magnitudes of flow in these channels. Intrinsic controls affect both the occurrence of low-order channels, as well as dictate the presence of flow within those channels. Major intrinsic controls include the underlying geology, bed-material, and channel and catchment characteristics such as slope and porosity (Winter, 2007; Waddington et al., 1993). Extrinsic controls include climate, weather, and antecedent conditions (Buttle et al., 2012; Levick et al., 2008; Blyth and Rodda, 1973; Gurnell, 1978; Morgan, 1972). Meteorological controls have high annual variability, as well as inter-annual variability. The response of streams to these fluctuations can differ based on this variability. While the variability and controls on streamflow is documented for perennial streams (e.g. Coulibaly and Burn, 2005; Dettinger and Diaz, 2000; Regonda
et al., 2005), there has been less research focused on documenting the controls on
flow timing in intermittent and ephemeral streams.

A major limitation in studying intermittent stream activity is the absence of
monitoring data in these spatially distributed low-order channels (Bishop et al., 2008;
Peirce and Lindsay, 2014; Buttle et al., 2012). As traditional stream monitoring
equipment is not always well suited to these highly variable environments, or is cost-
prohibitive, the need for inexpensive, specialized sensors has increased. Various types
of specialized intermittent stream sensors have been created and improved to meet
this need (Goulsbra et al., 2014; Bhamjee and Lindsay, 2011; Goulsbra et al., 2009;
Blasch et al., 2004; Constantz and Essaid, 2007). The majority of sensors are based
on an electrical resistance (ER) sensor design, where a circuit is closed when two
electrodes are submersed in water. This design, while robust and easily customizable,
had the limitation of measuring water presence or absence, not whether the water
was flowing. The introduction of a new flow detection sensor (Chapter 3) allowed for
the measurement of flow presence, rather than using water presence as a proxy for
flow. Bhamjee and Lindsay (2011) observed that expansion of intermittent low-order
streams was largely by the coalescence of isolated pools into a flowing network. As
such, the use of only one type of sensor does not allow for a complete description of
the conditions in intermittent channels.

By utilizing specialized sensor networks in intermittent streams, a better under-
standing of the activity and connectivity to downstream waterways can be gained,
which can assist in managing quantity and quality concerns (Bracken et al., 2013;
Wigington et al., 2005). Using a paired-sensor approach, with both flow and water
presence sensors, predictors of intermittent activity can be used to better examine
the activity in these channels. Few studies have examined predictors of flow in tem-
perate intermittent streams (Peirce and Lindsay, 2014; Goulsbra et al., 2014). Peirce and Lindsay (2014) studied the potential controls on intermittent flow (using water presence as a proxy for flow presence) in three adjacent channels using single-sensor networks in southern Ontario, observing that even in nearby channels, the controls on flow can be notably different. Peirce and Lindsay (2014) studied the spatial variability of controls over a period of four months. The channels in the Peirce and Lindsay (2014) study were relatively short, small in-field gullies, however are likely not representative of larger, more permanent intermittent streams. A logical advancement would be the use of a paired-sensor approach (Chapter 3) in larger intermittent streams, accounting for temporal variability in controls. This approach would more reliably characterize intermittent activity over a season and help to better quantify the complexity of intermittent streams, and their connectivity to the landscape.

This study used a novel paired-sensor approach to measure intermittent stream-flow activity in two southern Ontario catchments. Using the activity data from these monitoring networks, characteristics of flow timing and duration were examined, as well as the predictors of intermittent stream activity. Specifically, this study highlights the timing of predicting intermittent stream activity by exploring the monthly shifts in predictor variables and their affect on water presence and flow presence.

4.2 Methods

4.2.1 Study Sites

Two southern Ontario intermittent stream catchments were monitored in this study (Figure 4.1). Site 1 (43.7580 N, 79.9392 W) was located near Cheltenham,
Figure 4.1 The locations of the study sites within southern Ontario are denoted by the circles. The triangles show the locations of the Environment Canada climate stations used in Figures 4.3 and 4.4.
Ontario. The study reach of intermittent stream was located within a forest, adjacent to active corn fields, as well as two tributaries originating in an apple orchard (Figure 4.1). Where the stream bisected a corn field, the channel was surrounded by a riparian buffer. Within the forested section, the active stream is heavily incised within the banks and contained a variety of bed-surface conditions. Near the top of the study reach, there were large cobbles and boulders across the width of the channel, with progressive fining of bed-surface sediments downstream (Figure 4.2). The channel flattened and widened downstream, however, water did not occupy this cross-sectional width along the length of the channel. The surrounding forest was composed of large, mainly deciduous, trees, with a minimal understory. The minimal understory resulted in leaf litter accumulation during the autumn months, and contributed to the debris load in the channel. There was a high quantity of coarse woody debris within sections of the channel that impeded and altered flow. The channel emptied into the Credit River, near Cheltenham, Ontario. The long-term variability in average temperature and precipitation for Site 1 is presented in Figure 4.3 with data from the nearest Environment Canada weather station. Site 1 experienced an above average May in terms of both rainfall and temperature, followed by significantly wetter months of June and July, being the third wettest in the 40-year period. August was drier than the 40-year average but had near-average temperatures. September was about average, followed by a relatively warmer and wetter than average October. Site 2 (43.3798 N, 80.3433 W) was located near Cambridge, Ontario within a nature preserve. The intermittent channel had a wetland upstream that fed into the channel, especially during the spring and autumn months. Within the study reach, the catchment cross-section was relatively narrow, bounded by rock cliffs approximately 15 m away from each side of the channel (Figure 4.1). Similar to Site 1, the study reach had notable changes to the size of bed-material, with rockier areas downstream, and fining upstream. The surrounding forest was composed of predominantly
Figure 4.2 Photos of channel surface characteristics at Site 1. a) the upper parts of the channel were deeply incised and contained lots of pebble-sized grains on the bed-surface. b) the lower reaches of the channel had a relative absence of larger grains on the surface. c) in the mid-to-upper reaches, there was a mix of pebbles, cobbles, and boulder sized grains on the bed-surface. Photos taken June 26, 2012.
Figure 4.3 Site 1 climate comparison, showing mean temperature and rainfall values for each year between 1973 and 2013, with 2013 (i.e. the study period) denoted by the ‘X’. The mean value for each axis is denoted by the solid grey line, and one standard deviation above and below the mean by the dashed lines. Data from Environment Canada station number 6158733 (Toronto Lester B. Pearson Int’l A).
deciduous trees, and had a dense understory that protected the stream from leaf litter and coarse woody debris compared to Site 1. The upper contributing hillslopes of the stream included forest as well as active and fallow agricultural fields. The channel emptied into the Grand River, downstream of the confluence with the Speed River, in Cambridge, Ontario. The long-term variability of temperature and precipitation are presented in Figure 4.4. May was both slightly warmer and drier than the 40-year average. June was wetter than average, but had average temperatures. July was the third driest in the 40-year period, with near-average temperatures. August had slightly below average temperatures, but was the fourth driest August in the 40-year record. September was also much drier than average, but with near-average temperatures. Finally, October had near-average rainfall, and above average temperatures.

