Updating the Canadian Reference Hydrometric Basin Network to detect climate-related trends in streamflow

by

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Abstract

This thesis developed a new set of selection criteria to renew the Canadian Reference Hydrometric Basin Network (RHBN) and improve its coverage of non-atmospheric factors affecting streamflow such as geographic location, ecological factors as represented by ecoregions, and watershed characteristics (e.g., watershed size). This dataset was further analyzed to provide a national outlook on climate-related trends in streamflow. The usefulness of categorizing streamflows by ecoregion groups or major precipitation mechanism was confirmed. The development of a storage effect indicator that may be used to differentiate between stations with flows controlled by annual phenomena and those with significant carryover between years is an additional contribution.

Climatic effects on river flows can occur directly through changes in rainfall/snowfall, or indirectly through changes to snowmelt, long-term ice thaw, evapotranspiration, and ecological changes (Wrona et al., 2016). However, many long streamflow records have significant anthropogenic influence such as agriculture, deforestation, and urbanization, thus masking the climatic influence. A set of streamflow records called a Reference Hydrologic Network (RHN) may be selected to avoid anthropogenic influences. The existing RHN in Canada, the RHBN, was developed in 1999 (Brimley et al., 1999). This thesis undertakes a renewal of the RHBN based on five evaluation criteria: breadth of coverage, natural or stable conditions, length of record, data quality, and longevity. Land use maps, data quality screening, data consistency screening, and, where needed, historical searches were used to evaluate the criteria.

This resulted in a renewed RHBN consisting of 279 stations deemed appropriate for climate change studies (240 continuous flow, 38 seasonal flow, and 1 continuous level) compared to the 227 stations in the current RHBN (191 continuous flow, 32 seasonal flow, 3 continuous level, and 1 seasonal level). The renewed dataset shows a marked improvement in terms of number of stations, distribution amongst ecoregions, geographic distribution, and distribution of basin sizes. There is a small decrease in average length of record (54.5 compared to 58.5 years), but this seems acceptable given the improvements mentioned above. Some recommendations to improve transparency and confidence in the network are presented.

This renewed RHBN was used to detect trends in 28 streamflow metrics that may be attributable to climate change over four period lengths (40, 60, 80, and 100 years ending in 2016).

Local trend detection was accomplished using a non-parametric permutation approach (Mann-Kendall test for trend with block bootstrapping to account for serial correlation). Field significance in groups of stations defined by ecoregion and watershed characteristics (where pertinent) was evaluated using Walker's test. Field significance assesses the risk that identified trends are false positives (type I errors) by comparing the smallest identified trend p-value to the smallest p-value that could occur by chance in an equivalent sample size.

Results found increasing minimum flows occurred almost exclusively in the winter months for northern stations subject to permafrost changes and possibly autumn rainfall. Decreasing minimum flows were very localized in southern BC and south ON-QC. Previous studies showed similar spatial distributions of these trends, but with the current RHBN's lack of northern stations, may have overstated the importance of decreasing minimum flows when expressed as percentage of stations with trend. Grouping trends by ecoregion largely yielded consistent trend directions for most streamflow metrics with the exception of areas with strongly varying precipitation influences (e.g., rain shadow on the Prairies and increased precipitation near the Atlantic Ocean). This consistent response within ecoregions may be useful for evaluating future watershed responses to climate change. Stations with storage effects did not show many trends, perhaps due to the additional level of variability caused by carryover between years. However, stations identified as having weak annual patterns (pluvial) did show different trends than surrounding strong annual pattern stations. Mountainous watersheds with glaciers show mostly declining streamflow, an indication of final glacier decline. Recommendations to improve future trend detection studies in Canada are presented.

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Chapter 1 Introduction

1.1 Scope

The modelling of future atmospheric variables is essential research (Intergovernmental Panel on Climate Change, IPCC, 2014) that feeds studies on how these changes may affect many different fields, one of which is river flows. While it is tempting to assume that reported increases to daily maximum precipitation (Westra et al., 2013; IPCC, 2014) would lead to higher magnitude peak flows, this is not always the case (Do et al., 2017; Bennett et al., 2018). In addition, peak flow is not the only flow variable for which potential changes may occur; increased baseflow and increased volume (St Jacques and Sauchyn, 2009), earlier peak flow, both higher and lower peak flows (Burn and Whitfield, 2016), decreased seasonal flow (Stahl and Moore, 2006), increase in flow reversals (Monk et al., 2011) are among many examples of other changes. These changes can vary greatly across basin types, locations, and climates with little regard for political maps; for instance, the examples mentioned above are all in Canada. Changes in river flow can have impacts on human health, agriculture, hydropower, and human conflict. Freshwater fluxes into the Arctic Ocean may even affect the oceanic circulation patterns that in turn affect climatic patterns, creating a feedback effect (Prowse et al., 2015).

Climatic effects on river flows can occur directly through changes in rainfall/snowfall, or indirectly through changes to snowmelt, long-term ice thaw, evapotranspiration, and ecological changes (Wrona et al., 2016). The exact effect of these processes is not known and cannot be modelled at this time, so it is difficult to predict how the modelled climatic changes may affect flow. One way to address this is to assess long streamflow records for any changes that may have already occurred. Then attribution, data collection, modelling, and ultimately adaptation to changing water availability and flows can begin. However, many long streamflow records have significant anthropogenic influence such as agriculture, deforestation, and urbanization, thus masking the climatic influence. Merz et al. (2012) state that more effort needs to be put into attributing any flow changes to non-anthropogenic sources. In that vein, this thesis seeks to avoid confounding anthropogenic influences through careful streamflow station selection, then assess the presence, direction, and geographic pattern of trends within Canada. There is an existing set of streamflow stations in Canada that are appropriate for these purposes called the Reference Hydrometric Basin Network (RHBN; Brimley et al., 1999). However, this was developed in 1999 and has not been updated since; thus a renewal of this station set is appropriate.

1.2 Rationale for a Reference Hydrologic Network

Several countries have formalized a set of streamflow stations for evaluating the impacts of climate change on hydrologic variables. While their official names vary, they are commonly known as Reference Hydrologic Networks (RHN). The use of data from an RHN assures that changes in hydrologic variables, identified through trend analysis, for example, can be attributed to changes in climate as other possible causes of changes have been controlled for by examining only data from watersheds that can be considered to reflect near pristine conditions. RHNs have been used in many regions to study streamflow or streamflow-related variables (Europe – Stahl et al., 2010; Australia – Ajami et al., 2017, Zhang et al., 2016; UK – Harrigan et al., 2018, Hannaford, 2015; US – Lins and Slack, 2005, Sagarika et al. 2014; US and Canada – Burn and Whitfield, 2018; Canada – Whitfield et al., 2012, Burn et al., 2012, Hulley et al., 2018). Most of these datasets are curated by national governments ensuring their longevity. In Canada, the RHN is referred to as the Reference Hydrometric Basin Network (RHBN) and curated by the Water Survey of Canada (WSC).

1.3 RHBN circa 1999: evaluation criteria, current state, and issues

The original Canadian RHBN was developed in 1999 under the specter of budget reductions in order to maintain climate change monitoring capability and facilitate its assessment by a special designation (Brimley et al., 1999). Using a watershed discharge record as a proxy for climate may dampen the noise from instantaneous and local meteorological effects provided the chosen watershed lacks any other causes for discharge changes, such as land-use changes, abstractions or discharges from human activities (Slack and Landwehr, 1988). In an effort to identify a network of near pristine watersheds with long records suitable for the purpose, the following criteria were applied to the existing WSC archive (HYDAT, or hydrometric database) (Brimley et al., 1999):

1. *Breadth of Coverage:* Widest geographic coverage possible. Continuous stations were preferred, but those with seasonal records were included, particularly in the Prairie region, as comparisons of spring, summer and fall flows were still possible. Stations recording lake level data were also included as they could be useful in the study of climate effects on surface water. Only stations with observed values, or values estimated within national standards, were considered; stations for which data were constructed from other information were not included.

2. *Degree of Basin Development:* Pristine or stable land-use conditions. No systematic recordings were found for changes in landscape so rough estimates were made of the percentage of surface area modified in some way. 'Pristine' catchments were those with less than 10% modified catchment surface.

3. *No Significant Regulation or Diversion:* The national water meta-database (HYDEX, now HYDAT) contains information for all stations as being "natural" or "regulated". "Natural" simply means that flow at the station is similar to what would occur without regulation; it does not imply 'pristine' catchments and makes no mention of diversions. Watersheds with "regulated" systems could be included if the structures controlled less than 5% of the area of the watershed, although this percentage is not frequently reported.

4. *Length of Suitable Record:* A minimum of 20 years of record, with some discretion to accommodate under-represented areas.

5. *Longevity:* The stations must be active and be expected to remain active and in compliance with the criteria for the foreseeable future. This criterion relied on the judgment of regional staff as to the possibility of future land development within the basin and continued funding. In some cases, sites that had secured funding from other long term sources, such as for flood forecasting, were preferred.

6. *Accuracy of Data:* This was a qualitative evaluation undertaken by the regional offices of Environment Canada and the Ministère de l'Environment et de la Faune in Quebec. Stations were assessed for both open-water and ice-cover conditions and given a score of 1-5 (excellent to poor). Particular attention was paid to the stability of the control and accuracy of the rating curve. Assessors were also asked to identify any differences in accuracy between open-water and ice-cover conditions to provide information on possible seasonal differences in accuracy (Harvey et al., 1999). The Quebec portion used a criterion of less than 5% estimated flows using national standards and over 95% 'good' or better quality (Ouarda et al., 1999).

7. *Unofficial criterion:*

a. Represent most geographic areas: To accommodate this, the original developers of the RHBN used judgment and allowed the stretching of the preceding criteria in under-represented geographic areas.

b. Parsing decisions: Where there were several stations in close proximity that matched the preceding criteria, the original developers chose the best available station, applying judgment based mostly on criteria 1, 4, 5, and 6.

This resulted in a network of 255 hydrometric stations, of which 211 are continuous streamflow, 7 are lake level stations, and 37 are seasonal streamflow stations (Brimley et al., 1999). Unfortunately, not all the stations originally identified as part of the RHBN are still in operation. An analysis of the current RHBN identifies only 227 stations, of which 181 are continuous streamflows, 4 are lake levels, and 33 are seasonal stations (1 lake level station is a seasonal station). Only 217 of these 227 are reported as active, a reduction of 15% from the original 255 stations. Less than 100% agreement with the other selection criteria is possible, but as some stations were originally included despite not matching the criteria, there is no way to differentiate between a degradation or initial disagreement with the criteria. As noted in Whitfield et al. (2012), there doesn't seem to be any published reason for inclusion, in metadata or otherwise, of these 'disagreeing' stations. At the very least, including the justifications for decisions would have increased the end user's confidence in the product.

The geographic spread of current RHBN stations and the station types are shown in Figure 1. There is notably sparse data in northern regions, none in the Arctic Archipelago, and many stations in the Atlantic Maritime Provinces and southern British Columbia. Watershed size increases northward, which may affect the analysis of certain hydrological processes that only operate on larger scales (Blöschl and Sivapalan, 1995). Seasonal stations are almost all confined to the Prairie region, which limits the possibility of full year or winter analyses. Figure 1 also shows the length of record for each station in the current RHBN. Most long records are in the southern, populated, portion of the country. This imbalance limits the nationwide usefulness of the dataset. There were also some stations with a 'regulated' designation within HYDAT; while this designation does not necessarily mean that the flow was significantly controlled, the word itself seems at odds with the stated goals of the RHBN and may have caused some confusion.

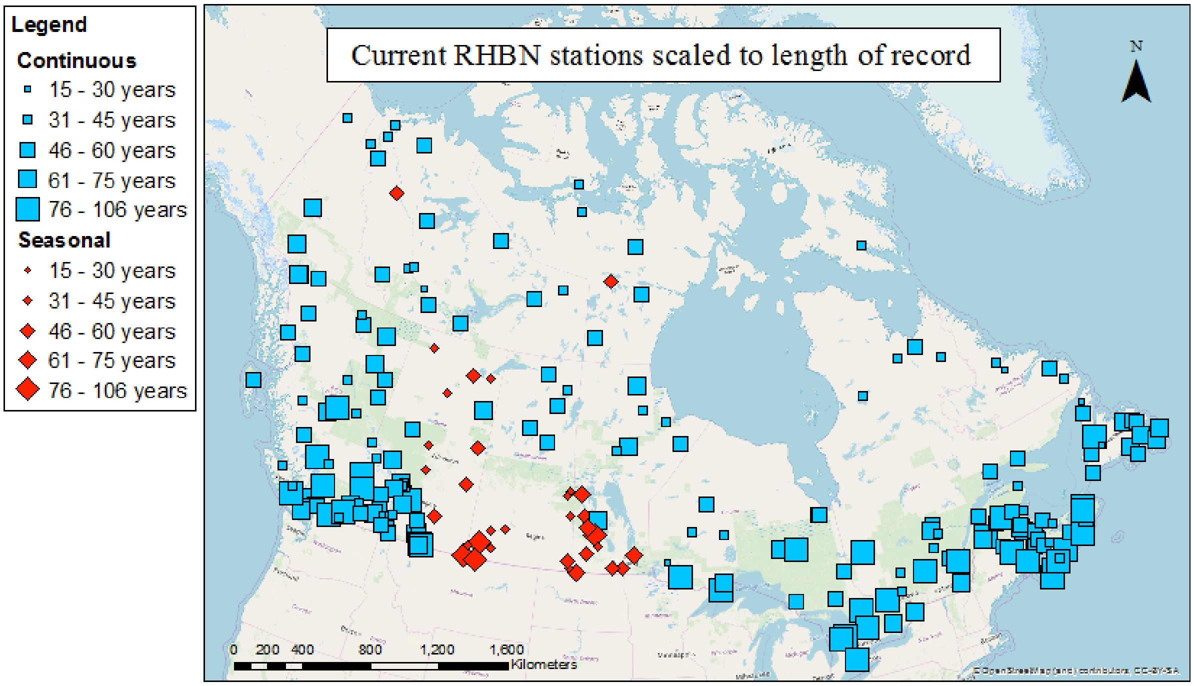


Figure 1. Current RHBN stations scaled to length of record. Continuous in blue squares, seasonal in red diamonds.

1.4 Review of other countries' RHN updates

As in most things, it is useful to review what others have done in similar situations. Many other countries have now developed an RHN, including Australia (Turner et al., 2012), France (Giuntoli et al., 2012), Ireland (Murphy et al., 2013), Norway (Fleig et al., 2013), the United Kingdom (UK) (Bradford and Marsh, 2003) and the United States (US) (Slack and Landwehr, 1992). Presented below are the approaches taken by the US, UK, and Australia to the creation and renewal of their respective reference networks. The US is unique in terms of geographic and hydroclimatic similarity to Canada and is also useful to profile since the US has recently gone through a renewal/update of their RHN. The UK is highlighted due to some of the novel considerations included in the development of their RHN. Australia had a particularly structured consultation of stakeholders.

1.4.1 United States Hydro-Climatic Data Network (1988)

The Hydro-Climatic Data Network (HCDN) was developed in 1988 by the US Geological Survey (USGS). It consists of 1659 streamflow sites extracted from the National Water Storage and Retrieval System (WATSTORE) that match the following six criteria (Slack and Landwehr, 1992):

1. *Availability of data in electronic form:* This criterion was relevant at the time, but not so much now.

2. *Breadth of Coverage:* Sought to have the largest geographic and temporal coverage possible for a representative range of climate and watershed conditions. There is no mention of how the climate or watershed conditions were evaluated; this was likely an informal portion of this criterion, evaluated by professional judgement. The temporal coverage used the definition of a water year (ending September 30th) instead of a calendar year to define the amount of available data and, more importantly, did not require the station to be currently active.

3. *Length of Record:* A minimum of 20 water years of monthly data was set. Less than 20 water years was accepted if it fulfilled the geographic or climate condition of the previous criterion. If only a portion of a station's record was acceptable, then this portion would be noted. In this criterion and others, the authors stressed that remarks or justifications for any divergence from hard criteria would be noted in metadata.

4. *Accuracy of Records:* This appears to be more detailed than the published RHBN methodology. Ratings of "poor", "fair", "good" and "excellent" were assigned to each record and year by the regional offices of the USGS. Ratings were based on the professional judgement of the office in charge of a station in question, similar to the RHBN, although there is a stated institutional standard for these ratings. For example, a "good" accuracy would ideally indicate that 95% of flows are within 10% of the true value. A few years of "poor" or "fair" data in an otherwise "excellent" long record could still be accepted, provided a comment is included in the metadata. The USGS publishes yearly reports that include accuracy evaluations for that year; this yearly evaluation is only available from regional offices in Canada upon request.

5. *Unimpaired basin condition:* Streamflow should be as close to "natural" as possible; no flow diversion or augmentation, regulation by containment structure, or reduction of baseflow by extreme groundwater pumping were allowed. Human activity and land use changes cannot be so large as to affect the monthly mean discharge, although how to evaluate this is not specified. Gauges downstream of dams and other structures were generally not accepted. If the human intervention in streamflow was deemed to be small and uniform across the period of record, then that station could be included.

6. *Measured Discharge Values:* Values must be "measured". The original HCDN paper went on to say that estimated values in the case of occasional equipment malfunctions would be acceptable so long as the dataset still met the overall accuracy criterion. Corrected values in the case of measured diversions upstream would also be accepted. Datasets constructed from several other stations, but not measured at the purported station site, would not be accepted. Neither would datasets that had been filled in using an algorithm.

The original HCDN predates the Canadian RHBN and significantly influenced the establishment of the original RHBN criteria.

1.4.2 US HCDN-2009 (GAGES-II)

HCDN-2009 is an updated version of the HCDN consisting of 743 stations taken from another dataset evaluation (Lins, 2012). GAGES (Geospatial Attributes of Gages for Evaluating Streamflow), developed by the USGS National Water-Quality Assessment (NAWQA) Program, identified natural and altered streamflows to assess their effect on aquatic ecosystems. These data needed to have at least 20 years of complete-year flow during the period 1950-2007. A subset of reference sites within the GAGES database were assessed as having minimal direct human impact and were identified on three criteria:

1. All sites having been previously separated into nine ecoregions, the hydrologic disturbance of the watershed should be less than 75% of the other gaged watersheds in the ecoregion. Disturbance was evaluated by an index based on geospatial measures of reservoir storage, dam locations and density, freshwater withdrawal, road density, and the US Environmental Protection Agency's National Pollutant Discharge Elimination System (NPDES) discharges. If a region was short on stations, the next lowest percentile of disturbance would be considered.

2. USGS Annual Water Data Reports did not show a "regulated" streamflow, although some sites with minor modifications were retained.

3. The watershed passed a visual screen of satellite images for evidence of human activities suggesting flow diversions, groundwater withdrawal, and other factors known to affect natural streamflow.

An update to GAGES completed in 2011 created the GAGES-II database with 9,322 stream gages, 2,057 of which are identified as reference gages. Since the GAGES-II reference definitions so closely overlapped with the HCDN, it was used as the basis for an updated HCDN. The USGS applied four tightened criteria to the GAGES-II reference stations:

1. Must currently be identified as "reference" in the GAGES-II database.

2. Must have at least 20 years of complete and continuous discharge record through 2009.

3. Must have less than 5% impervious surface area as measured in the Federal National Land Cover Data (NLCD, 2006).

4. Must pass a review at the discretion of the State USGS Water Science Centers.

The update is named HCDN-2009 and is listed as a special designation within the GAGES-II database. These criteria are much more stringent than the original HCDN and so the reduction of stations from 1,659 to 743 may not be solely a degradation of the original station watersheds. GAGES-II also had a watershed maximum limit of 50,000 km^2 and so this size limit is transferred to HCDN-2009.

1.4.3 United Kingdom

The United Kingdom has a different set of challenges and advantages in comparison with the US or Canada; their National River Flow Archive has a very dense network of over 1,500 stations with very long records. Some daily streamflow measurements date back as far as 1879 (National River Flow Archive, 2017). There are also significant human impacts over many of the watersheds. Additionally, the UK data have benefited from a large quantity of consistent basin description, flow type, and data quality information that was not widely available for the original HCDN or RHBN. The criteria used in the selection of the roughly 100 stations in the UK reference network were the following (Bradford and Marsh, 2003):

1. *Natural or nearly free of direct anthropogenic impacts*: Any impacts were to be reported according to their effect on flows or flow regime. A partially qualitative Factors Affecting Runoff (FAR) category has been listed for each station. For example, an 'N' designation in FAR, or 'Natural' flow, means that any possible variation from abstractions and discharges is so small that the gauged flow is considered to be within 10% of real flow at or above the 95th percentile flow. 'N' sites met the current criterion, but sites that were not 'Natural' were not immediately excluded as this designation is quite

stringent. Sites with impacts that were considered ‘stable’ over the length of record could also be considered in order to meet other criteria.

2. *Data quality*: Stage-discharge relationships are well defined and essentially stable. It should be possible to measure the full range of flows with data quality evaluated for both low and high flows. For stations to be included there should be well-documented knowledge of artificial influences and changes in measurement techniques. There are several parameters that help in making this decision; an accuracy grade for low flow and another for high flow (both following specific evaluation criteria applied nationally in Gustard et al. (1992) and the Natural Environment Research Council (1975), respectively), the number of available annual maximum flows, the maximum of the measurement structure divided by the median flow (an indication of station capacity), and finally the percent completeness as the number of years with less than 5 days missing over the total years of record.

3. *Record Length*: Ideal record length for the UK network was over 25 years, but stations with record lengths of only 10 years could be included if they met other critical criteria. Where sites had similar responses and characteristics to those nearby, the longest record was chosen.

4. *Representation:* Good geographical spread that also reflects different basin characteristics affecting flow regime, such as vegetation cover, catchment orientation, rainfall or snowmelt dominant, and geology. Several data sources were used in this effort, but an example used for geology in Bradford and Marsh (2003) was base flow index (BFI); a large BFI value means the soil or rock is very permeable and groundwater makes large contributions to streamflow, a small BFI represents a more impermeable soil/rock and a flashier streamflow response. As BFI varies significantly in the UK, a full range of BFIs was desirable.

5. *Accessibility and ‘protection’*: Accessible sites are more likely to remain operational and protected basins, such as those within national parks, are more likely to remain ‘natural’. This criterion is meant to assure the longevity of measurement and of a catchment’s undeveloped state.

6. *Confirmation*: Local Measuring Authorities need to confirm a station’s suitability for the benchmark network.

This benchmark network’s usefulness is greatly increased by the availability of spatial and reference data (e.g., quality of measurements and basin characteristics).

1.4.4 Australia

The RHN for Australia, Hydrologic Reference Stations (HRS), was developed by the Australian Bureau of Meteorology (ABM) (Turner et al., 2012) and currently consists of 222 stations spread through all the hydro-climatic regions. However, these are distributed mostly towards the coast, especially the southeast, with few stations in the interior, an artefact of the existing streamgauge distribution. There were four criteria: record length of 30+ years, data quality which in this case meant less than 5% gap-filled data (Australia uses a gap-filling procedure using lumped rainfall-runoff model GR4J (Perrin et al., 2003)), no intervention of human activities in the basin (no dams, weirs, irrigation, and minimal land use change), and spatial representativeness in terms of climatic regions and flow regimes. The ABM followed four phases set out by a commissioned report (SKM, 2010):

- *Phase 1* is "to collate a list of potential hydrologic reference stations" based on data availability, location upstream of major dams, minimum length (1975 onwards), and previous benchmarking studies (Stewart et al. 1991, Peel et al. 2000, and Viney 2010).
- *Phase 2* is to "undertake stakeholder consultation to identify and understand impacts in upstream catchments that may impact on the quality of the streamflow reference stations." Over 70 participating government agencies and water authorities answered questions on diversions, irrigation structures, point source discharges, potential future impacts, regional importance and data quality of the potential reference stations. These organizations provided data where possible and could recommend stations be added to the list from Phase 1. These were then divided into 3 groups: Group 1 where the catchment is either considered pristine or to have minimal land use impacts, Group 2 where there needs to be more study on land use impacts, Group 3 where the stations are removed from consideration due to land use change impacts, poor hydrological quality, planned closure, or redundancy/ proximity to station in Group 1 or 2.
- *Phase 3* is to "quantify land use changes and hydrological quality of streamflow series." The Australian Department of Climate Change, Environment and Energy completed a spatial analysis of the catchments to determine the land use changes between forest and non-forest cover between 1972-2010 (data constraint). Forest cover was deemed sensitive to most urbanization, agricultural clearing, and forestry practices. A soft limit of less than 10% land use change was set.
- *Phase 4* was "to identify climate regions" based on Köppen classification (Stern et al., 2000; original Köppen, 1900 and Geiger, 1961).

The HRS network is scheduled to be reviewed and updated every two years. The ABM also developed a web portal that contains key standard trend products on 10 flow metrics (Zhang et al., 2014).

1.5 Background on Trend Analysis

Once direct anthropogenic influences have been ruled out, trends can be assessed statistically and be assumed to be climate-related changes. Streamflow data are viewed as a synthesis of all the hydrological processes that occur in a basin and thus trends associated with that data could be linked with any of them; further analysis would be needed to narrow down the cause and may be greatly aided by watershed characteristics (see section 1.5.3).

1.5.1 Statistical Tests

There are three broad hypothesis levels for trend tests: local tests for an individual timeseries, field significance tests to determine if a set of local tests are collectively significant, and regional consistency tests that show the degree to which local tests agree with each other (Renard et al., 2008; Kundzewicz, 2012; Madsen et al., 2014).

Local tests must contend with streamflow data that has a bounded lower end, an unbounded/unknown upper end, missing data, and generally non-normal distributions (Kundzewicz and Robson, 2000). These characteristics make it difficult to estimate the probability distribution of hydrological data, perhaps this is why non-parametric tests, where statistics are performed on the ranked values rather than the values themselves, have been preferred (Khaliq et al., 2009a; Mortsch et al., 2015). Parametric tests may compare lumped or sliding periods for changes (Pinter et al., 2006; Ntegeka and Willems, 2008) or identify a trend with regressions (Fleming and Weber, 2012; Hannaford and Marsh, 2008; Strupczewski and Kaczmarek, 2001; Galiatsatou and Prinos, 2007). Lumped periods could easily coincide with peaks or troughs of low frequency oscillations thereby identifying a difference between oscillation phase instead of longer climate-related trends (section 1.5.2 and 1.5.4). Even if the periods are chosen based on a step-change test (e.g., Pettit, Mann-Whitney, distribution-free CUSUM, or others from Kundzewicz and Robson, 2000), the available data duration may simply not be sufficient to capture the full distribution range in the case of rare events.

Estimating the magnitude of a trend in hydrological data directly through linear regression is not appropriate as standard regression assumes a normal distribution for residuals. Data may be transformed by normal scores to adhere to the normal distribution assumption, but this still requires independent data and makes interpretation difficult (Kundzewicz and Robson, 2000). The Theil-Sen (TS) slope estimator (Sen, 1968; Theil, 1950) is based on rank correlation (i.e. is non-parametric) and is less sensitive to outliers (or non-normality). TS finds the median slope of all pairs of data but does not suggest a calculation for the intercept. Dietz (1987) finds that an intercept as the median intercept of TS applied to all data points (Adichie, 1967; which would split half the data above and half below the trend line) and as the intercept of TS applied to a point composed of the median x and y values (Conover, 1980) are the best options for large or asymmetric errors.

Assessing the mere presence of non-zero trend may be done using non-parametric tests like the Mann-Kendall test (Mann, 1945; Kendall, 1975) or the Spearman rank correlation (Kendall and Gibbons, 1990) which identify monotonic trends or step changes (specifying whether the movement is positive or negative), and the Petitt test for abrupt step changes (Petitt, 1979). According to Yue et al. (2002a), the Spearman's test has similar power to the Mann-Kendall (MK) test in synthetic data. Since the MK test is used much more widely in Canada (Mortsch et al., 2015), more details on modifications to this test are given below.

MK assumes independent samples while most streamflow data show some serial correlation. There are several ways to modify the test to account for this:

- *Pre-Whitening (PW)* removes the sample serial correlation from each data point (von Storch, 1995).
- *The Variance Correction Approach* seeks to modify the MK test statistic variance based on the effective sample size (Hamed and Rao, 1998).
- *Trend Free Pre-Whitening* removes any trend as calculated by TS before applying a PW procedure and re-adding the TS slope (Yue et al., 2002b).
- *Block Bootstrap Resampling (BBS)* is a permutation method of reshuffling the data many times within blocks of a length that internally preserve the serial correlation to get a modified distribution of the MK test statistic (Önöz and Bayazit, 2012; Khaliq et al., 2009a). BBS has a recommended block length of 4 or 5 for most streamflow data (Önöz and Bayazit, 2012).

Field significance may be verified by counting the significant local tests. However, this technique is extremely sensitive to the cutoff value for the chosen local significance test and cross-correlation between tests. Walker's test and the False Discovery Rate (FDR) are both based on local test p value and are not as sensitive to the cutoff value or cross-correlation (Wilks, 2006). Walker's test compares the smallest local *p* value to a value based on α_{global}, the chosen field significance level (typically 0.05 or 0.1) and *K,* the number of local tests. The False Discovery Rate (Wilks, 2006) establishes a sliding scale for the ranked local *p* values which, contrary to Walker's test, allows for the case where the smallest local *p* value is not the most significant result. Both were developed under the assumption of local test independence but have been shown to be insensitive to significant cross-correlation (Wilks, 2006). Walker's test was used in this thesis.

Regional consistency is the degree to which local tests agree with each other (Renard et al., 2008). This may be evaluated by i) lumping local data into a regional metric defined by common attributes before assessing trend, ii) taking the Regional Average Mann-Kendall test (Douglas et al., 2000; Yue and Wang, 2002), or iii) using a semi-parametric approach described in Renard et al. (2008).

1.5.2 Time Period

The time periods chosen for analysis are important for identifying climate-related trends due to the limited availability of long duration data, statistical challenges of identifying trends in high variance data, and confounding natural low frequency oscillations.

Streamflow data often requires a compromise between increasing the duration of data coverage while compromising the geographic coverage, or vice versa. Other studies have used shifting (Burn and Whitfield, 2018), uniform (Monk et al., 2011), and/or multiple (Burn et al., 2016) time periods depending on the relative importance of data duration and geographic coverage.

The probability of correctly rejecting a null hypothesis of no trend (i.e. limiting the number of false trends), of a statistical test increases with increasing sample size (Yue et al., 2002a). Chiew (1993) mentions that the length of record needed to identify trends depends on the interannual variability and magnitude of change. In a study using Canadian streamflow data, Khaliq et al. (2009b) recommended a time period of at least 40 years to identify climate-related trends.

Hosking (1984) has recommended a time period of at least 100 years to account for long-term persistence (LTP), an un-attributed tendency for very low-frequency fluctuations. It is not possible to differentiate between LTP and climate change at this time (due to data duration) and this may not be an important distinction; while LTP would suggest that the distribution of streamflow values will eventually return to previous levels, it may not within the planning lifespans used in water management. However, oscillations on the decadal scale related to ocean-atmospheric teleconnections (e.g., Pacific Decadal Oscillation or PDO) have a well-documented influence on streamflow (Whitfield et al., 2010; Rood et al., 2005; Burn et al., 2004; Burn, 2008; Brabets and Walvoord, 2009; St. Jacques et al., 2010); if precautions aren't taken, then identified trends may be related to oscillation phase shifts instead of the overriding climatic influence. Chen and Grasby (2009) suggest a time period of at least 60 years (or 3 times the dominant oscillation) to identify trends with the caution that the start and end should not be located at a peak or trough of climatic oscillations.

1.5.3 Basin Characteristics and Hydrological Metrics

Some studies have limited the size of catchments to narrow the range of effects measured (Stahl et al., 2010), while others maximize the range of basin sizes to show possible effects of scale-dependent processes (Petrow and Merz, 2009). In an effort to capture the most area, some simply take the stations closest to the oceanic outlet and end up with a wide range of basin sizes (Su et al., 2018).

Physical characteristics of basins can help inform the attribution of trends. Streamflow records may be divided into categories based on flow regime (Monk et al., 2011), climatic area or ecoregion (Hulley et al., 2018), or drainage area (Bring et al., 2016). Categorizing basins based on the presence of permafrost and thick overburden (St. Jacques and Sauchyn, 2009), or glaciers (Stahl and Moore, 2006) has been found to be useful.

Hydrologic metrics can describe the timing, magnitude, duration, volume, frequency of events, rate of change, or seasonal variations (Koshida et al., 2015). Water management-related metrics like total volume, timing of peak flow, number of high flows, or duration of low flows are very useful. Carefully selected metrics and seasons may be indicators for the ecological health of a stream (Monk et al., 2011), or groundwater flow (St. Jacques and Sauchyn, 2009).

1.5.4 Attribution

One way to aid in attributing trends is to control influencing factors by excluding direct anthropogenic changes with an RHN; although this is sometimes compromised in favour of geographic coverage (Do et al., 2017; Su et al., 2018) or very long records which tend to be for large rivers near human settlements (Pinter et al., 2006). Correlation to nearby precipitation or temperature stations can link atmospheric trends to streamflow metrics (Bennet et al., 2018). Correlation to oceanic oscillations, such as the PDO, North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), Arctic Oscillation (AO), etc. can link streamflow to large-scale weather patterns (Fu et al., 2012; Hodgkins et al., 2017).