### 4.2.2 Data Collection

Intermittent stream activity was measured using a paired-sensor monitoring network. This network design is novel in intermittent stream research. To measure water presence, the electrical resistance (ER) sensor design from Bhamjee and Lindsay (2011) was used. This design is robust, and was designed for similar conditions to those found at both study sites. To determine flow, the flow detection sensor from Chapter 3 was used. The ER sensor relies on two electrodes being submerged in water to close a circuit, while the flow detection sensor relies on moving water to open and close a vane. Also, the limitations inherent in either sensor were compensated for by the other sensor in the pair. The sensors in each pair were setup as close together as possible, given the site conditions. The sensors were setup in the thalweg and on riffles to increase the probability of the sensors being in the path of flow, while minimizing the amount of time spent in stagnant water. Each sensor pair was
Figure 4.4 Site 2 climate comparison, showing mean temperature and rainfall values for each year between 1973 and 2013, with 2013 (i.e. the study period) denoted by the ‘X’. The mean value for each axis is denoted by the solid grey line, and one standard deviation above and below the mean by the dashed lines. Data from Environment Canada station number 6147188 (Roseville).
separated by approximately 10 m, which helped to maximize the spatial resolution, while minimizing redundancy in the data. At Site 1, the monitoring network consisted of 14 sensor pairs (Figure 3.2) and at Site 2 there were 12 sensor pairs (Figure 3.3). Each sensor was also assigned an ordinal sensor-position index value based on their location in the channel corresponding to the values found in Figures 3.2 and 3.3. The sensor-position index was included as certain sensors might be more likely to record activity than others based on their relative position within the channel, and the greater catchment area upstream of that area. The use of the sensor-position index rather than calculated catchment areas resulted from the absence of a reliable high-resolution DEM for both sites. This absence of a reliable DEM also meant that commonly used DEM-derived terrain attributes could not be used. The advantage of using these types of sensors, compared to traditional hydrological measurements (e.g. weirs), is that they are able to record stream network connectivity well, at the expense of measuring water quantity, which is minimal anyhow.

In addition to intermittent stream activity, meteorological data, terrain attributes, and soil samples were collected at each site. Meteorological data consisted of rainfall, temperature, and wind speed. Data were collected at both sites to ensure that localized weather, such as thunderstorms, was captured. Rainfall and temperature were collected using Onset HOBO RG3-M tipping bucket raingauges with HOBO UA-003-64 pendant event data loggers with integrated temperature sensors. The temperature sensors were housed in Stevenson screens. Cross-sectional topographic data were collected at each sensor-pair location using a Leica TC407 Total Station. Finally, bed-material samples were collected using a known volume cylinder for bulk density measurements along the longitudinal profile of each site. 6 samples were collected at Site 1, and 5 samples were collected at Site 2 when there was no water in the channels.
4.2.3 Data Processing

Meteorological Data Processing

Meteorological pre-processing consisted of converting rain-gauge bucket-tip events to millimetres of rainfall (0.2 mm of water per event). The rainfall data were then parsed into individual storms. Storms were determined where the end of one storm was defined as a period of inactivity (i.e. no tips of the bucket) of 24 hours. This threshold allowed for appropriate parsing of long, but less intense, storms, and storms with short pauses in rainfall. Total rainfall, maximum rainfall intensity, and the antecedent precipitation index (API) (Shaw, 1994) for the day prior to the start of the storm were calculated for each storm. API was used as a proxy for catchment wetness as no soil moisture data was available at either study site, and no suitable digital elevation model (DEM) was available to calculate wetness indices. API was calculated using the following equation:

$$API_t = (k_t)(API_0) + P$$  \hspace{1cm} (4.1)

where $k$ is a constant dependent on the potential loss of moisture (mainly through evapotranspiration), $API_0$ is the API on the previous day and $P$ is the sum of the precipitation at the end of the current day (mm).

Topographic Data Processing

Using the survey-level data collected at both sites, roughness and slope were determined for each sensor pair. Cross-sectional roughness was calculated for each sensor pair as the ratio between the straight-line length and the path-length between channel banks. Slope was calculated for each sensor pair by calculating the slope between the sensor pairs on either side of it in the channel.
Porosity

Bulk density was calculated for the samples taken at each site using oven-dried samples. Bulk density measurements were converted to porosity equivalents using:

\[
\phi = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{particle}}} \tag{4.2}
\]

where \(\rho_{\text{bulk}}\) is the bulk density of the sample, and \(\rho_{\text{particle}}\) is the particle density. The particle density was assumed to be 2.65 at both sites.