1.6 Thesis Objectives

The renewal of Canada's RHBN will first seek to develop a new set of selection criteria based on a review of other RHNs (e.g., US, UK, Australia). By applying these new criteria, the network will improve its coverage of non-atmospheric factors affecting streamflow such as geographic location, ecological factors as represented by ecoregions, and watershed characteristics (e.g., watershed size). This is expected to increase the number of stations, especially the number of smaller stations in northern areas. The justifications for membership decisions incongruent with the criteria will be recorded while maintaining current RHBN stations where possible. The new RHBN will avoid anthropogenic influences to maintain suitability for monitoring climate-related changes to streamflow.

This thesis also seeks to detect climate-related trends in Canadian streamflow by using the renewed RHBN from above. First, a national outlook on local positive and negative streamflow trends and field significance will be conducted. Then, the analysis will be re-aggregated in smaller groups that limit the factors affecting streamflow (e.g., by ecoregion or watershed characteristic). Identified trends will be investigated by comparing to concurrent atmospheric, ecological, or long-term ice trends in the relevant areas, providing a guide for potential attribution.

1.7 Thesis Format

The renewal of Canada's RHN seeks to update an existing network of streamflow stations to control for direct anthropogenic effects, data quality and length, all while covering the widest possible range of ecozones, watershed characteristics, and geography. The statistical assessment of the renewed RHBN for trends has its own, separate, goals; it does not seek to also assess the effectiveness of the renewal. Thus, the two goals are independent and will be treated as such in the following chapters. Chapter 2 will cover the methods used in renewing Canada's RHBN, chapter 3 will present the results of this renewal, chapter 4 will cover the methods for trend detection, chapter 5 will present the results of the trend tests, and chapter 6 will include conclusions and recommendations for both.

Chapter 2 Methods for RHBN Renewal

2.1 Overview

Many Canadian studies have used the current RHBN to circumvent the presence of direct anthropogenic impacts (Burn and Whitfield, 2016; Burn and Whitfield, 2018; Hulley et al., 2018; Monk et al., 2011; Tan and Gan, 2015; Cunderlik and Burn, 2004; Hodgkins et al., 2017). Although the current RHBN was developed in 1999, analyses use data far beyond this year (up to 2010 for Hodgkins et al., 2017 and Tan and Gan, 2015; up to 2015 for Burn and Whitfield, 2018). However, the further from the RHBN development year, the potentially weaker the assumption that RHN criteria are still met, especially the 'natural' watershed criterion. With new data products, particularly geographic data, and more powerful analysis tools (e.g., R programming language, ArcGIS), there is an opportunity to confirm that existing stations meet all criteria. Furthermore, with 19 years of additional data, there is also an opportunity to expand the network.

2.2 Criteria for RHBN Renewal

Presented below is the proposed set of five evaluation criteria for a renewed RHBN: breadth of coverage, natural or stable conditions, length of record, data quality, and longevity. The criteria were developed upon review of other RHNs in chapter 1, first presented in a report by Pellerin and Burn (2017) to Environment and Climate Change Canada (ECCC). The criteria are in order of importance, with each containing a definition, supporting data products, and methods paragraph.

2.2.1 Breadth of Coverage

This criterion seeks the most extensive coverage possible of the non-anthropogenic processes affecting streamflow by representing geographic and ecoregion spread as well as a range of watershed characteristics. Canadian Ecoregions have been developed by the Commission for Environmental Cooperation (CEC) to represent climatic, biological (flora and fauna), landform, soils, and land use groups. These Ecoregions may be useful when evaluating long-term trends as climate changes may be exacerbated or mitigated by changing interactions between the biotic inhabitants and their environment. Changes to streamflow may also be attributed to processes that only operate in watersheds with certain characteristics. For example, changes to small thundershowers may affect streamflow in small watersheds much more than large ones, or the extent of wetlands may affect the magnitude of peak flows after rainfall events. Due to data availability, the watershed characteristics considered for RHBN renewal are watershed size and wetland area.

2.2.1.1 Breadth of Coverage Data

2.2.1.1.1 Watersheds

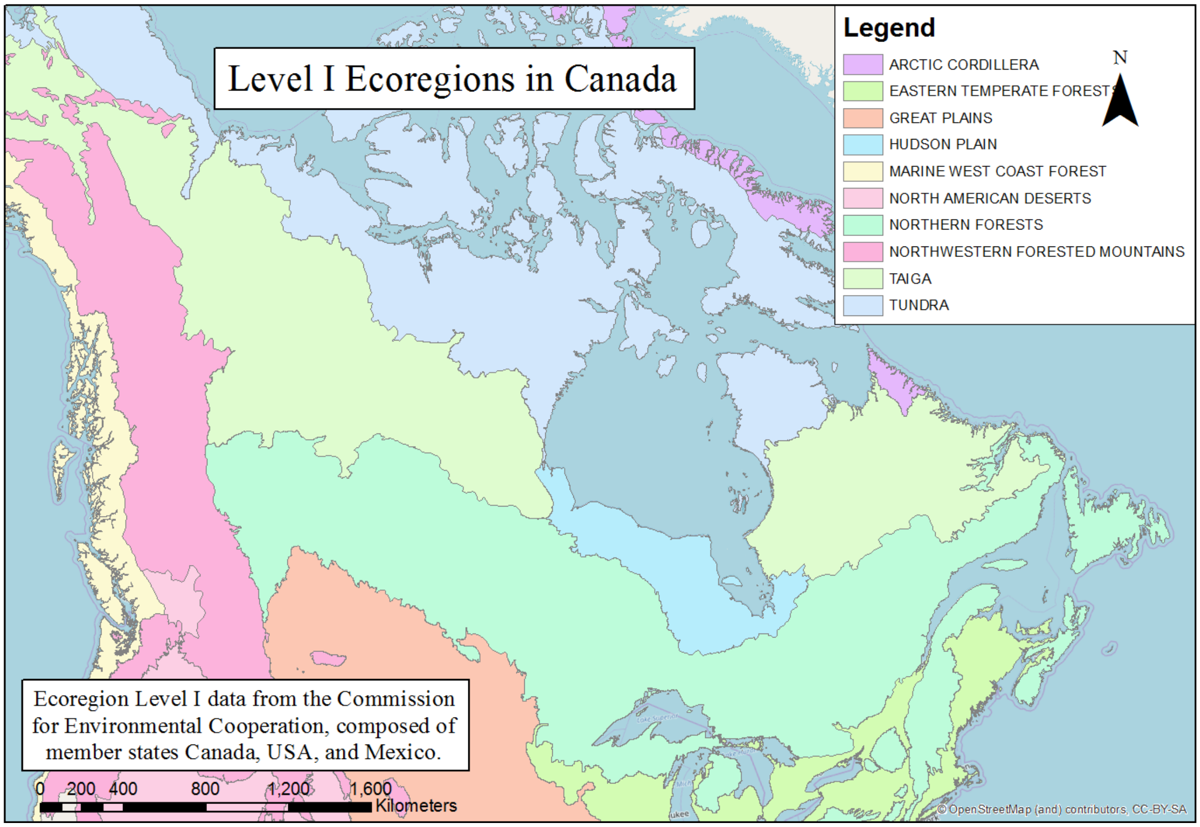
An initial selection of available watersheds was provided directly by ECCC and updated with newly delineated watersheds following a request for high priority gaps. Most stations were also available through the National Hydrometric Network (NHN) Basin Polygons, divided by major drainage area, available on the government of Canada's Open Government Portal (Environment and Climate Change Canada, 2017). A few in Quebec had not yet been included in this ongoing effort, so basin polygons were also downloaded from the Centre d'Expertise Hydriques de Québec, a division of the Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques (MDDELCC, 2017). The relevant watershed data from Quebec also needed to be extracted, formatted and merged to match the NHN basin file format. Watershed areas, along with basic streamgauge station information such as coordinates and length of record, were already available within the Water Survey of Canada's Hydrometric Database (HYDAT).

2.2.1.1.2 Ecoregions

Level I Ecoregions in Canada (Figure 2) were initially developed by the National Ecological Framework for Canada (Ecological Stratification Working Group, 1995) and have since been updated by the CEC (2009). While there are more granular Ecoregion divisions (Level II and Level III), the first level has 10 regions within Canada, sufficient division for our purposes.

2.2.1.1.3 Wetlands

Land Use (LU) data for the year 2010 from Agriculture and Agri-Food Canada (2015) and CanVec (Natural Resources Canada, 2016) were used to calculate the percent of each watershed which is wetland (refered to as percent wetland). LU data were only available south of 60 degrees North, so LU was only used for watersheds completely below 60 degrees; CanVec was used for the rest. LU and CanVec data also required merging as they were subdivided into longitude ranges for LU and by province/territory for CanVec.



Ecoregion Level I data from the Commission for Environmental Cooperation, composed of member states Canada, USA, and Mexico.

© OpenStreetMap (and) contributors, CC-BY-SA

Figure 2. Level I Ecoregions in Canada.

2.2.1.2 Breadth of Coverage Methods

2.2.1.2.1 GIS metrics

The composition of each available watershed area in terms of land use category, wetland area, and ecoregion membership was calculated using the "Tabulate Area" tool within ArcGIS and three GIS data sources (LU, CanVec, and Ecoregions). However, "Tabulate Area" will ignore the overlapped area between polygons as is also the case for an updated "Tabulate Area 2" (this one specifically says it accepts overlapped polygons but does not work as advertised). As a workaround, the large watershed shapefile was manually divided into groups that do not overlap. Tabulate Area was then run on these groups without incident. The output from Tabulate Area on each group was merged to create one summary text file with the percent of watershed belonging to each class (columns) for all stations (rows).

2.2.1.2.2 Cluster-aided Manual Selections within Ecoregions

National summaries of RHBN streamflow using the ratio of positive to negative trends are influenced by the distribution of the stations analyzed (Burn et al., 2012; Monk et al., 2011; Burn et al., 2010; Khaliq et al., 2008); in the past, that meant that the results skewed towards southern stations in the East and West (section 1.3). This thesis seeks to balance the stations in the final selected stations list, in both their number and total watershed area, with the distribution of ecoregions within Canada (see Table 1). However, there are simply not enough stations in the northern areas, or enough continuous stations in the Great Plains, to achieve this goal. To help balance the number of stations across ecoregions, a low and a high target number of stations was set by matching a reference number to the desired ecoregion percentages (Table 1). The 'low' target is based on the maximum number of candidates available in the most underrepresented ecoregion; the 'high' target is based on the number of current RHBN stations in the most overrepresented ecoregion. Candidate stations are divided into their respective ecoregions (threshold of >10% for the underrepresented and matched ecoregions, >50% for the overrepresented ecoregions, while allowing for multiple membership), and an additional list for those without GIS data.

Table 1. Level I Ecoregions within Canada by Percent Area

Ecoregions Level I	*Percent Area (Canada)*
ARCTIC CORDILLERA	9.2
TUNDRA	44.1
TAIGA	19.7
NORTHERN FORESTS (Boreal)	14.3
NORTHWESTERN FORESTED MTNS (Rockies)	6.3
GREAT PLAINS	2.3
HUDSON PLAINS	2.1
MARINE WEST COAST MTNS	1.1
EASTERN TEMPERATE FORESTS	0.8
NORTH AMERICAN DESERT	0.3

Starting from most overrepresented ecoregion to least, station selection is manual (i.e. user's judgement). Station selection in each ecoregion seeks a full range of basin sizes with a wide geographic range while choosing the station with the longest length of record available. To help in selection, stations in very large ecoregions may be clustered geographically using the R package *dbscan* (Hahsler et al., 2017). If more differentiation between stations is needed, then another basin characteristic may be used; in this case the distribution of percent wetland values within the ecoregion was taken and an attempt was made to match this distribution with the candidate stations for the renewed RHBN (Figure 3). Each group of stations was then viewed in ArcMap to ensure there was not excessive overlap (usually no more than one station nested inside another, and the nested basin should be no larger than 30% of the larger basin). The manual selection was repeated for each ecoregion. Finally, ArcMap is used to check for overlaps and to visually confirm the geographic distribution of the stations Canada-wide.

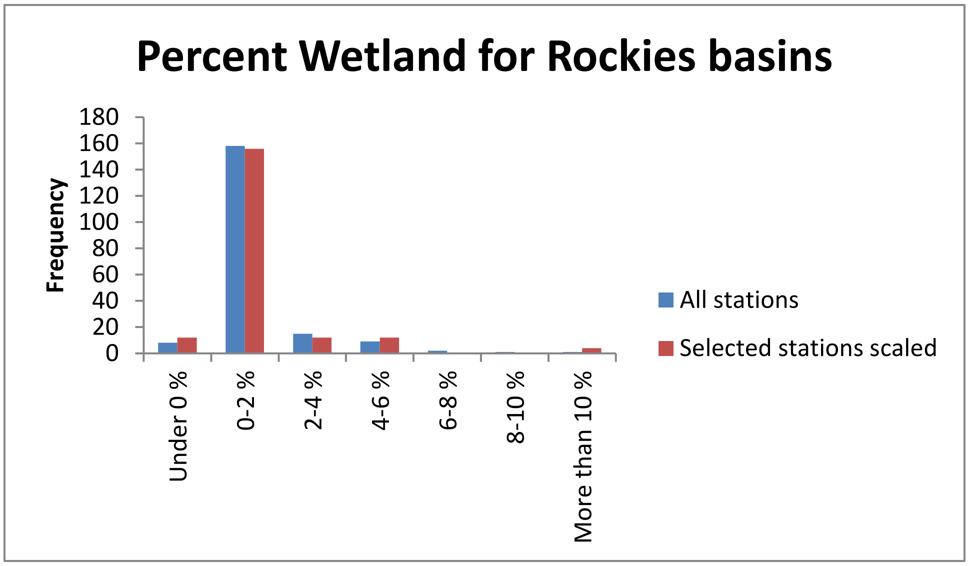


Figure 3. Example of matching the overall distribution of a basin characteristic (percent wetland) to the distribution of stations selected for RHBN status. The 'selected stations' bars have been scaled to the total number of stations within the ecoregion.

If there are noticeable gaps in a geographic area or ecoregion, then other criteria may be loosened to identify additional candidate stations in a second round of manual selection from the deficient areas. For example, the minimum record length criterion (section 2.2.3) may be reduced, or the ‘natural’ criteria may be substituted for ‘stable’ (section 2.2.2). Stations for which GIS data were not available due to a lack of digital watershed polygons were also checked for any that may be in underrepresented areas or have very long records.

2.2.2 Natural or Stable

To properly control for direct anthropogenic influence, the watershed upstream of a station must be minimally developed or in a stable state of development for the entire record. The original RHBN criterion of less than 10% impacted catchment surface may be sufficient, barring the development of a disturbance index similar to GAGES-II (Falcone et al., 2010). Stations should have no significant regulation, abstractions or discharges.

2.2.2.1 Natural or Stable Data

Land Use (LU) data for the year 2010 from Agriculture and Agri-Food Canada (2015) also includes categories for settlements, roads, and croplands which combined may be viewed as the land ‘impacted’ by humans.

The streamgauge database for Canada (HYDAT) contains daily flow and level data that may be analyzed for abrupt changes. There is also a Station Regulation table, which contains information on regulation.

2.2.2.2 Natural or Stable Methods

2.2.2.2.1 Impacted Area

The percentage of impacted area may be calculated for each watershed completely covered by LU data (below 60 degrees North); stations that are not covered may be visually checked via satellite images but are generally assumed to have minimal impacts. Stations with more than 10% impacted area, defined as settlements + roads + cropland, are removed from the first round of manual selections. If the percent impacted metric needs to be loosened for second round selections, a modified percent impacted metric may be calculated without cropland to identify the watersheds with minimal urban influence. This could be useful in areas with long agricultural histories as long as care is taken to avoid areas with significant irrigation and diversion as determined via satellite images (circular crop patterns are often indicators of commercial irrigation) or provincial water resource reports (e.g., AMEC, 2007 and Gaia, 2007).

2.2.2.2.2 Regulation

Stations that are designated ‘regulated’ within HYDAT are not considered for a renewed RHBN. However, ‘regulated’ stations that are included in the current RHBN are considered in the interest of continuity (section 2.2.5).

2.2.2.2.3 Abrupt Hydrometric Changes

Daily streamgauge flow data itself may give some indication of human impacts; for instance, a sudden increase in baseflows and decrease in high flows may indicate the installation of a dam and further investigation should be done. FlowScreen (Dierauer et al., 2017) is an R package that detects trends (via the MK test with TFPW) and changepoints, or abrupt changes to means (via the binary segmentation method; Killick and Eckley, 2014), in up to 30 flow metrics related to baseflows, low flows, and high flows. If there are several changepoints within a single year, this suggests there has been an abrupt change that may be associated with some drastic intervention in the watershed. Each candidate station was looped through a simple FlowScreen evaluation, saving a plot of the changepoints over time and reporting the maximum number of changepoints in a single year. An informal study of stations with known abrupt changes (forest fires (Shakesby and Doerr, 2006), pine beetle infestation and salvage logging (Dhar et al., 2016 and Zhang and Wei, 2014), dam construction and diversions (Dierauer et al., 2017)) found that roughly 5 changepoints in a single year could be an indication of important changes and warrant more attention. Candidate stations for a renewed RHBN that had 5 or more changepoints in a single year were investigated for possible sources of abrupt change by satellite image search, local history search, hydropower maps, and any other reported changes to water flow.

2.2.3 Record Length

There is a general consensus that 20 years of not necessarily sequential data is sufficient, provided that each year meets the data quality criteria (section 2.2.4). Continuous records are preferred over seasonal.

2.2.3.1 Record Length Data

HYDAT contains daily streamgauge flow and level data for all stations. HYDAT also contains three metadata tables that may contain information on each station needed to assess the quality record length: the Station Data Range, which contains the data type and a range of data years; the Station Data Collection, which contains the data type, a range of data years, along with the operation type (seasonal, continuous, or miscellaneous); the Station Operation Schedule, which contains the data type, each year of operation along with the earliest and latest recording month for that year (January to December for continuous stations, March to October standard for seasonal, all other schedules are deemed miscellaneous).

2.2.3.2 Record Length Methods

All HYDAT data manipulations were facilitated by R, an open-source code popularly used for statistical purposes (R Core Team, 2017) and the package *HYDAT* (Hutchinson, 2016). Michelle Fairbrother at Environment and Climate Change Canada developed the first draft of R code designed to acquire a list of available data and filter for HYDAT-related criteria (sections 2.2.2-2.2.5). The author improved upon this first draft and added data from other sources. The record length for each station can be assessed once the recording schedule and data quality is known (seasonal or continuous, and which years). The metadata table called Station Operation Schedule should contain all the information needed to evaluate the data quality criteria, however, it could not be used in full confidence due to missing and/or erroneous data.

There are three metadata tables containing overlapping information that can be compared against each other and the raw daily timeseries as a quality control; all data within the Operation Schedule should be found within and agree with the Data Collection table, and likewise from the Data Collection to the Data Range tables. A new Operation Schedule was constructed based on the widest information, the Data Range table, and the following steps:

1. Data Range data type was limited to flow or level data. Various sediment measurements are also available and were excluded.

2. Match the Data Collection range years to the Data Range years. A single station may switch operation type several times and could have several entries in Data Collection for only one entry in the Data Range.

3. Expand the matched and complete entries from step 2 into an operation schedule-type table with columns: station number, data type, year, month from and month to. The months are determined by the operation type; continuous is January to December and seasonal is March to October. Miscellaneous operation type is reserved for non-standard or point measurements; not useful for this study.

4. If a range of station years did not have an operation type, it would be assigned the most recent operation type for that station then expanded as in step 3.

5. If a range of station years still had no operation type, then the operation type would be assumed based on the daily data. The range of station years is then expanded as in step 3.

    a. If the difference between the latest median month and earliest median month for the recorded years was under 6, this range of station years was assumed to be miscellaneous as it could not pass the data quality criteria (section 2.2.4).

    b. If the median earliest month was under 3 and the median latest month was over 10 for the recorded years, this range of station years was assumed to be continuous operation.

    c. The remainder were assumed to be seasonal.

Once each year is evaluated for data quality (section 2.2.4), the number of qualifying years prior to a reference year is summed. The reference year for a renewed RHBN is determined by data availability (e.g., reporting lag for streamgauge data or measurement year for critical GIS data).

2.2.4 Data Quality

The quantitative evaluation of data quality is completed by calculating the percent missing data over the annual operation period; only the years with less than 5% missing daily data are summed to reach the 20 years of data for the preceding criterion. The qualitative evaluation of the accuracy of streamflow measurements is currently dependent on the knowledge of the regional Water Survey offices. Brimley et al. (1999) discuss a composite accuracy rating based on accuracy in ice or ice-free conditions that could be of use (although it is unclear if this has been implemented). This vetting of the renewed RHBN by the local offices is a necessary and valuable follow-up that will be revisited in section 6.1.1.1.

2.2.4.1 Data Quality Data

HYDAT contains daily streamgauge flow and level data for all stations. The constructed Operation Schedule from the previous step determines the annual maximum number of data points.

2.2.4.2 Data Quality Methods

The reconstructed operation schedule (section 2.2.3) may be used to calculate percent missing daily data for flow or level stations in a calendar year with a maximum of either 365 or 366 days (for continuous) or 245 days (for seasonal). Station years with more than 5% of data points missing do not count towards the 20 years used for the Length of Record criterion. Measurement flags such as estimated values, backwater ice, partial days, or dry stream are also reported for each station and year. While the annual percent missing used calendar years in this thesis, the R code is capable of using water year variables with user-defined wateryear dates for flow or level continuous stations; calendar year was used in this analysis to include the seasonal stations. When a station has both flow and level data of sufficient quality and length, the flow data are preferred.

2.2.5 Longevity

Since there are a multitude of factors affecting flow in any given watershed, switching monitoring between ‘similar’ watersheds is not advisable. Thus, continuity of streamgauge location, and of that watershed’s qualifying properties (particularly the natural or stable criterion), is desired.

2.2.5.1 Longevity Data

HYDAT contains a metadata table called Stations that contains general descriptive information along with the recording status (either active or discontinued).

2.2.5.2 Longevity Methods

Candidate stations for a renewed RHBN must be actively recording and be scheduled to remain active for the foreseeable future. In the interest of continuity of the network, any current RHBN stations are favoured for inclusion as long as there is no valid reason for its exclusion. Other than active or current RHBN stations, this criterion would be used mostly to define the 'best' station within a subset of stations with similar features that are in close proximity. This criterion is meant for parsing decisions, likely only necessary in the denser network of the south and east. For example, a station that is easily accessible is less likely to be cut in the event of budget restrictions, or a watershed within a national or provincial park is more likely to remain undeveloped or minimally developed.

2.3 Evaluation Order

The order of evaluation does not follow the criteria; it is more practical to assess objective criteria with clear membership rules (e.g., stations with more than 20 years of data, section 2.2.3) before analyzing the more subjective criteria (e.g., stations that represent a region adequately, section 2.2.1). The first stage of evaluation involved all the HYDAT-sourced data and R-based methods as these could be largely automated. This reduced the number of candidate stations that would need to be evaluated with the computationally heavy GIS-based methods in the second stage. In the third stage, the more subjective final selections described in the Breadth of Coverage criterion (section 2.2.1) could occur. There is potentially a fourth stage (not undertaken as part of this thesis) that involves institutional confirmation, promotion, and plans for regular renewal; these recommendations are covered in chapter 6.

Chapter 3 RHBN Renewal Results

3.1 Introduction

The criteria described in chapter 2 sought to improve the RHBN's coverage of non-atmospheric factors affecting streamflow while continuing to avoid anthropogenic influences by conducting R code and GIS-based assessments of watershed areas monitored by WSC streamflow stations. Additional screening was conducted by reviewing satellite images, local irrigation and watershed reports, and historical searches where necessary. Some data errors within HYDAT required changes to the methods laid out in the previous chapter. Presented below is the renewed RHBN station list with some caveats, interesting features, and decision justifications. The renewed RHBN is compared to the current RHBN in terms of ecoregion and geographic coverage as well as the distribution of watershed sizes.

3.2 Changes to Methods – Unreliable HYDAT metadata

The initial renewal attempt used a single HYDAT metadata table (the Operation Schedule) to filter for stations meeting the length of record criteria (20 years) and found 277 RHBN-quality stations after manual selections: 240 continuous flow, 36 seasonal flow, and 1 continuous level. However, some stations that seemed to meet the length of record requirement had not made it to the manual selection rounds. Upon further investigation, it was found that the Operation Schedule metadata table within HYDAT contains some errors relative to the Data Collection and Data Range tables; the months within were incorrect for some stations (see station 05LA003 example in Table 2) or there were missing years (see station 03FA003 example in Table 2). Based on the Operation Schedule table, station 05LA003 did not meet the length of record criteria and station 03FA003 was missing ~13 years of data. Some stations were entirely missing from one or more of the three tables, but these stations were very recently established (post-2010). The Data Collection table consistently reports a later end-year than the Data Range table (Table 2). This is essentially a reporting lag; where Data Collection shows the most recently collected data, Data Range shows the most recent data available through HYDAT.

Table 2. Examples of inconsistencies and errors between HYDAT metadata tables (Operation Schedule, Data Collection, and Data Range) for two stations.

Station # 05LA003	**Years**	**Months**	**Corrections (*)**
Operation Schedule	1967-1987	-blank-	
	1990-1992	MAR-OCT	
	1993-2016	*JAN-DEC	MAR-OCT
Data Collection	1967-2017	MAR-OCT	
Data Range	1967-2016 (50 yrs)	-NA-	

Station # 03FA003	**Years**	**Months**	**Corrections (*)**
Operation Schedule	*1974-1997	-blank-	1974-2013
Data Collection	1974-2017	JAN-DEC	
Data Range	1974-2013 (38 yrs)	-NA-	

To evaluate the length of record criteria, the information required is the data type (level or flow), the years recorded, and the range of months for those years (March to October for seasonal stations, January to December for continuous).There are three metadata tables that contain some or all the pertinent information: Operation Schedule (station number, data type, year, month from, and month to), Data Collection (station number, data type, year from, year to, operation: seasonal, continuous, or miscellaneous), and Data Range (station number, data type, year from, year to, record length). By checking for inconsistencies between the tables and cross-referencing these with the daily data record through R comparison functions, the Data Range table was found to be the most reliable. As noted above, this table does not contain the information in the format required for the length of record evaluation, so a revised Operation Schedule was constructed as described in methods section 2.2.3.2. The altered Operation Schedule table found 81 additional candidate stations after HYDAT-based criteria had been evaluated; it did not overlook any existing candidate stations. These 81 additional candidate stations were evaluated the same way as set out in section 2.2.1.2.2, but only as second round evaluations to fill gaps in already selected stations; no attempt was made to replace stations. Only two seasonal stations were ultimately added to the renewed RHBN (05HH003 and 05LA003 – the station in Table 2), bringing the total to 279 stations. A full description of the renewed RHBN is given in the next section.

3.3 New RHBN list

The final 279 stations in a renewed RHBN are displayed in Figure 4 with their watersheds, and in Figure 5 underlain by Level I Ecoregions. Select details for the stations may be found in Appendix A.
A comparison between the current and renewed RHBN follows in section 3.4.

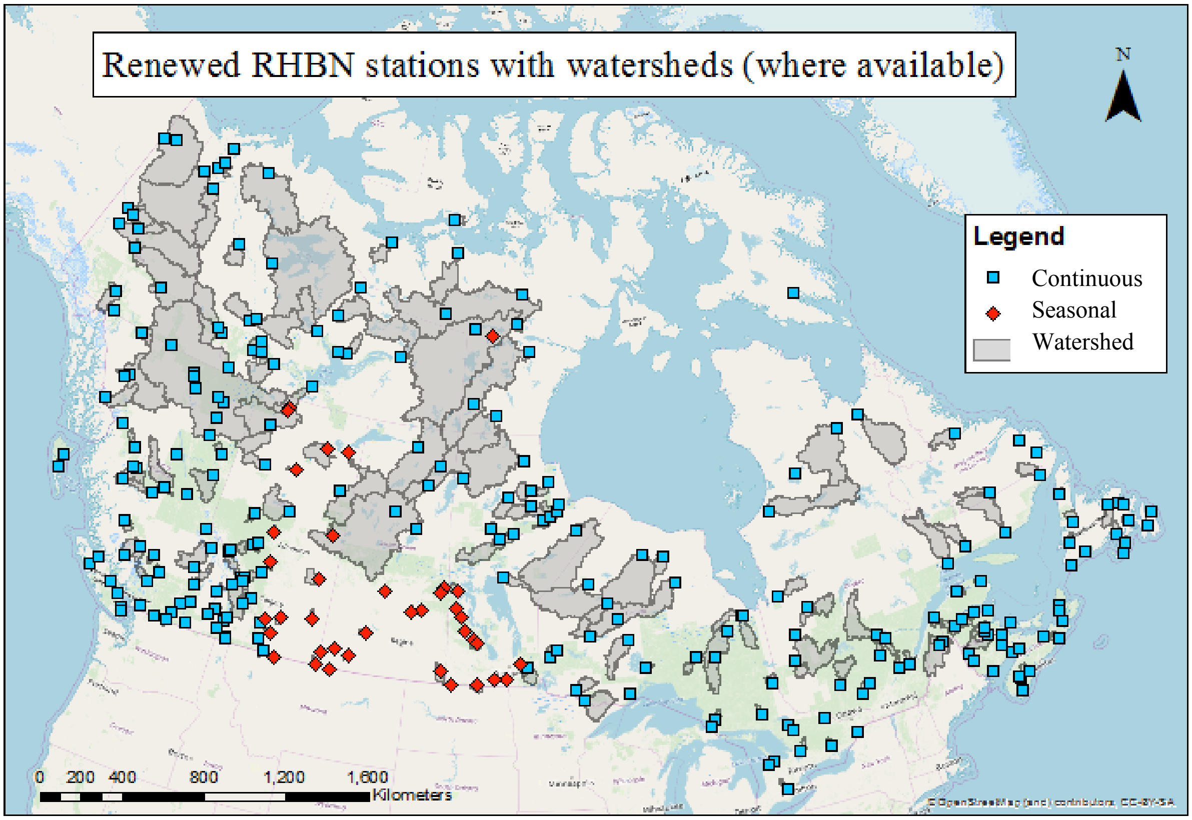


Figure 4. Renewed RHBN stations and watersheds, where available. Continuous in blue squares, seasonal in red diamonds.

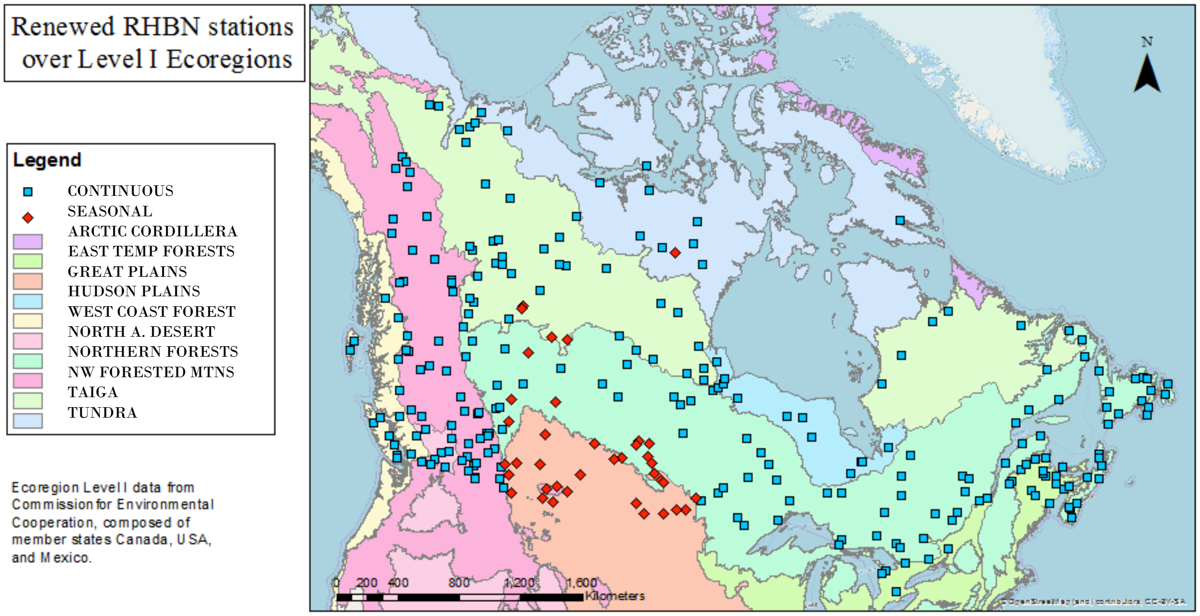


Figure 5. Renewed RHBN stations underlain by Level I Ecoregions.