Stream Network Activity Data Pre-Processing

The intermittent activity data, from both sensor types, were processed to remove noise using a 30-second filter (Bhamjee and Lindsay, 2011; Peirce and Lindsay, 2014). The filter reduced the high-frequency noise that was common during periods where the sensors were at the threshold for measurement. For the ER sensors, this threshold was at the level of the electrodes, while in the flow detection sensor, this occurred when the flowing water was at the threshold for opening the vane. The filter first determined the previous state of the sensor. If it was reporting water/flow presence, and less than 30 seconds had elapsed before it reported no-flow, the state was changed to show that water/flow was present. If the change from water/flow presence to water/flow absence had occurred outside of the 30-second buffer, then no change was made. Water/flow presence was prioritized over water/flow absence because if there was enough water in the channel to activate the sensor, even for a few seconds, then it was likely that water/flow was present during brief moments of the sensor not reporting flow.
Streamflow Timing & Duration

The initial change from a continuously-flowing stream, to the first instance of the channel exhibiting an intermittent state was reported as the week of the year. Total seasonal flowing time was reported as the time, in hours, from May 1 to October 31, that the stream was flowing. Total intermittent flow time was calculated as the time from when the stream entered an intermittent state, to when it resumed continuous flow (i.e. only stormflow).

4.2.4 Stream network expansion regimes

How intermittent stream networks expand or contract can affect their connectivity to downstream areas. These can also play a role in providing insight into the types of processes initiating streamflow during periods of rainfall and the cessation of flow after rainfall. Three modes of expansion and two modes of contraction have been described in the literature (Figure 4.5). There is evidence that the majority of network expansion occurs by the coalescing of pools into a flowing network (Bhamjee and Lindsay, 2011). Using the same methods as Bhamjee and Lindsay (2011), the expansion and contraction regimes for each storm were identified.

Predictors of intermittent Activity

The predictors of intermittent channel activity were determined using monthly binary logistic regression models for each site. Binary logistic regression was used, as it allowed for the probability of an event occurring when only two possible outcomes exist (i.e. flow/no-flow, or water present/not present). This analysis was completed
Figure 4.5 Models of stream network expansion. A) Downstream expansion refers to the movement of water from upstream, likely as a result of wetland-dominated channels; B) headward expansion describes the movement of the hydraulic head upstream as the ground saturates; C) coalescence describes the formation of pools that expand to create a continuous or discontinuous flowing network; D) disintegration describes the receding of the flowing network into isolated pools; and E) downstream contraction is the movement of the hydraulic head downstream. (Bhamjee and Lindsay, 2011)
for each site, and each month independently, as well as a combined analysis of all six study-months for each site. The dependent variable in the analysis was sensor activity, which was determined by whether sensors reported water or flow presence during each storm. Activity was considered under three scenarios: 1) if there was activity in the ER sensor, 2) if there was activity in the vane sensor, and 3) if there was activity in both sensors in a pair. The independent variables in the analysis were the sensor-position index, total rainfall, maximum rainfall intensity, API of the previous day, slope, porosity, and roughness. The ‘backward conditional’ method was used as the selection method for the binary logistic regression. Independent variables are excluded between steps based on their contribution to the regression equation using this method. This determined which variables were likely predictors on intermittent activity, as well as which were statistically significant predictors.

4.3 Results

4.3.1 Meteorological Data

During the study period, there were 14 individual storm events at Site 1, and 28 storms at Site 2 (Table 4.1). Only storms from the first instance during the season when the streams had ceased to flow continuously were used in the study. Based on the daily API and daily rainfall, Site 1 had more storms earlier in the season, while Site 2 had frequent dry periods between storms (Figures 4.6 and 4.7).

4.3.2 Intrinsic site predictors

The three intrinsic site predictors of intermittent activity were local slope, cross-sectional roughness, and porosity (Table 4.2). The average slope for each sensor pair...
Table 4.1 Storm details.

<table>
<thead>
<tr>
<th>Storm Date</th>
<th>Duration (h)</th>
<th>Rainfall (mm)</th>
<th>Intensity (mm/h)</th>
</tr>
</thead>
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<td></td>
</tr>
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</tr>
<tr>
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<td>22.61</td>
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<td>0.10</td>
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<td>4.00</td>
<td>0.29</td>
</tr>
<tr>
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<td>10.80</td>
<td>1.44</td>
</tr>
<tr>
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<td>2.92</td>
<td>4.80</td>
<td>1.64</td>
</tr>
<tr>
<td>09/21</td>
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<td>11.80</td>
<td>0.90</td>
</tr>
<tr>
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<td>2.00</td>
<td>0.12</td>
</tr>
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</tr>
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</tr>
<tr>
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</tr>
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<td>7.40</td>
<td>0.96</td>
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<td>1.02</td>
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<td>4.29</td>
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<td>19.14</td>
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<tr>
<td>10/08</td>
<td>13.39</td>
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<td>0.03</td>
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**Figure 4.6** Site 1 daily API and rainfall.

**Figure 4.7** Site 2 daily API and rainfall.
Table 4.2 Site characteristics for each sensor pair.

<table>
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<tr>
<th>Site 1 Pair ID</th>
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<th>Roughness</th>
<th>Porosity %</th>
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<tr>
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<td>0.92</td>
<td>45.64</td>
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<td>45.64</td>
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<td>0.52</td>
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</tr>
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<td>45.64</td>
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<table>
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<th>Porosity %</th>
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</tr>
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<td>11</td>
<td>0.047</td>
<td>0.93</td>
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</tr>
<tr>
<td>12</td>
<td>0.012</td>
<td>0.94</td>
<td>64.91</td>
</tr>
</tbody>
</table>

at Site 1 was 3.4%, and Site 2 was 3.5%. The range of slopes was between 2.03% and 4.40% at Site 1, and 1.23% and 4.84% at Site 2. Roughness at Site 1 had a mean value of 0.616, while Site 2 had a mean value of 0.963. The difference is largely due to the presence of large boulders present at Site 1 causing a greater ratio between straight-line channel width, and path-length width. Porosity at Site 1 had a mean value of 47%, with a range between 44% and 52%, and a standard deviation of 3%. Porosity at Site 2 had a mean value of 68% with a range between 64% and 71%, and a standard deviation of 2%.
4.3.3 Seasonal intermittent Flow Timing and Duration

Both streams in this study are seasonally intermittent, where they exhibit continuous flow during the wetter spring and autumn months. The timing of this shift from a perennial regime to an intermittent regime occurred during the 34th week of the year (late-August) at Site 1. At Site 2, this shift in flow regime occurred earlier, during the 21st week of the year (late-May).