Appendix A also contains four new suggested data columns for the Stations table in HYDAT: Notes, RHBN_start, RHBN_end, and Rationale. "Notes" would include any reasons the data should be used with caution, like "significant multiyear storage effects", "winter flow measurements suspect" or other data quality descriptors pertinent to trend detection. "RHBN_start" and "RHBN_end" are data limits to be used if the recommended length of record fit for use in trend studies is different from the full length of record for that station (examples in section 3.3.1). For "RHBN_end", it is important to note stations that had once been RHBN status but have since been removed because they no longer meet some criteria. These can still be useful in studies comparing a previous to a modern time period. "Rationale" would detail the reasons for an RHBN start or end date that is different from the full length of record. This column would need to be quite large to include some perhaps detailed explanations.

3.3.1 Recommended data limits

RHBN watersheds are not always pristine and in such cases an attempt is made to ensure that any human impacts that do occur are small. Some human impacts, such as dam construction, cause abrupt changes to the character of streamflow and these should be avoided when evaluating for climatic changes. Recommended data limits were established for five stations; one associated with regulation (dam) and four found through investigations of abrupt hydrometric changes flagged by FlowScreen (methods section 2.2.2.2.3). FlowScreen evaluations also identified a few stations that were later fully excluded from selection after significant land use or regulation was found. Below are some details for the five data limit cases.

3.3.1.1 Bear Creek near Piapot, SK (05HA003)

Bear Creek has been regulated since 1963 according to HYDAT, but an effort should be made to include this station for continuity as it is a member of the current RHBN. Only using data post-regulation (i.e. 1963-present) is recommended. More details on Bear Creek are given in section 3.3.3.4.

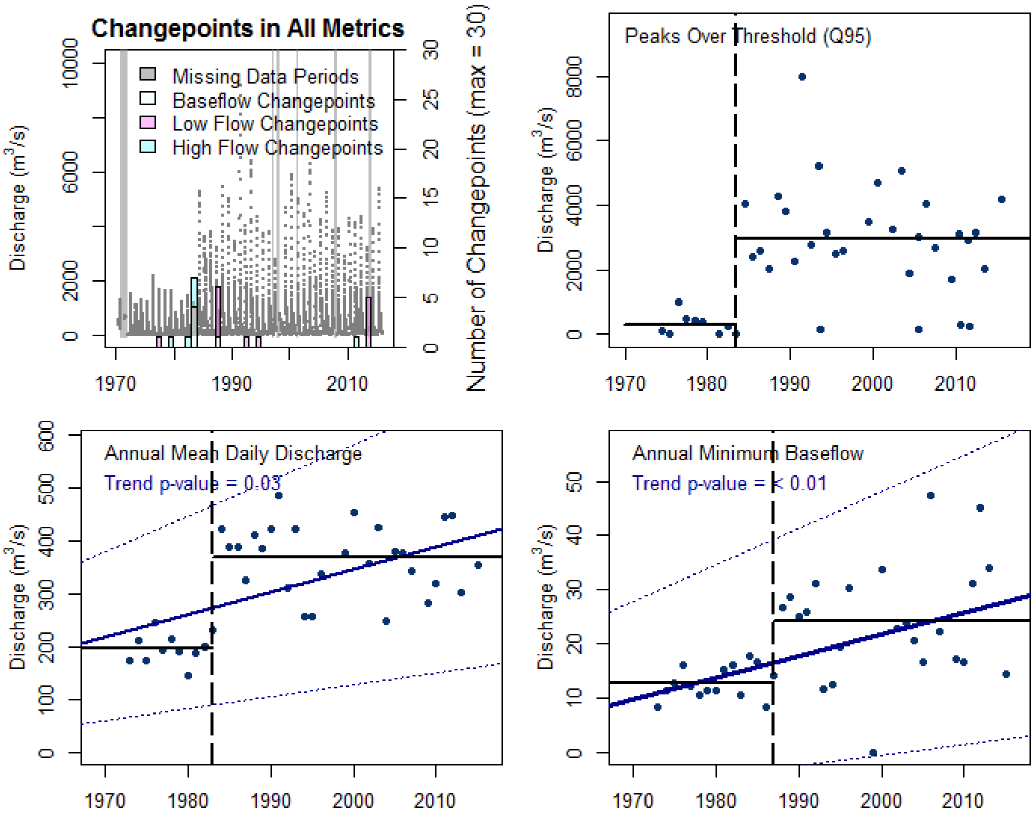


Figure 6. Select FlowScreen results for 06JC002 (Thelon River, NU): top-left is a summary figure showing the daily flows for the entire length of record with the number of abrupt changes; the other three figures are the annual values (shown by points), changes in means (black dashed and solid lines), and trends (blue lines) for the identified streamflow metric.

3.3.1.2 Thelon River above Beverly Lake, NU (06JC002)

The Thelon River was flagged by FlowScreen evaluations for 7 changepoints in 1984. The HYDAT Remarks table notes that high flows were all estimated before this year and should be used with discretion; the top-left of Figure 6 shows that high flows are drastically lower prior to 1984. According to the FlowScreen evaluations, there were also low flow and baseflow changes around this time (Figure 6). Excluding data prior to 1984 is recommended.

3.3.1.3 Turtle River near Mine Centre, ON (05PB014)

Turtle River was flagged by FlowScreen evaluations for 8 changepoints in 1926 and another 7 in 1941. As seen in Figure 7, the magnitudes of changes are significant. Examinations of satellite images could not rule out or confirm human impacts and this watershed does show multiyear storage. However, in an abundance of caution, excluding data prior to 1941 is recommended.

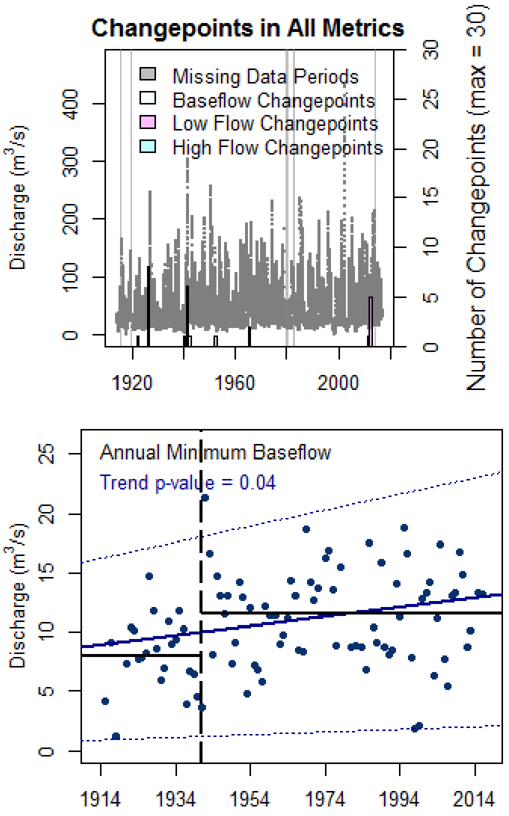


Figure 7. Select FlowScreen results for 05PB014 (Turtle River, ON): top-left is a summary figure showing the daily flows for the entire length of record with the number of abrupt changes; the other three figures are the annual values (shown by points), changes in means (black dashed and solid lines), and trends (blue lines) for the identified streamflow metric.

3.3.1.4 Sydenham River near Owen Sound, ON (02FB007)

Sydenham River was flagged by FlowScreen evaluations for 6 changepoints around 1967. As seen in Figure 8, there were some increases in low flows and baseflows that seem to indicate dam operation for management of low flows. Although there are a few recreation dams in the watershed, their dates of construction and information on their management plans could not be found within public sources. Only using data past 1967 is recommended.

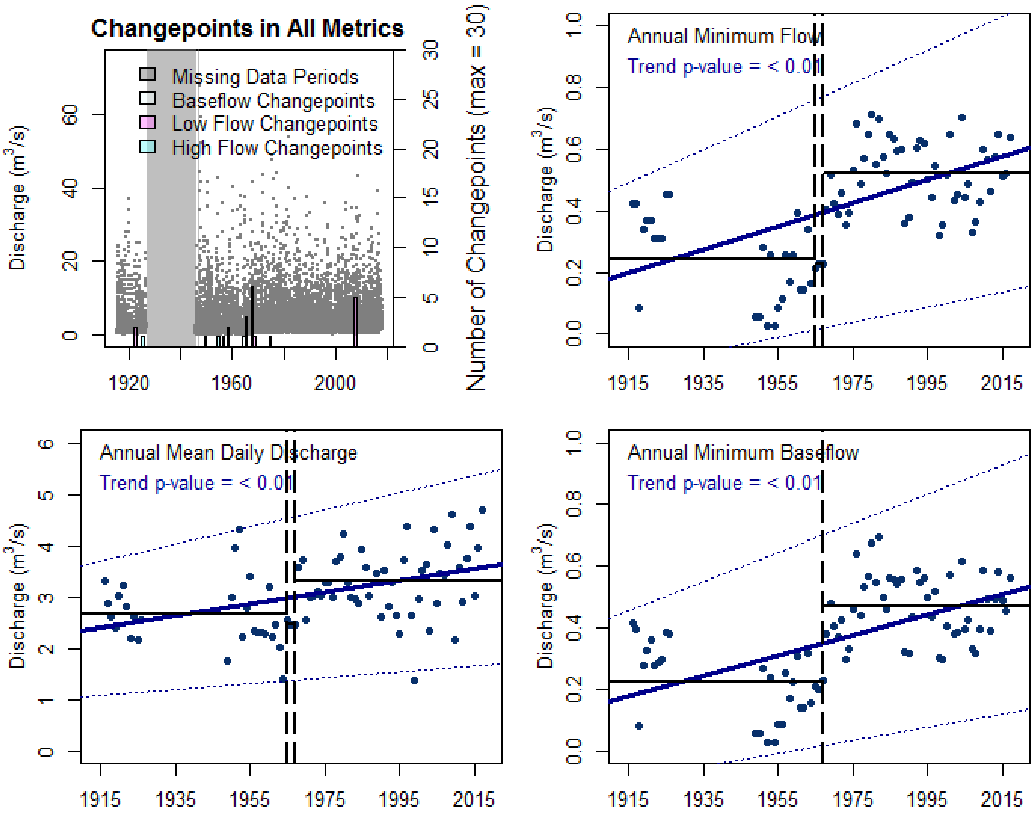


Figure 8. Select FlowScreen results for 02FB007 (Sydenham River, ON): top-left is a summary figure showing the daily flows for the entire length of record with the number of abrupt changes; the other three figures are the annual values (shown by points), changes in means (black dashed and solid lines), and trends (blue lines) for the identified streamflow metric.

3.3.1.5 Adams River near Squilax, BC (08LD001)

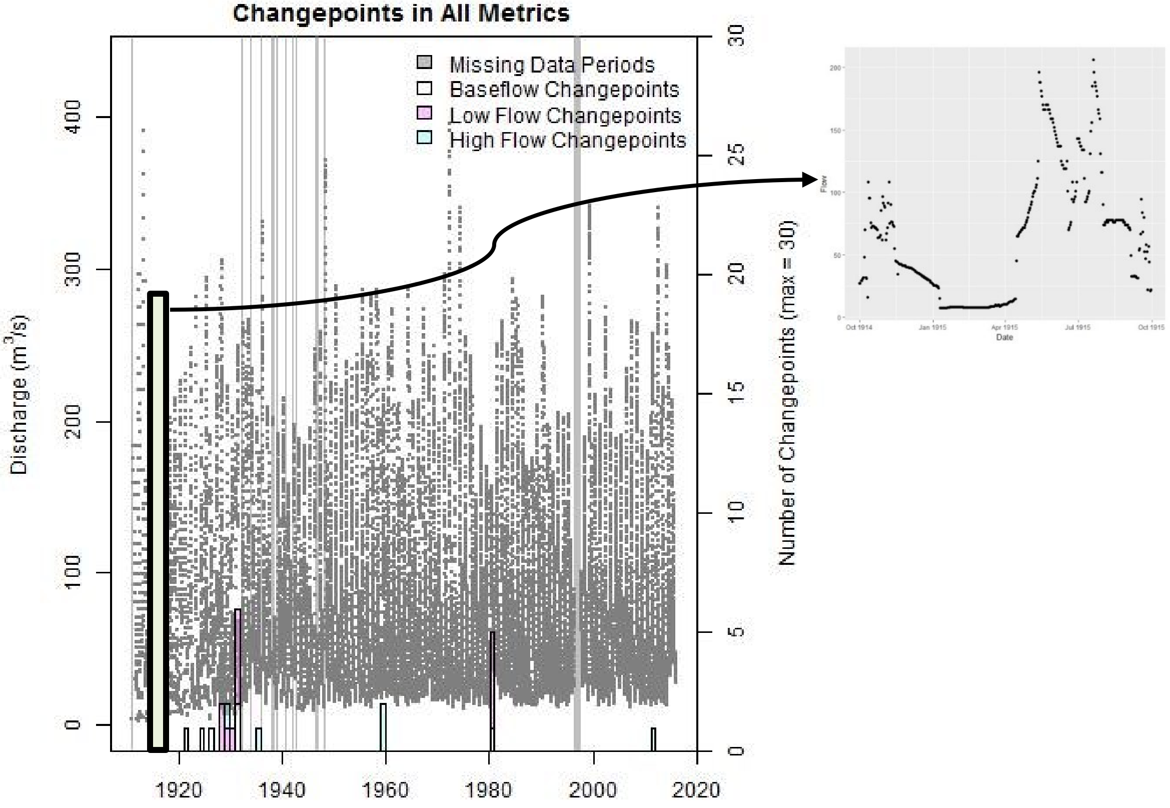


Figure 9. Daily discharge over time overlain by FlowScreen changepoints for the Adams River station (08LD001). Insert shows the discharge for the year 1915, at the height of splash dam use.

The Adams River was flagged by FlowScreen evaluations for 6 changepoints occurring in 1931. In Figure 9, the data prior to 1931 is particularly choppy and it's tempting to put that down to severe recording issues, but no recording changes are shown in HYDAT. Nothing is apparent from satellite images and there is no current regulation on this river. However, an internet search for the history of the area yielded a particularly useful virtual museum (Chase and District Museum and Archives Society) that detailed the historical logging activities of the Adams River Lumber Company, one of the largest in British Columbia at the time. If the name of this logging company did not coincide with the name of the river, it is doubtful that anything would have been found. The Adams River Lumber Company operated in this watershed from 1909 until the sawmill closure in 1925. In this era, the most common way to transport logs used waterways and two particular logging activities could have had a significant effect on streamflows; flumes and a “splash dam” (see Figure 10). Flumes diverted water along raised structures to transport logs from higher elevations (potentially in other watersheds) to Adams Lake, above the stream gauge site. A "splash dam" is a dam structure that is periodically opened to flood downstream while transporting the logs that had collected above it. Clearly, these would have significant effects on the streamgauge trends. While the Adams River Lumber Company ceased operations in 1925, it appears the logging works were abandoned or sparsely used by smaller logging companies for a time after. Based on the FlowScreen results, it would be reasonable to assume 1931 represents the final degradation of the logging works and it is recommended to exclude data prior to this year in natural trend analyses.

Figure 10. Left: Brennan Creek Flume; Right: Lower Adams River splash dam (Chase and District Museum and Archives Society, credit for left image to Walter F. Montgomery).

3.3.2 Stations with significant multiyear storage effects

Another interesting basin feature highlighted by the FlowScreen changepoints was multiyear storage effects (see Figure 11). While these stations could still be useful if storage changes are of interest, they should not be evaluated in the same way as those that do not have such large carryover from previous years. A tentative technical definition for a “Storage Effect” station is presented in the Trend Methods (chapter 4) and is subsequently used for evaluating trends.

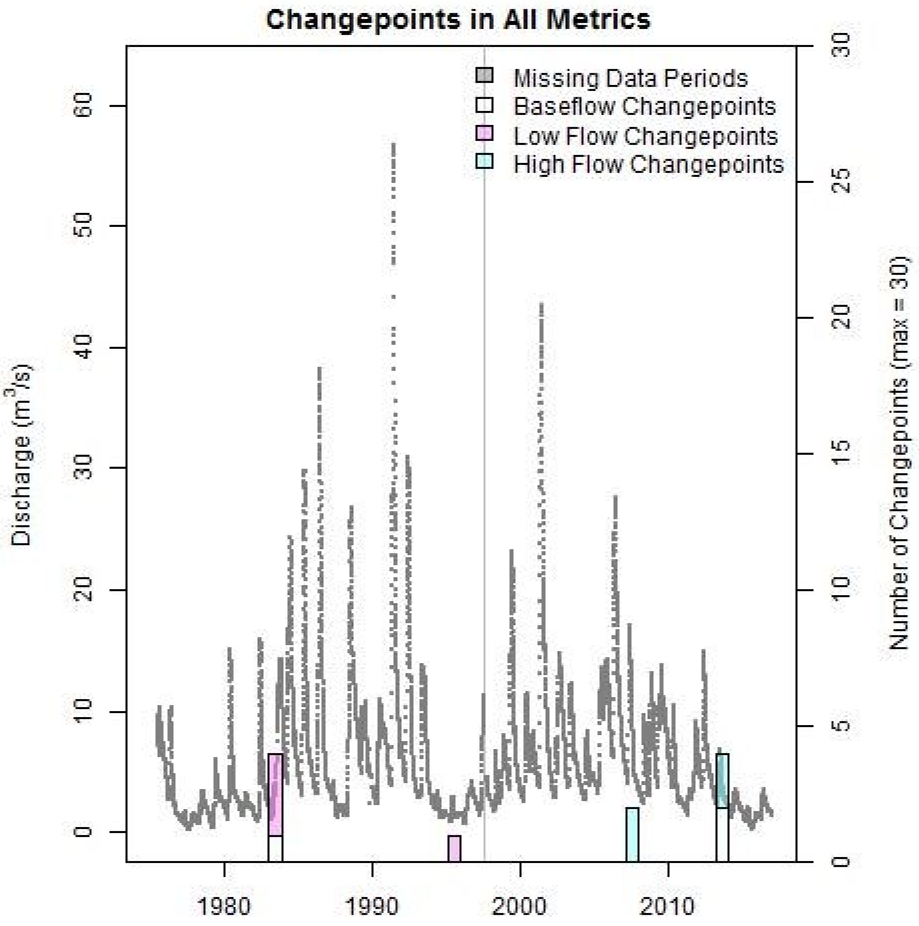


Figure 11. Example of multiyear storage effects from station 07SB010, Cameron River below Reid Lake, NT.

3.3.3 Rationale for including some regulated stations from the current RHBN

While regulated stations are not considered for new additions to the RHBN, there are regulated stations within the current RHBN. In the interest of continuity, these were considered for inclusion in the renewed RHBN on an "opt-in" basis rather than using the "rule-out" tests used for most of the RHBN renewal methods. Four regulated stations had some important qualities (Table 3): Three had very long records where the regulation started prior to the start of streamgauge operation, as well as one station (05HA003) in the underrepresented Great Plains that could be used with data limits. These four have been identified in the "Notes" column of the full list in Appendix A and are included in the renewed RHBN on a provisional basis, pending an investigation into their regulation impacts. More details for each are included below.

Table 3. Station regulation information according to HYDAT tables and recommended data limits.

Station Number	Regulated Since	Recorded Years	Recommended data limits
02FC001	1900	1914-present	
02KB001	1900	1915-present	
05LJ019	1900	1954-present	
05HA003	1963	1908-present	1963-present

3.3.3.1 Saugeen River near Port Elgin, ON (02FC001)

The Saugeen River is an important station due to a very long record and a relatively rare underdeveloped watershed (mostly agricultural) in highly populated Southern Ontario. It also contains several protected areas, notably wetland areas (i.e. Greenrock Swamp, Beaverdale Bog, Osprey Wetlands, Glammis Bog). Station 02FC001 has many dams (based on satellite images, there are at least 13 small dams and one large dam). Most appear to be intended for early 20th century local mills with the exception of one dam large enough to be associated with a 0.6 MW hydroelectric power plant. As fishing is a popular recreation on this river, there is ongoing pressure to remove dams to facilitate fish migration. There is little information on the timeline of these potential regulation changes. A study of the impacts and timeline of regulation on the Saugeen is recommended.

3.3.3.2 Petawawa River near Petawawa, ON (02KB001)

The Petawawa River station also has a very long record and most of its watershed is within the protection of Algonquin Provincial Park. This station is not associated with any modern dams, although there may be several logging dams from historical forestry within Algonquin Park. There is a proposed set of run-of-the-river dams on the Petawawa to supply a 5.3 MW powerplant from Xeneca Power Development, but no construction so far. If construction of the new dams goes ahead, the construction period and any effects to the streamgauge (including moving the gauge) should be noted.

3.3.3.3 Mink Creek near Ethelbert, MB (05LJ019)

Mink Creek is a long record at the edge of the Great Plains and Boreal ecoregions. There are no hydroelectric dams in the watershed and no dams could be located via satellite images. The dam (or dams) associated with the HYDAT-indicated regulation flag are likely related to logging and agriculture. The town of Ethelbert was only incorporated in 1950, which indicates that settlement of the area began around this time, not long before the start of record for this station. Investigating possible effects associated with land clearing for agriculture is recommended, along with any dam effects.

3.3.3.4 Bear Creek near Piapot, SK (05HA003)

Bear Creek is a very long record in the sparsely gauged Southern Saskatchewan region (within the Great Plains ecoregion). There are no hydroelectric dams in the watershed and no dams could be located via satellite images. The headwaters of this watershed are located in the Cypress Hills (a rare mountainous outcrop within the Great Plains) and drain into the saline Crane Lake. Runoff from this area only rarely, if ever, reaches the larger South Saskatchewan River; this watershed provides useful information on the non-contributing areas of the Great Plains. Although the 1963 regulation referenced in HYDAT could not be found, it is recommended that data from this station used in natural trend studies be limited to after 1963, pending study on any dam or other regulation effects.

3.3.4 Rationale for excluding stations from current RHBN

Since the continuity of RHBN stations is very important, a review of current RHBN stations excluded from the renewed version was undertaken to make sure there were strong arguments for each exclusion. Forty stations were excluded from the current RHBN (Figure 12); details can be found in Appendix B. In summary, the reasons for exclusion are as follows: 10 were discontinued, 1 did not meet the minimum length of record, 4 did not meet the minimum length of record if years with over 5% missing data were excluded (these stations did not have consistent recording), 9 were regulated and did not have the acceptable redeeming features of those in section 3.3.3, 13 had over 10% impacted area (i.e. were deemed not natural), 2 had suspected direct human impacts (one is part of the irrigation management strategy of Kelowna, BC; the other is near historical and continued placer gold extraction in Atlin, BC), and finally one station is a nested watershed between two better stations with longer record lengths and continuous rather than seasonal recording.

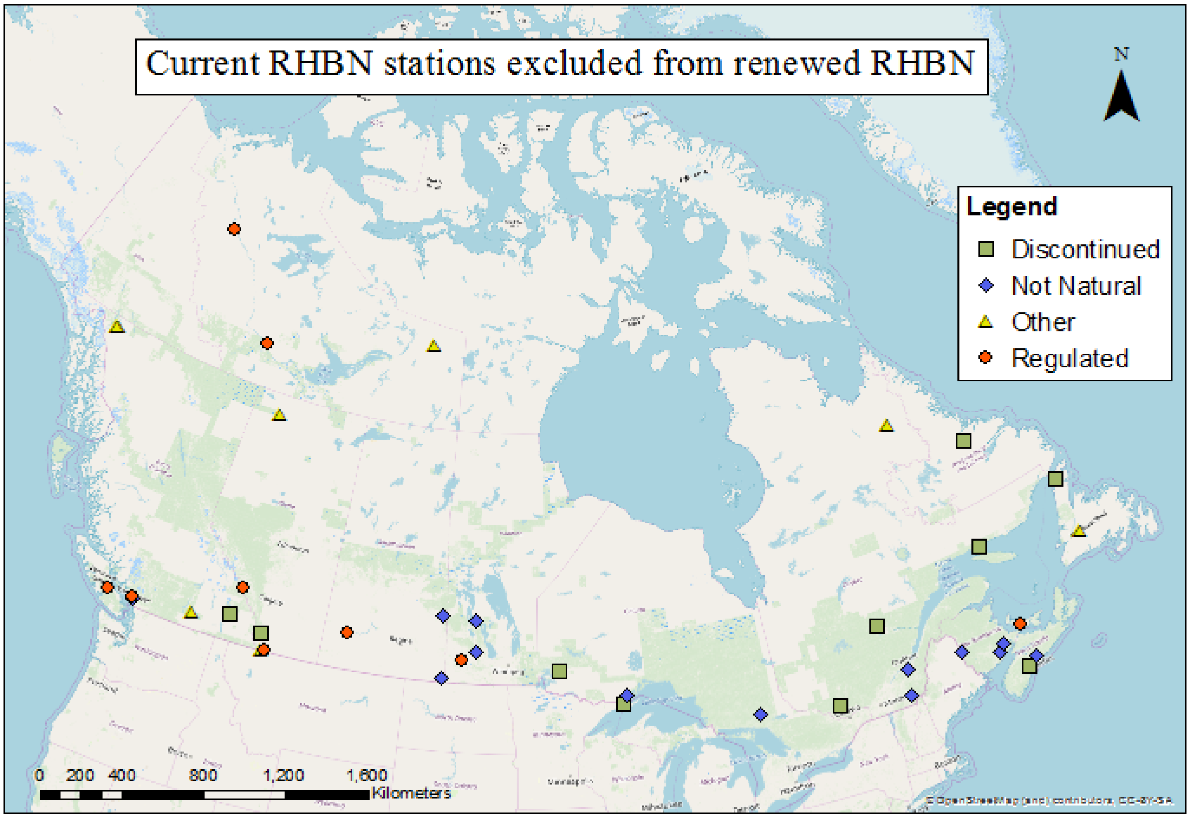


Figure 12. Current RHBN stations excluded from renewed RHBN with broad justification groups for exclusion.

3.4 Comparison of current and renewed RHBN

A comparison between current and renewed RHBN is evaluated here mostly in terms of the Breadth of Coverage criterion. The renewed RHBN inevitably retains some of the weaknesses of the current RHBN in that the Great Plains are mostly represented by seasonal stations, there are more stations in the southern part of the country, and the largest watersheds are all in the northern part of the country (Figures 4 and 5). However, these are symptoms of the existing streamgauge network. Below are some tables and figures illustrating major differences between the current and renewed RHBN in terms of ecoregion and geographic coverage.

3.4.1 Ecoregion Coverage

Ideally, the stations in the final selected stations list would balance, in both their number and total watershed area, with the distribution of ecoregions within Canada (see Table 4, column A) to limit the southern skew in national trend aggregations (section 2.2.1.2.2). According to the data in Table 4 (refer to Figure 2 for ecoregion extents), there were several ecoregions that did not have enough candidate stations and would act as limiting factors on the balance goal stated in section 2.2.1. One way to address this is to take the ecoregion with the greatest disparity between its coverage of Canada (column A in Table 4) and its number of potential stations (column B in Table 4) and set this number of stations to the percentage to develop a target for the number of stations in other ecoregions. The Arctic Cordillera has zero stations and setting the 13 potential Tundra stations to 44% of the network would limit the RHBN to a maximum of 30 stations. The next least represented ecoregion is the Taiga, which would yield the targets given in Table 4 column D.

Table 4. Percentage area of each Ecoregion with the available stations that have more than 10% of their area in each Ecoregion.

Ecoregions	**A: Percent of Canada covered by ecoregion**	**B: Number and percentage of candidate stations***	**C: Over (+) or Under (-) represented (B – A)**	**D: low target**	**E: high target**
Arctic Cordillera	9.30%	0 0%	NA	NA	NA
Tundra	44.00%	13 1.9%	-41.20%	13	More
Taiga	19.60%	75 10.1%	-9.60%	75	More
Hudson Plains	2.10%	12 1.7%	-0.40%	9	16
Northern Forests (Boreal)	14.20%	271 39.3%	25.10%	55	109
NW Forested Mtns (Rockies)	6.30%	218 31.6%	25.30%	25	49
West Coast Forest	1.10%	47 6.8%	5.70%	5	9
East Temperate Forests	0.80%	30 4.3%	3.50%	4	7
Great Plains	2.30%	4 0.6%	-1.70%	9	18
Deserts	0.30%	30 4.3%	4.00%	2	3

***Note: Table is based on the 690 stations that met the HYDAT-based criteria. Some may be counted more than once due to the small threshold (10% area within an ecoregion); some are not counted at all as they did not have a watershed polygon.**

Unfortunately, there were so many current RHBN stations within the Rockies that the minimum number of stations that met the other criteria was 49. So this was used to set a "high target" in a similar manner to the Taiga-based "low target" (Table 4, column E).

Table 5. Number of stations per ecoregion targets and final numbers.

		Number of stations*		Average Drainage Area (km^2)		Length of Record (years)	
Ecoregions	**Target numbers**	**Current RHBN**	**Renewed RHBN**	**Current RHBN**	**Renewed RHBN**	**Current RHBN**	**Renewed RHBN**
Tundra	13+	5 (9)	7 (14)	23068	19378	44	42
Taiga	75+	32 (37)	51 (70)	80278	23676	46	43
Hudson Plains	9-16	1 (4)	4 (12)	4250	4152	48	42
Northern Forests (Boreal)	55-109	87 (91)	108 (114)	6416	7302	60	56
NW Forested Mtns (Rockies)	25-49	51 (53)	56 (67)	3394	11205	62	60
West Coast Mtns	5-9	12 (14)	13 (16)	392	922	63	55
East Temperate Forests	4-7	22 (25)	17 (20)	921	1032	66	67
Great Plains	9-18	14 (17)	19 (23)	929	803	59	60
Deserts	2-3	3 (5)	4 (5)	145	224	58	48

***Note: Number of stations is based on over 50% drainage area within the ecoregion; number in brackets is over 10% drainage area within the ecoregion. Drainage Area and Length of Record averages were calculated with the >50% station lists**.

The rough targets in Table 4 guided the number of stations ultimately selected for a renewed RHBN. The number of stations, average drainage area, and average length of record for the renewed and current RHBN in each ecoregion are given in Table 5. There is some overlap between ecoregions; the total for the renewed RHBN without overlap is 279 stations, the total for the current RHBN without overlap is 227. The renewed RHBN generally matches the target number of stations better than the current RHBN (Table 5). The East Temperate Forest ecoregion already had far more RHBN stations than its targets, so RHBN criteria were rigidly applied and identified a smaller number of ideal stations for the renewed RHBN. There are more stations in the West Coast Mtns, Great Plains and Desert ecoregions than the targets as well, but these stations generally have smaller drainage areas and so more are needed to cover the region (Table 5). The Rockies and Boreal ecoregions also have more stations than their targets, but these include stations that cross into the underrepresented Hudson Plains and Taiga ecoregions; some stations were included as they were partial members of the underrepresented ecoregions (see bracketed values in Table 5).

There is generally a small reduction in the average length of record per ecoregion between the current and renewed RHBN due to the addition of lower record length stations. The exception is in the Desert ecoregion; however, there are so few stations in that category that the additional station in the renewed RHBN could have pulled the length of record down. Overall, the average length of record for the current RHBN is 58.5 years, for the renewed RHBN it is 54.5 years (Figures 14 and 15 in the next section give more detail).

The range of drainage areas shrinks between the current and renewed RHBN, with significant reductions in Tundra and Taiga and increases in Deserts, West Coast Mtns, and Rockies. Figure 13 shows the changes in drainage area distributions for four ecoregions; the other ecoregions showed no significant changes. The distribution of Tundra stations becomes more concentrated in the renewed RHBN, but there are very few stations in this category (Table 5). The renewed RHBN distributions of Taiga, West Coast Mtns, and Rockies are all flatter and extend over more of the central range of drainage areas (Figure 13).

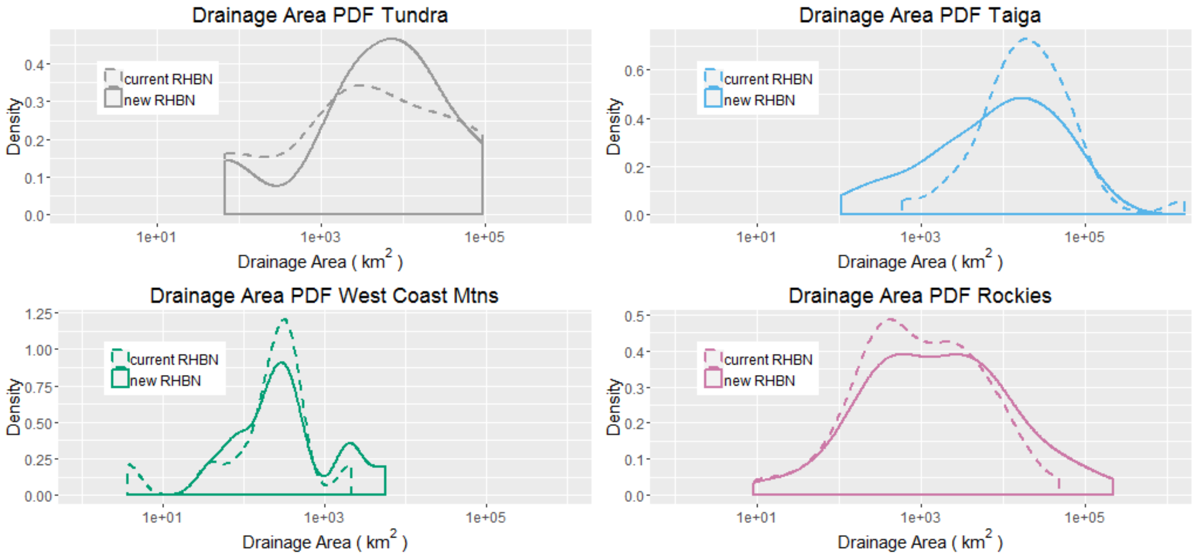


Figure 13. Drainage area density distributions for the current and renewed RHBN for the Tundra, Taiga, West Coast Mtns, and Rockies ecoregions.