During the intermittent period of the season, the ER sensors recorded water presence for 1820 hours at Site 1, and 3560 hours at Site 2. Likewise, the flow detection sensors recorded flow for 1578 hours at Site 1, and 2170 hours at Site 2. Including the early, and late-season periods when the streams were continuously flowing, this amounts to flow durations of 4218 hours at Site 1 and 2628 hours at Site 2. This equated to the channels exhibiting flow during 95.5% (Site 1) and 59.5% (Site 2) of the study season.

4.3.4 Stream network expansion regimes

At both sites, the overall stream networks exhibited coalescence during the onset of flow for all monitored storms. Cessation was predominantly by way of disintegration for the overall stream networks. When observing only certain portions of the monitored networks at each site, localized patterns of downstream expansion could be observed in the upper reaches of Site 2.

4.3.5 Predictors of intermittent Stream Activity

No logistic regression models were run for May, June or July at Site 1 as the stream was still exhibiting continuous flow (Table 4.3). The three monthly models for Au-
August, September, and October were able to predict water presence between 83.7% and 89.3% of the time, with August having the strongest model. The sensor-position index, total rainfall, slope, roughness, and porosity were found to be predictors on water presence in August at Site 1. All the variables, but API were found to be significant predictors of water presence in September. The sensor-position index, total rainfall, API, and roughness were found to be significant predictors of water presence in October. Finally, when combining the three months, the sensor-position index, total rainfall, maximum rainfall intensity, slope, and roughness were all significant predictors of water presence. Predictors of flow presence in August were the sensor-position index, total rainfall, roughness, and porosity. The sensor-position index, total rainfall, slope, roughness, and porosity were each found to be significant predictors of intermittent flow in September. In October, total rainfall and roughness were significant predictors of flow activity. Finally, when combining the three months, the sensor-position index, total rainfall, maximum rainfall intensity, and roughness were significant predictors of flow activity. At Site 1, sensor-position index, total rainfall, slope, roughness, and porosity were predictors for both water presence and flow presence in August. The sensor-position index, total rainfall, slope, and roughness were significant predictors in September. In October, total rainfall, API, slope, and roughness were all significant predictors of both water presence and flow presence. The sensor-position index, total rainfall, maximum rainfall intensity, and roughness were significant predictors when combining all records for the season. In all three cases, the individual monthly models had higher prediction rates than the combined monthly models.

At Site 2, monthly models were run for water presence, flow presence, and both water and flow presence (Table 4.4). Total rainfall, slope, roughness, and porosity were predictors of water presence in May. Total rainfall, slope, and roughness were
all significant predictors of water presence in June. Total rainfall, maximum rainfall intensity, API, and slope were predictors of water presence in July. Maximum rainfall intensity, API, roughness, and porosity were significant predictors of water presence in August. The sensor-position index, total rainfall, API, and porosity were predictors of water presence in September. API was a significant predictor in October. In the combined month model for water presence, total rainfall and maximum rainfall intensity were significant predictors. In May, total rainfall, slope, roughness, and porosity were predictors of flow presence. Total rainfall, slope, and roughness were significant predictors in June. In July, slope was the only significant predictor. All the variables were included as predictors in August, however, only the sensor-position index and API were significant predictors. API was the only significant predictor in September. There were no significant predictors in October, but API, roughness, and porosity were included as non-significant predictors. This was also the weakest monthly model for Site 2. The combined months showed the position-index and total rainfall as significant predictors. When considering if both water and flow were present, there was overlap in the predictors with both the water presence models, and the flow presence models. May had the same predictors as both the water presence and flow presence models. June, August, September, October, and the combined month models had the same predictors and significance outcomes as the flow presence models. July was the only month to have a different outcome, with only roughness being a significant predictors. Similar to Site 1, the individual monthly models performed better than the combined monthly models at Site 2.
Table 4.3 Summary of logistic regression at Site 1. The three scenarios are water presence, flow presence, and both water and flow presence. The p-values are shown for each of the predictors with significant predictors (p < 0.05) bolded.

<table>
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<th>Month</th>
<th>n=</th>
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<th>Total Rain</th>
<th>Max. Rain Intensity</th>
<th>API</th>
<th>Slope</th>
<th>Roughness</th>
<th>Porosity</th>
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Table 4.4 Summary of logistic regression at Site 2. The three scenarios are water presence, flow presence, and both water and flow presence. The p-values are shown for each of the predictors with significant predictors (p < 0.05) bolded.

<table>
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<th>Max. Rain Intensity</th>
<th>API</th>
<th>Slope</th>
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4.4 Discussion

4.4.1 Paired-sensor Network

Using a paired-sensor approach allowed for a distinct set of intermittent activity characteristics to be monitored (i.e. water presence and flow presence) allowing for a more robust method to monitor intermittent activity. The ER sensors were robust and less susceptible to interference from stream debris, largely due to the lack of moving parts on the sensor head. The flow detection sensors performed better in areas were debris was not prevalent in the stream, or was small enough to pass through the sensor completely. However, the flow detection sensors provided a method to separate water presence from flowing water presence with a difference of 242 hours at Site 1, and 1390 hours at Site 2. Given that previous studies used water presence as a proxy for flow, the differences in water and flow presence times highlight the limitation of a single sensor approach, and the advantage to using multi-sensor networks.

4.4.2 Intermittent Flow Timing and Duration

Both sites transitioned from continuous flow to intermittent flow at notably different points in the season. Site 1 received a high proportion of rainfall during the first three months of the season (Figure 4.6) and the high API values that persist until the end of August correlate with this shift. As well, it was rainier than the 40-year mean at Site 2 (Figure 4.3). Both June and July were more than one standard deviation above the mean rainfall, both being the third-wettest in 40-years. These extreme rainfall amounts were followed by a relatively dry August. This helps to explain the late shift from continuous flow to periods of intermittent flow. By comparison, at Site 2 the API exhibited many peaks over the season, however, with lower API values
than Site 1. In addition, May, July, August, September, and October were below the
40-year average contributing to an earlier transition (Figure 4.4).