3.4.2 Geographic Coverage

A comparison of the geographic distribution of stations in the renewed and current RHBN can be seen in Figure 14. The columns in this figure compare record length as a function of drainage area and latitude/longitude for the renewed (top row) and current (bottom row) RHBN stations while Figure 15 provides a similar comparison for operating schedule as a function of record length and drainage area. In the first column of Figure 14, drainage area does seem to increase with latitude, but the renewed RHBN shows more small drainage basins at high latitude. Shown by the colours of the data points, the largest lengths of record continue to be in the south, however that is due to the available data, not the selection process. In the second column, the key improvement between the two is the infilling of large and medium sized watersheds in Ontario and Quebec around Hudson's Bay (longitude -100 to -75). Figure 15 shows roughly similar distributions in terms of record length and drainage area. However, the renewed RHBN has removed the very small and very large watersheds from the current RHBN, creating a wider peak and more compact overall distribution of basin sizes (right image in Figure 15).

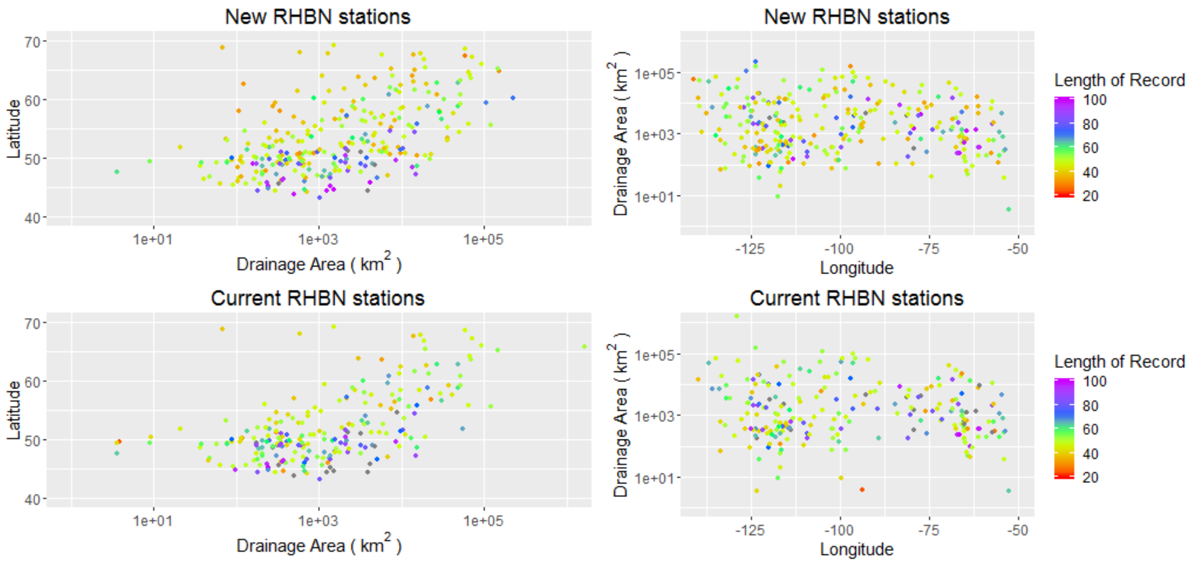


Figure 14. Distribution of drainage area across latitude and longitude for the new RHBN, top row, compared to the current RHBN, bottom row. Colour denotes length of record.

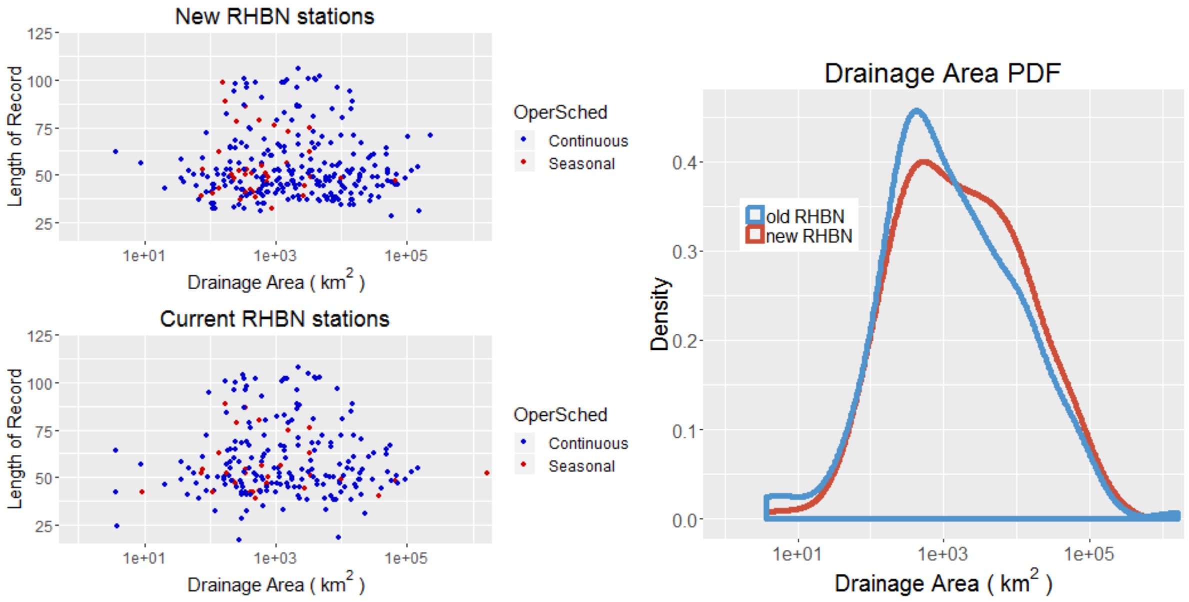


Figure 15. Drainage area versus length of record for the new RHBN, top scatterplot, and the current RHBN, bottom scatterplot. Plot to the right is the drainage area density distributions of the current RHBN in blue and the new RHBN in red.

3.5 Conclusions

The renewed RHBN shows a marked improvement on the current RHBN in terms of number of stations, distribution amongst ecoregions, geographic distribution, and distribution of basin sizes. There is a small decrease in average length of record, but this seems acceptable given the improvements mentioned above. The renewed RHBN has a total of 279 stations (240 continuous flow, 38 seasonal flow, and 1 continuous level) compared to the 227 stations in the current RHBN (191 continuous flow, 32 seasonal flow, 3 continuous level, and 1 seasonal level).

Chapter 4 Trend Detection Procedure

4.1 Overview

This chapter covers the data, methods, and parameters chosen to detect trends in the streamflow data of the renewed RHBN. By using a RHN, direct human impacts are assumed to be screened out and thus any remaining trends are most likely climate-related. A potential indicator for the storage effects described in section 3.3.2 is presented. The data are further limited to time series of useful lengths and quality, as well as separated into ecoregions and stations that do or don't exhibit multiyear storage effects. The statistical methods for the local and global trend tests are presented, and finally the implementation for the tests is outlined.

4.2 Streamflow Data

All streamflow data are taken from renewed RHBN stations within HYDAT. However, there are data limitations in terms of data length and quality, as well as the applicability of certain annually measured metrics to stations with multiyear storage effects. These limitations are presented below.

4.2.1 Timeseries Lengths

As seen in section 3.4.2, the streamflow records are not all the same length nor are they all very long. Since there is a tradeoff between lengths of timeseries and the number of stations that meet that length, multiple test lengths were selected to show trends on different scales; shorter periods will maximize the number of stations with the requisite data, longer periods are more robust to climatic fluctuations (Chen and Grasby, 2009). The time periods selected for trend analysis were 40, 60, 80, and 100 years ending in 2016 as well as the full length of record for all local tests. The minimum length of 40 years was set based on the minimum for showing climate trends reported in Khaliq et al. (2009b) and 2016 was the most recent year with reported data for most stations.

4.2.2 Streamflow Metrics and Quality Control

Streamflow metrics were calculated for each wateryear (October 1st to September 30th) and below are presented the 28 selected streamflow metrics with abbreviations and quality control steps taken before trend analyses:

- **Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec:** Average daily flow for each month is calculated if over 90% of the daily data for that month are available.

- **Annual:** Average daily flow for the wateryear is calculated if more than 90% daily data are available (out of 245 for seasonal, out of 365 for continuous stations).
- **Min_1:** Minimum one day flow, data requirements are the same as Annual.
- **Max_1:** Maximum one day flow, data requirements are the same as Annual.
- **Min_julian:** Julian date of minimum one day flow, data requirements are the same as Annual.
- **Max_julian:** Julian date of maximum one day flow, data requirements are the same as Annual.
- **Min_3, Min_7, Min_30, Min_90:** Minimum average flow over 3, 7, 30, 90-day windows (Monk et al., 2011). Rolling averages of each window length were taken within the wateryear. A mean within each window was only calculated if over 90% of the daily flows in that window were available. The overall metric for that wateryear was only calculated if over 90% of the possible 'windows' had a value.
- **Max_3, Max_7, Max_30, Max_90**: Maximum average flow over 3, 7, 30, 90-day windows (Monk et al., 2011). Similar procedure to above, but the maximum of the rolling averages is taken.
- **Annual_range:** Maximum one day flow minus Minimum one day flow, data requirements are the same as Annual.
- **Max_fall:** Maximum one day fall in flow, data requirements are the same as Annual. The lag-1 difference in daily flow is calculated (Q_t -Q_{t-1}) and the greatest magnitude negative is taken.
- **Max_rise:** Maximum one day rise in flow, data requirements are the same as Annual. The lag-1 difference in daily flow is calculated (Q_t -Q_{t-1}) and the greatest magnitude positive is taken.

Metrics that are not compatible with seasonal recording stations are set to NA for all wateryears (Min_julian, Min_1, Min_3, Min_7, Min_30, Min_90, Annual_range). Local trend tests are only run on stations and metrics with less than 10% missing data and less than 10% zero values within the evaluation periods (40, 60, 80, or 100 years).

4.2.3 Storage Effect Definition

For most streamflow stations, the variability of flow is overwhelmingly associated with processes connected to annual weather variations; the temperature for spring thaw, the rate of rainfall during a particular season, the length of time with little or no rain, etc. Some station flows are heavily controlled by storage from previous years (example in section 3.3.2 and another in Figure 16); large lakes and wetlands can have large capacities that take over a year to drain, or a groundwater table that is highly reactive to surface influxes may still have a travel time of several years to the surface water outlet. Since this is a sharp departure from most basins, these Storage Effect (SE) stations should not be evaluated and interpreted in the same way as basins controlled by annual phenomena.

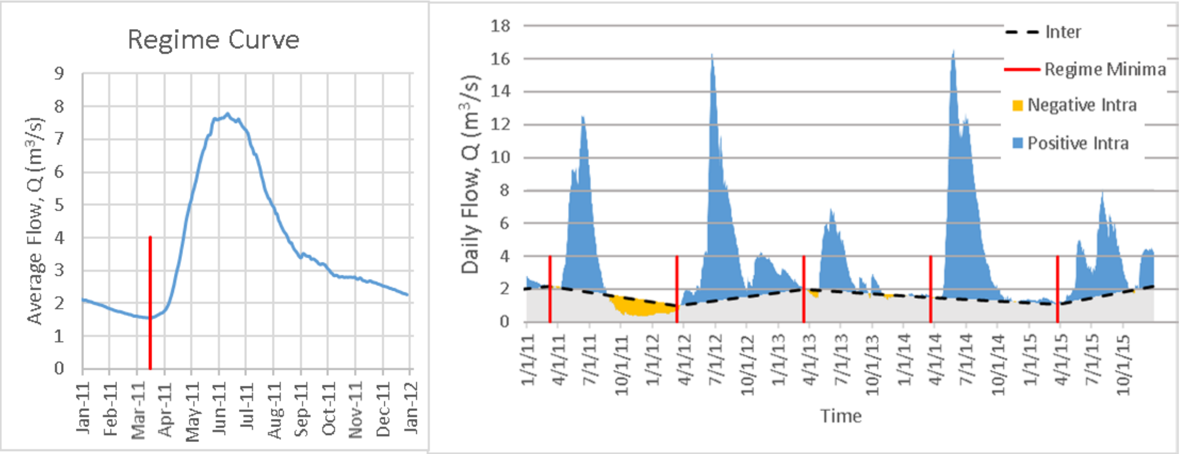


Figure 16. Example of division between Intra- and Inter-annual flows. Left image is a regime curve with the minima on March 23rd noted by the red line. In the right image the flow values at the regime minimum date (red lines) are used as the basis for the Inter-annual flow (black dashed line) and the Intra-annual flows are the difference between the regular flow and Inter flow. Data from station 05QE012.

In an effort to identify stations where an annual metric may not be appropriate, flows were divided into volumes that had travelled less than a year within the watershed and volumes that were assumed to have travelled longer. A linear interpolation between the flows on the date of a watershed's regime minima (red vertical lines in Figure 16) was used to describe flows that are carryover between years, or "Inter-annual". The difference between actual daily flows and Inter-annual was assumed to be associated with annual phenomena and called "Intra-annual" (Figure 16). If a station is largely unaffected by SE, then a ratio of the variability of Intra-annual flows to the variability of regular flows should be close to one. A ratio of standard deviations from Intra-annual flows and regular flows (determined from the entire record of daily values) was calculated for each continuous station.

$$SE\ indicator = \sigma_{Intra}/\sigma_{Q} \tag{1}$$

4.3 Statistical Methods

Streamflow data for a single watershed is variable on several scales: hourly (i.e. a single storm), seasonally (i.e. spring thaw temperature, snowpack depth, rain frequency), and even on decadal scales related to ocean-influenced weather patterns. Amongst all these periodicities and stochastic behavior, it is difficult to find a trend. Long-term trends may be assessed using parametric methods which often consist of fitting a single or several trend lines (linear, multiple or polynomial regressions, etc.) to the data. However, parametric methods of this kind assume data have a Normal distribution and are very sensitive to outliers. In such non-normal or outlier cases, non-parametric methods, such as Mann-Kendall (Mann, 1945; Kendall, 1975), Spearman's rank (Kendall and Gibbons, 1990), Petitt's (Petitt, 1979), or the Theil-Sen slope (Sen, 1968; Theil, 1950) are preferred as they do not assume a distribution and are not sensitive to outliers. MK has become the most widely used trend test in Canada (Mortsch et al., 2015) and has been adapted in several ways to account for its serial correlation assumption (e.g., Pre-Whitening, von Storch, 1995; Variance Correction, Hamed and Rao, 1998; Trend Free Pre-Whitening, Yue et al., 2002b; Block Bootstrap Resampling, BBS, Önöz and Bayazit, 2012 and Khaliq et al., 2009a). Khaliq et al. (2009a) argue that a MK test paired with BBS is a good approach for real hydrometric data and Wang et al. (2015) show that it retains good power and accurate type I errors compared to alternatives.

However, detecting trends in individual watersheds may be inadequate for attributing trends to climate change. The individual (local) tests need to be assessed together to determine if they are collectively significant; this is called field significance. Field significance may be verified by summing the results from local significant tests, but this technique is often sensitive to the cutoff value chosen for local significance (quite arbitrarily, it is usually 0.05) and cross-correlation between local tests (Douglas et al., 2000). Field significance may also be assessed using the p values of the local tests by Walker's test or the False Discovery Rate (FDR; Wilks, 2006). Wilks (2006) shows that Walker's test is almost as powerful as FDR and both are insensitive to the assumption of no cross-correlation. However, Walker's is easier to implement.

4.3.1 Local Trend Test

Local trends for each station were determined using the Mann-Kendall test (Mann, 1945; Kendall, 1975) which identifies significant monotonic trends using the relative rank of values in a timeseries. The MK test is robust to non-normal distributions and outliers due to its non-parametric nature. It does not identify the magnitude or shape (e.g., linear, exponential, etc.) of a trend, simply the presence and direction (increasing or decreasing) thereof. The MK test statistic *S* is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{2}$$

where every *x* value is compared to each of the subsequent values in a timeseries of length *n*, and

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \tag{3}$$

The test statistic *S* has a normal distribution if there is no autocorrelation. Since streamflow data commonly exhibit some autocorrelation, a block bootstrap resampling procedure (Önöz and Bayazit, 2012) was implemented to define a new test statistic distribution. Block bootstrap resampling (BBS) takes a large number of permutations of a timeseries by randomly reordering blocks of a chosen length. The blocks are designed to retain any serial correlation present in the original data in each permutation. The MK test is performed on each permutation to obtain a distribution of the test statistic; if the original MK *S* value is within the tails of this distribution, then it is considered a trend and the *p* value may be reported based on the BBS-derived distribution.