4.4.3 Stream network expansion regimes

The overall prevalence of expansion by coalescence and cessation by disintegration is
unsurprising given the results of Bhamjee and Lindsay (2011). However, at the site-
scale, none of the other expansion regimes were observed at either site in this study,
contrary to the aforementioned results of Bhamjee and Lindsay (2011). This study
utilized larger, more permanent streams, and measured over a greater length than
the other study, bringing into question the effects of scale on the results. Observing
only parts of the channels (i.e. shorter reaches) other modes of expansion could be
observed, particularly at Site 2. During intense rainfall events, the upper reaches of
Site 2 expanded by way of downward expansion. This expansion was also observed
in the field during a large storm. This expansion is likely due to the fill-and-spill
nature of the wetland upstream of this area. During less intense rainfall events, the
entire channel expands by way of coalescing pools of water. This would indicate that
during the less intense events, flow is generated by way of subsurface and groundwater
interactions with the channel, versus an element-threshold interaction in the upper
reaches during intense storms. While the element-threshold effect may still be present
during less intense storms, it is not as evident in the data as the channel has likely
already expanded. No observations of upward expansion were noted, and this is likely
due to the larger size and relative slope of these streams compared to Bhamjee and
Lindsay (2011), which studied smaller, flatter streams.
4.4.4 Predictors of intermittent Activity

The most common significant predictors of water presence at Site 1 were the sensor-position index, total rainfall, and roughness. The study reach at Site 1 had two confluences that would sharply increase the sensor catchment areas immediately downstream of them. Roughness varied over the length of the reach, where upstream was rougher than downstream and pooling was more likely to occur in these rougher areas. Total rainfall would dictate how much water was available for pooling, either from rising the groundwater table, or providing water to the channel via through or overland flow. At Site 1 maximum rainfall intensity was a significant predictor in September, while at Site 2, it was in August. The seasonal minima of API (Figures 4.6 and 4.7) occurred during the same months that both sites had maximum rainfall intensity as a significant predictor. It was expected to find maximum rainfall intensity as a predictor, as convective storms are common in these catchments during the driest months. At Site 2, API and roughness were the only two significant predictors to appear in more than one monthly water presence model. There was more variability in the predictors at Site 1 than at Site 2, during the study season.

The most common predictors of flow presence were total rainfall and roughness at Site 1, and API and roughness at Site 2. Similar to the predictors of water presence, total rainfall and roughness were both the most common at Site 1 likely for the same reasons. Because rougher areas already had pools formed, it is likely that flow would be initiated in these areas first. This is supported when considering the water and flow presence models. These same predictors were found to be significant, and common, in these models as well. Surprisingly, the maximum rainfall intensity was not a significant predictor of flow presence at either site. At Site 2, API was a significant predictor of flow in August and September. In both months, the API values are
relatively low for Site 2, reaching minimum values. Slope was a significant predictor in June and July, when the catchment was relatively wetter. Sensors sited on gentler slopes likely resulted in larger pools forming before flow was initiated. During larger storm events, enough water would fill the channel to initiate flow, while during some of the small events in both months, flow was not initiated, despite pooling occurring.

Finally, the most common predictors for both water and flow presence were total rainfall, slope, and roughness at Site 1, and API at Site 2. At Site 1, the total rainfall and roughness were the most common predictors of water presence and flow presence individually. Slope was a significant predictor of water and flow presence individually and combined in September, but it was also a predictor of both water and flow presence in October. This shows that each type of intermittent activity (i.e. water or flow presence) are often common, but under different scenarios the strength/dominance of any given control may vary due to seasonal or storm conditions (total rainfall, API, maximum rainfall intensity) or site specific variables (sensor-position index, slope, roughness, porosity). However, in the majority of cases, the significant predictors match those found for the vane sensor. At Site 2, this is even more pronounced, where the models were the same in five of the six months. The remaining month (July) had no significant predictors.

The combined-month models had lower prediction rates than the individual monthly models in all three scenarios at both sites, highlighting the benefits of modelling intermittent activity by month. Examining significant predictors by month allowed for a better understanding of what variables were likely always predictors, versus those that are seasonal. As well, separating the predictors of water presence and flow presence highlighted how the predictors of each can vary for the same months. Including models of whether both sensors were active highlighted where both sensors were in
agreement (i.e. there was water and flow present) and showed similar predictors of flow to the other intermittent activity scenarios. Comparing this to the Peirce and Lindsay (2014) study, it is possible that higher prediction rates might have been achieved in the models if the temporal aspect was accounted for. In addition, it would highlight the seasonal changes to predictors of flow.

4.4.5 Limitations

Groundwater undoubtedly plays an role in the flow in these channels, especially during the early spring and late autumn where the channel has moved from continuously flowing to dry, or vice-versa. Ideally, groundwater measurements would be used to determine the influence of groundwater on flow in the channels under different precipitation regimes. However, no groundwater monitoring wells were available for this purpose. In addition, the absence of a high-resolution DEM limited the ability to derive related topographic variables such as flow accumulation, or wetness index grids for the catchment.

4.4.6 Implications

Monitoring intermittent streams is important in understanding water resources in terms of both quantity, and quality. Understanding the predictors of intermittent activity can allow for better prediction of that activity occurring, the timing of activity, and the connectivity to downstream waterways. However, without long-term monitoring datasets, the understanding of how those controls change throughout the year, as well as inter-annually in relation to monthly climate normals, is severely diminished. In agricultural areas, where many low-order streams in southern Ontario are located, best management practices (BMPs) affecting soil and nutrient transport
into waterbodies is directly affected by flow timing in these channels. Knowing what
the timing, and magnitudes of flow will be under certain climate regimes, can allow
for a more informed application of these BMPs. Relating this to the results from this
study, the annual transition to an intermittent flow regime can be greatly affected
by the amount of precipitation received in the spring. This is important as this is
often when agricultural fields are bare in southern Ontario, and actions would be best
taken to reduce soil erosion into these channels. In addition, knowing the amount of
time these streams flow during a month and their connectivity to downstream water
sources allows for better timing of the application of agricultural controls (e.g. pesti-
cides). Understanding the ways in which these stream networks expand and contract
can also shed light on the processes driving flow initiation.

4.5 Conclusions

This study used data from two southern Ontario paired-sensor intermittent stream
networks to describe the timing and duration of intermittent activity in two southern
Ontario catchments. The timing of the no-flow period, the duration the stream flowed
during that period, and the temporal shifts of the predictors of intermittent activity
were described at two field sites. The major conclusions of the paper are:

1. A monitoring network that coupled an electrical resistance sensor, for detect-
ing water presence in the channel, with a flow detection sensor, for detecting
presence of flowing water within channels, was advantageous for monitoring in-
termittent streamflow activity. Each sensor had benefits and limitations that
were offset by the other sensor.

2. Using a paired-sensor approach allowed for distinguishing between different
types of intermittent activity, specifically, where water was present, and where
flow was present. This amounted to a difference of 242 hours at Site 1 and 1390 hours at Site 2. The difference between these types of activity have water resource management implications.

3. The timing of the transition from a continuously flowing stream, to an intermittent stream occurred at different points in the season for each site. This was largely as a result of differences in rainfall during the spring, where one site had a lot of rainfall, and the other was notably drier than the 40-year average.

4. The combined-month models for both water and flow presence activity performed worse than the individual monthly models showing there is merit in studying predictors on a monthly-basis. There was variability in significant predictors of intermittent activity for each month and for each type of intermittent activity. Predictors such as total rainfall and roughness were predictors in all three model scenarios, while others were only significant predictors at certain times. Predictors such as maximum rainfall intensity were significant during dry periods in both catchments. Overall, Site 1 showed less variability in significant predictors than Site 2.
The aim of this thesis was to quantify and describe the dynamics of low-flow conditions in temperate low-order streams. In Chapter 2, larger-scale observations were made about trends in Canadian discharge and indicators of low-flow over 40-years. Increases and decreases in the number of low-flow days and low-flow events, and the length of low-flow events exhibited regional patterns. One of the conclusions of the paper was that regardless of the direction of trends in low-flow the current hydrologic network does not focus on seasonally intermittent low-order basins. The main setback in monitoring these areas is largely technical, as described in Chapter 3. A new flow detection sensor was introduced that addressed the limitations of previous intermittent stream sensor designs, mainly, the inability to distinguish between standing and flowing water. This sensor, in conjunction with the previously used electrical resistance sensors, were found to perform well as a pair in a monitoring network. The performance of these sensors exemplified how the limitations of one sensor could be offset by the strengths in the other. The paired-sensor approach also enabled multiple types of intermittent stream activity (i.e. water presence and flow presence) to be captured. In Chapter 4, this paired-sensor approach was utilized to understand the characteristics of intermittent activity in two southern Ontario catchments. Being able to separate standing water from flowing water in the channel showed that there was a notable difference between the times that the streams had water and when that water was flowing over a season. The timing of the transition between a continuously flowing stream, and one that experiences periods of no-flow was noted for
each stream, with meteorological evidence of why the transition occurred when it did. The expansion regimes of the channels was described, and this was related to factors of connectivity, and the possible processes acting on the initiation of flow. Finally, this paper explored the controls on flow for each month, showing that they were not consistent over a season, nor were the predictors of water presence the same as those for flow presence.

5.1 Intermittent stream monitoring

There is evidence to support that low-order basins are experiencing changes to their flow regimes, possibly at even greater rates, however, little data exists to determine the magnitude of those changes (Schindler, 2001). Uys and O’Keeffe (1997) identified a relationship between intermittency, flow variability, and flow predictability in streams, where episodic streams were more variable, but less predictable than perennial streams (Figure 1.1). This lack of predictability is arguably a result of a gap in monitoring in temperate low-order intermittent streams. The general deficiency of data in low-order basins has been noted (Bishop et al., 2008), as have some of the potential implications of change to these areas (Gomi et al., 2002a; Brooks, 2009; Chin and Gregory, 2001; Meyer et al., 2007) as well as issues surrounding connectivity of low-order streams to downstream waterways (Bracken et al., 2013; Bull, 1997). Because many low-order streams are spatially disperse, and often inactive, traditional hydrological monitoring methods are not always suitable in these environments, either because of technical or financial limitations. Inexpensive specialized sensors were fashioned to address both of these limitations (Bhamjee and Lindsay, 2011; Goulsbra et al., 2014; Constantz et al., 2001; Blasch et al., 2002). However, the designs
to date have been based around electrical resistance (ER) sensors, that used water presence as a proxy for flowing water. Using water presence as a proxy for flow presence worked to describe how networks expand and contract, however, Bhamjee and Lindsay (2011) noted that the main method of expansion in these streams was by coalescence of disconnected pools. This means that discontinuous flowing networks or non-flowing networks of large pools can form, which these sensors could not distinguish from a fully flowing network. There are water resource implications related to the dynamics of flow, such that a fully connected flowing network can transport water, sediments and pollutants to downstream waterways, where isolated pools, or isolated flowing segments cannot. Chapter 3 introduced a flow detection sensor that addressed the limitation of using water presence as a proxy for flow, by explicitly monitoring downstream movement of the water in the channel. However, exclusively monitoring either water presence or flow presence is not ideal, as each has their own implications. Using a paired-sensor approach allowed for a better understanding of the predictors of water presence and flow presence, and demonstrated how those predictors changed monthly (Chapter 4). The transition period between a continuously flowing stream to a stream exhibiting no-flow conditions was greatly affected by how wet the catchment was as a result of rainfall. However, observing the 40-year variability in rainfall for each month (Figures 4.3 and 4.4) alluded to the fact that the timing of the transition could also be equally variable.

5.2 Intermittent stream controls

Some of the results from Chapter 4 can be compared to few recent studies that analysed intermittent flow activity in temperate regions. However, given that the study in Chapter 4 was the first time both water presence and flow presence were
monitored in intermittent channels, only the water presence results can be compared. (Peirce and Lindsay, 2014) monitored three adjacent intermittent streams and found each had different controls. Their study also used a logistic regression analysis as was employed in Chapter 4, with some of the same variables. However, they only ran models for the complete study season, rather than on a monthly basis. In Chapter 4, the combined monthly models performed worse than the individual monthly models in all cases and highlights that predictors of intermittent activity are also temporally dependent. Comparing the result of Peirce and Lindsay (2014) to the combined monthly water presence models from Chapter 4 (Tables 4.3 and 4.4), similarities can be found. In the Chapter 4 study, total rainfall and maximum rainfall intensity were significant predictors of water presence at both sites. (Peirce and Lindsay, 2014) had total rainfall as a significant predictor in two of their four models. Unlike in Chapter 4, (Peirce and Lindsay, 2014) did not have any significant predictors that were common to all three sites, showing that there is a high degree of complexity, even in comparing nearby streams. This is further solidified where (Peirce and Lindsay, 2014) combine their three streams, resulting in the poorest performing model, where the most significant predictor was the channel number. (Goulsbra et al., 2014) had an extensive water presence network, with other variables monitored in the hillslopes in a UK peatland. They found that water table depth was the greatest predictor of water at their sites under many scenarios. However, given the differing methods used, it is harder to draw comparisons between that study, and Chapter 4 and (Peirce and Lindsay, 2014) despite a similar sensor setup.
5.3 Weather, climate, & intermittent activity

Given that number of low-flow days and events, and the length of those events showed decreases overall in Canada, it might seem that intermittent streams will exhibit longer flowing periods over any given year. In some regions, the opposite trend was observed, where low-flow indicators showed increasing trends, which likely means intermittent streams in these areas will have less flow per year. However, the timing of the changes to low-flow conditions might be a better signal of how change might manifest in these streams. A greater proportion of stations in the hydrometric network had increasing discharge trends during the winter months, with decreasing trends in discharge appearing during the summer months. Many intermittent streams in Canada are likely frozen during the winter months when larger streams are experiencing increases in discharge, and water resource and ecological implications are likely not significant during these colder periods. However, given that decreasing trends in discharge are expected during the driest parts of the year, this could result in more sporadic flowing conditions in intermittent streams, and by extension, less predictable flow. In Chapter 4, the study year exhibited rainfall amounts outside one standard deviation in half of the months at both sites (Figures 4.3 and 4.4). However, the timing of these deviations from normal rainfall resulted in different effects on transition times at each of the streams. Simply knowing whether overall rainfall is increasing or decreasing is not as important as knowing when the timing of that rainfall occurs. More rainfall in the summer months would result in greater flowing time, while more rainfall during the winter months (instead of snow) can affect both the winter flow dynamics, and the spring flow dynamics, as less snowpack is available. In addition, a better understanding of the relationship between monthly precipitation and the onset of a no-flow regime, would help to improve predictions of when (or if) streams
transition from perennial to intermittent.

This transition point becomes more important in perennial streams that are currently near the threshold for becoming seasonally intermittent, or in streams that are currently intermittent, but may become ephemeral due to variability of, or progressive change in, climate. For instance, low-order perennial streams in regions where overall discharge rates are decreasing, especially during the drier months, could become intermittent, affecting both hydrological and ecological connections (Schindler, 2001; Brooks, 2009). This transition from perennially flowing toward greater intermittency can affect how these streams are managed and protected. Gomi et al. (2002a) highlighted that headwaters differ from downstream reaches by their close coupling to the hillslope processes, greater temporal and spatial variation, and their need for different means of protection from landuse. Streams that are currently perennial are often well protected in relation to intermittent streams, and a transition in this direction may not prove to be as harmful as the contrary, when streams become more perennial. With projected increases in precipitation during traditionally drier months, areas may have streams that were once highly episodic or intermittent seasonally, moving along the continuum (Figure 1.1) toward perennial streams. Wigington et al. (2005) discussed the expansion of intermittent stream networks headward into agricultural fields where no riparian buffers were present. This in itself has major water quality issues, but in streams where flow is evermore present, the impact on water quality could be even more pronounced.

5.4 Disturbance

Intermittent low-order streams are also sensitive to anthropogenic changes, such as land-cover change, to a greater degree than perennial streams (Buttle et al., 2012;
Bull, 1997; Levick et al., 2008; Chin and Gregory, 2001). The largest changes to these streams in Canada come from urbanization and agriculture. Urbanization of intermittent streams generally results in streams being buried, either in underground pipes, or by changing the topography of the landscape to eliminate them (Levick et al., 2008). Covering the channels and the hillslope with impervious surfaces changes the hydrological characteristics of a drainage basin, and in intermittent streams that are left intact, but with modified hillslopes, this could change water availability in the streams. Chapter 4 examined one season, and thus land-use changes were not considered predictors of intermittent stream activity, though they undoubtedly affected the movement of water in the catchment. Long-term monitoring of intermittent activity would allow for better understanding of how land-use changes can affect the presence of water in channels and the flow of water in channels. In agricultural areas, many of these streams are either eliminated, by altering the topography, or enhanced in size, through trenching. In the former case, the results are often high rates of erosion where the stream once sat, while in the latter, flow is largely increased. The increase in flow is usually from the diversion of water into these modified channels either above ground from features like road-side ditches, or underground through agricultural tile drains. Tile drainage was not present in the study in Chapter 4, and can complicated studies of hydrological predictors of flow, however, should not be avoided. Because many intermittent streams in Canada are located in agricultural environments where this type of drainage is prevalent, it is important to gain a better understanding between the relationship tile drains have on intermittent flow and downstream connectivity.
5.5 Extending the methodology

The use of the methods outlined in Chapter 3 were applied in Chapter 4 for two catchments in southern Ontario, however, can be applied to many landscapes with different intermittent stream characteristics. The paired-sensor network is ideal in many areas in Canada, where water presence and flow presence occur to different degrees. This would especially be the case in gentler topographies, where pooling of water would likely be more common. Modifications of the sensor-heads to match site conditions were described in Chapter 3, and would help to maximize both capability of the sensor to withstand the specific environment, and the signal-to-noise ratio in the recorded data. In flatter areas, such as the prairies, debris load is likely less of an issue, and the same sensor designs could be used as in this study. In steep, mountain streams, where high-debris load could either block the flow detection sensor open, or otherwise dislodge the sensors from the ground, alternate measures would need to be taken. Regardless, monitoring both the water and flow presence would be best suited to understanding these streams.

5.6 Contributions

Bringing awareness to the gap in research in low-order streams is a major contribution stemming from this research; particularly, the areas between the most upstream hydrometric stations and the hillslopes. These streams are the proverbial canaries in the coal mine, the first to respond to shifts in climate, landuse, and other disturbances. A new flow detection sensor was introduced that addressed the major limitation in previous intermittent stream research. More specifically, the introduction of a new methodology for measuring stream network connectivity was introduced that utilized
this novel sensor. The limitations and possible solutions to monitoring streams in these zero-flow conditions are described, as well as the importance connectivity can have on hydrological and ecological factors. Finally, the types of process related data that can be gained from monitoring these areas is presented, helping to fill the gap in the nexus between the hillslopes and downstream waterways.

5.7 Future research

Future research on intermittent stream dynamics should focus on long-term monitoring of stream networks in different Canadian landscape environments, especially in areas sensitive to change. Intermittent stream studies in Canada have been sparse, and differences in intermittent stream dynamics and controls in diverse landscapes are not well documented. Intermittent streams do not exist isolated from other areas of hydrology and the use of networks of specialized sensors, alongside traditional hydrometric monitoring techniques (e.g. Goulsbra et al., 2014) will provide a better understanding of the relationship between changes to discharge, and changes to connectivity in these streams. In addition, monitoring of variables in the surrounding hillslopes (e.g. soil moisture, water storage, source areas, etc.), will also help solidify the function of intermittent streams in other aspects of hydrology. Future studies should also focus on water quantity and quality, as well as ecological aspects. This more holistic view of monitoring will increase the understanding of hydrological variables in intermittent streams and help to increase prediction of intermittent activity timing and magnitude. Increasing prediction of intermittent activity will allow for better models of hydrological connectivity and discharge relationships, and provide a better understanding of what the implications of the outputs of those models mean. However, to do this on a larger scale, initial steps still need to be taken.
A logical starting point would be to identify where these intermittent streams are on Canadian landscapes. Currently, many intermittent streams are missing from, or incorrectly located in, ‘blue-line’ datasets in Canada (and beyond) (Hansen, 2001). Our understanding of stream network connectivity should arguably start with a spatial inventory of these streams, before progressing to understanding when and how they connect to, the better inventoried, downstream waterways (e.g. White and Crisman, 2014). Mapping of these streams could be achieved through simple field reconnaissance or from more technologically inclined methods such as high-resolution digital elevation models (DEMs), specifically those derived from airborne LiDAR systems (James et al., 2007). Given that access and the labour needed to accomplish this through field reconnaissance, the latter is more likely. Being able to extract the location of intermittent low-order streams, and their connectivity to the landscape would provide a better estimate of extent of these waterways in Canada. This thesis described a methodology for monitoring the hydrological characteristics of intermittent streams, however, given their high flow variabilities, some stream exhibit a lot of geomorphic change. Very high-resolution DEMs could be created from ground-based LiDAR to track fine-scale changes to stream morphology over the course of a season, and over multiple years (Notebaert et al., 2009). These DEMs could also be used to delineate metrics describing the physical characteristics of the streams and provide insight into relationship between topography, and water presence and flow presence. Being able to locate, and describe the similarities in both the physical and hydrological characteristics would allow for a detailed inventory of intermittent streams in Canada to be established. Using this inventory, temporary stream classification schemes (Buttle et al., 2012; Uys and O’Keeffe, 1997) could be used to study the impacts and sensitivity of different types of intermittent stream, and to influence BMPs in a more effective manner. Ultimately, understanding the forms, processes,
and function of these critical, but vulnerable, temporary waterways has a long way to go in Canadian hydrology. The magnitude of local and regional changes to both hydrological and ecological changes in these streams are poorly understood, and the effects of climate variability and change on these resources are hindered by a dearth of long-term monitoring data.

5.8 Conclusions

1. The use of paired sensors to monitor two different aspects of intermittent activity improved upon previous monitoring efforts in low-order basins. Specifically, being able to distinguish between the presence of water, and the downstream movement of that water allows us to quantify how long, and how often intermittent channels occupy these states. Hydrologically, the connectivity difference between water being present in isolated pools, and water flowing into downstream areas can affect water resources in terms of quantity and quality. Ecologically, the formation of isolated pools and the timing of downstream connectivity can affect species development more than habitat suitability. Changes to that timing of connectivity, or the formation of pools, can change the presence and abundance of species in intermittent streams. This paired-sensor approach provides a guideline for longer-term, large-scale intermittent stream monitoring.

2. Predictors of intermittent activity varied monthly, and showed different amounts of variability at both study sites. Certain predictors were more common than others, while others were seasonally driven. Given how predictors of flow change intra-annually, knowing how they change for the same time periods inter-annually would allow for a more thorough understanding of the variability inherent in intermittent streams. Being able to account for changes to both
intrinsic and extrinsic predictors (e.g. land-use and rainfall), would help to explain why some predictors are more prevalent during certain months, but not others, and whether the variability in predictors is consistent year-to-year.

3. Long-term trends in discharge and low-flow in Canada are varied regionally. These timing of these changes vary over the year, and will result in shift in the patterns of intermittent activity. Low-order basins are more sensitive to changes in climate, and are potential indicator streams for change. As well, changes in these areas are likely to be more extreme, as many of these streams exist at an equilibrium threshold. Small changes to water availability can result in notable changes to connectivity to downstream waterways, and ecological make-up in intermittent waterways.


IPCC (2007). *Climate change 2007: the physical science basis*. Cambridge University Press.

IPCC (2013). *Climate change 2013: the physical science basis*. Cambridge University Press.