4.3.2 Field Significance

Field significance for each group of local tests was determined using Walker's test (Wilks, 2006). The global null hypothesis for Walker's test is that all the local null hypotheses are true (i.e. there is no trend and any trends detected in the local tests may be false positives/type I errors); the alternative to the global null hypothesis is that some local tests are in fact true. The global null hypothesis is rejected when the smallest *p* value of a set of local tests is below what would be expected from a similar size sample of local tests that are all true. This critical value is defined as:

$$p_{Walker} = 1 - (1 - \alpha_{global})^{1/\mathrm{K}} \tag{4}$$

where *K* is the number of local tests and α_{global} is the chosen significance level. Walker's test technically assumes independence of the samples, but Wilks (2006) notes that it is relatively insensitive to this assumption.

4.4 Implementation

All tests were automated through the R programming language (R Core Team, 2017) and the packages *boot* (Davison and Hinkley, 1997; Canty and Ripley, 2017) and *kendall* (MacLeod, 2011) in a series of nested loops. Results were gathered into summary tables and figures were generated in R using various helper and plotting functions (Appendix C).

Local trend tests were completed for each time period and metric that met the quality control criteria for all renewed RHBN flow stations. The local test was a MK test at a significance level, α_{local}, of 0.05, modified by a BBS procedure with a permutation number of ten thousand and a block size of five. The block size of five was chosen based on Önöz and Bayazit (2012); although the authors noted that the optimum value changes with sample size, for the range of sample sizes used here (40-100 years) a single value was deemed acceptable.

Field Significance tests were completed on sets of local tests in the following groups: Canada-wide, Canada minus SE stations, all nine ecoregions, and ecoregions minus SE stations where applicable (only four ecoregions have SE stations). The field significance tests chosen was Walker's with a α_{global} of 0.1.

Chapter 5 Trend Results and Discussion

5.1 Introduction

Streamflow data from the renewed RHBN over periods ranging from 40 to 100 years were analyzed using a MK BBS local test for trend and Walker's test for field significance in various groups. Local tests were grouped nationally and by ecoregions, as well as by storage effect, for new field significance tests. Goals and limitations of trend detection studies are reviewed before presenting results and discussing key findings.

5.2 Goals and Limitations of Trend Detection

Trends cannot be responsibly used for forecasting without understanding contributing factors or processes and providing error estimates. The use of an RHN limits the confounding effects of direct human impacts on trend studies, thus allowing a more confident attribution to long-term and cyclical climatic influences. Basic trend detection studies applied to an RHN are starting points that need to be followed by further studies to fully understand the effects (and potential future effects) of climate change. This exploratory analysis may be used to correlate (statistically, observationally, or categorically) with other phenomena or processes and identify poorly understood connections.

Correlation to oceanic oscillations (Burn et al., 2008; Brabets and Walvoord, 2009; Assani et al., 2010) is a common approach that provides the most direct path to understanding potential future flows (Robertson and Wang, 2012; Berton et al., 2017). The IPCC worldwide models (IPCC, 2013) for the oscillation, precipitation, and temperature patterns are widely used to help estimate future streamflows (Kerkhoven and Gan, 2011; El-Jabi et al., 2013; St. Jacques et al., 2013). However, there are watershed-scale factors (see below) related to atmospheric changes that are not fully integrated with current models and need to be better understood.

St. Jacques and Sauchyn (2009) studied baseflow in Canada's north by using winter flows to conclude that permafrost thaw was increasing streamflows; the seasonal focus excluded other direct liquid water inputs. However, the exact nature of permafrost changes to streamflow are still active areas of research and subject to debate (Spence et al., 2011; Walvoord and Kurylyk, 2016). Several studies (Stahl et al., 2006; Moore et al., 2009; Marshall et al., 2011) differentiate between mountainous watersheds with and without glaciers to show the effects of glacier wastage and the stage of glacier retreat on streamflow. Northern advance of Tundra shrubs in response to temperature increases have been observed and are expected to continue (Myers-Smith et al., 2013), but effects on streamflow are poorly understood (Krogh and Pomeroy, 2018). One process that is difficult to integrate into streamflow trend studies is natural forest succession after fire, mountain pine beetle infestation and/or logging (Shakesby and Doerr, 2006; Dhar et al., 2016; Zhang and Wei, 2014). These forest stressors have generally not been integrated into streamflow studies but can affect streamflow for up to 35 years, particularly in snowy conifer forests (Jones et al., 2004; Kuras et al., 2012).

5.3 Storage Effects

The attempt to identify SE stations used the ratio of standard deviations from Intra-annual flows and regular flows (determined from the entire record of daily values). This should be close to one if there are no storage effects (see section 4.2.3). Most stations (178 out of 215 continuous stations that met data quality criteria) had a ratio of 1±0.01 and show strong annual patterns associated with nival or nival-pluvial controls (middle of Figure 17); the 26 stations with a ratio below 0.99 show typical SE station flows (left of Figure 17); the 11 stations with a ratio above 1.01 show something more chaotic (right of Figure 17). Stations with a ratio above 1.01 have weak annual patterns; the spring freshet is not always the highest flow and the regime minimum is often not the lowest flow. The weak pattern stations (SE indicator above 1.01) are all pluvial (rain-controlled), but the SE indicator does not identify all pluvial stations as it was not designed to do so.

Figure 18 shows the 26 SE stations, 11 stations with weak annual patterns, and all other renewed RHBN stations across Canada. The SE stations are all roughly clustered in the central part of the country and the weak pattern stations are all on the coasts, mostly the Atlantic. Figure 18 also clearly shows that most stations have strong annual patterns.

Stations with a SE indicator below 0.99 do not show clear correlation with drainage area, percent wetland, or percent surface water (Figure 19). Drainage area may limit the magnitude of the storage effect as the most extreme cases are all large watersheds. Weak pattern stations (above 1.01) also do not seem to show any trend with drainage area, percent wetland, and percent surface water (Figure 19).

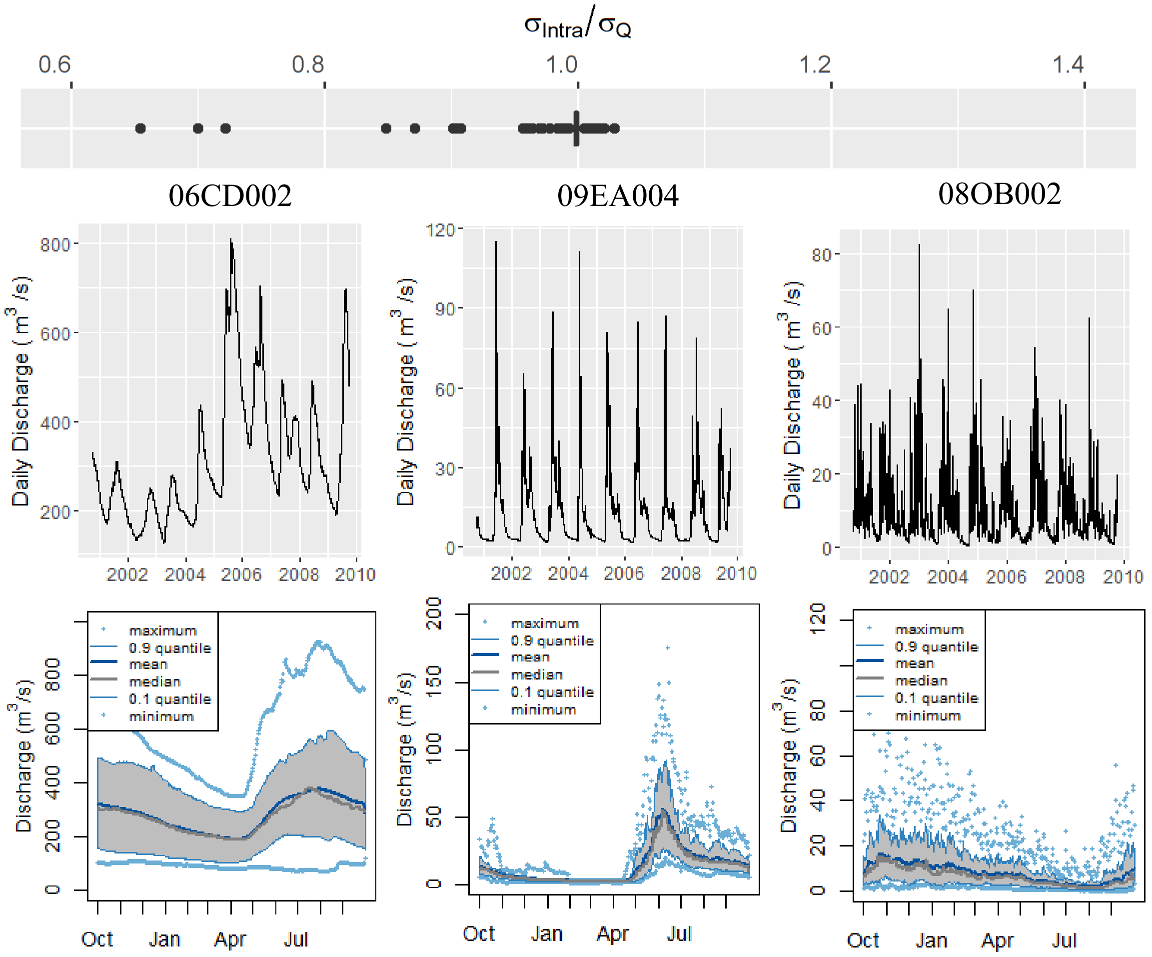


Figure 17. SE indicator at the top, 10 years of streamflow in the middle, and regime curves at the bottom for three example stations: 06CD002 – Churchill River, SK (left, SE indicator = 0.870), 09EA004 – N. Klondike River, YT (center, SE indicator = 1.000), and 08OB002 – Pallant Creek, BC (right, SE indicator = 1.013).

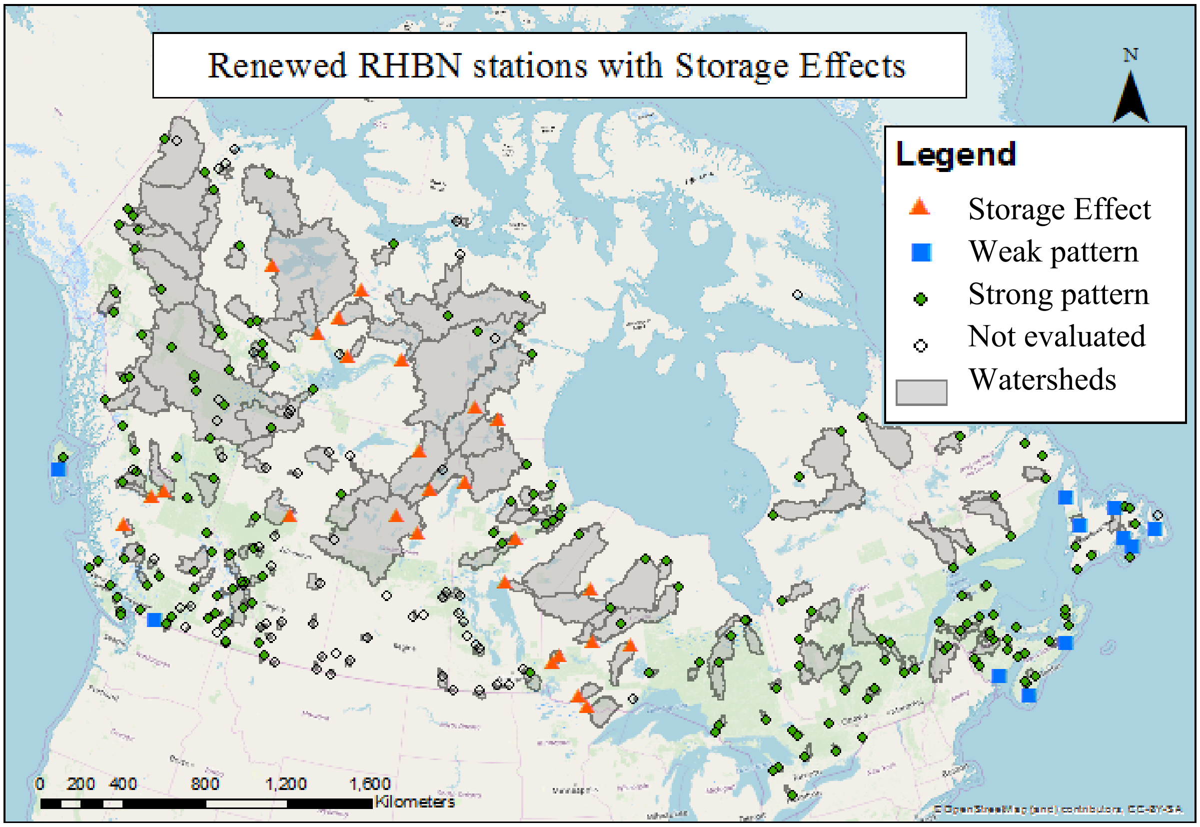


Figure 18. Map of renewed RHBN stations and watersheds where available. SE stations are shown by orange triangles, stations with weak annual patterns by blue squares, stations with strong annual patterns by green circles, and not evaluated stations are empty circles.

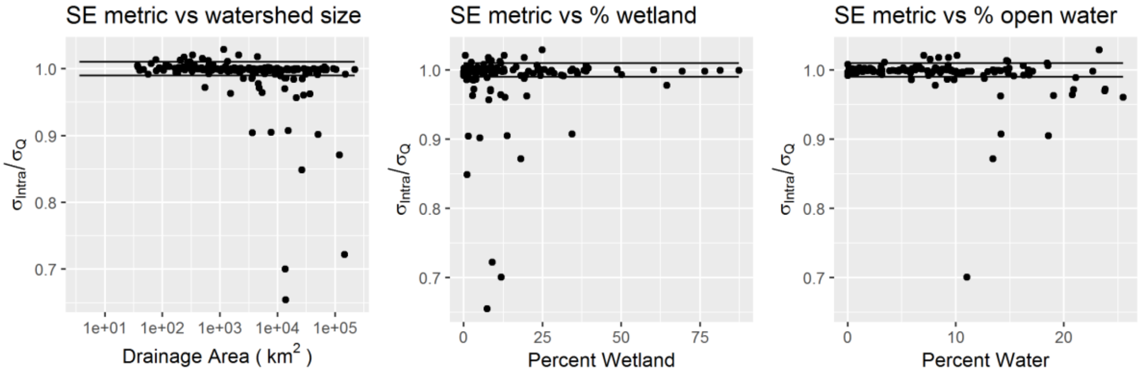


Figure 19. Scatterplots of SE indicator versus watershed size (left), percent wetland (center), and percent open water (right) for renewed RHBN stations.

Most metrics are invalid for strong storage effect stations except perhaps the difference-based metrics like Annual Range, Max 1-day rise, and Max 1-day fall. However, a watershed's maximum 1-day rise or fall may also be dependent on its storage level in special cases. For example, in a Prairie Pothole landscape (i.e. isolated lows) the potential 1-day rise in flow would be much higher when the 'potholes' are filled, increasing effective watershed area, than when they are empty. The 26 SE stations are used to create groups that may be considered to be controlled by annual phenomena; a Canada-wide minus SE station group (section 5.4), and four ecoregion groups minus their SE stations (section 5.5). Since there are so many weak pattern stations in Atlantic Canada, a sub-group of Atlantic stations without weak patterns was created for exploration purposes (section 5.11).

5.4 Trend Summaries for Canada

Local trend tests were applied to all renewed RHBN flow stations and timeseries lengths for all of Canada (Table 6) and all of Canada minus SE stations (Table 8). Results in Tables 6 and 8 show positive/negative results from MK tests with BBS at a significance level of 5% along with the number of stations that met data quality criteria for that period and metric in brackets. Criteria are defined in section 4.2.2 and may result in a different number of qualifying stations for each metric within the same time period. Field significance at the 10% level is shown by bold outlines and bold font denotes whether the local test(s) that met Walker's field significance test was(were) positive, negative, or both. Background colour shows percentage of significant local tests (trend counts); light green shows >20% positive, dark green >40% positive, light red >20% negative, and yellow where the combined positive and negative local trends are >20%.

Table 6. Table of results for renewed RHBN stations in Canada for 28 streamflow metrics and 4 evaluation periods. Shows percentage of positive significant trends/percentage of negative significant trends (number of stations that met data quality criteria). Field significance is shown by thick black boxes with bold numbers identifying the local tests that proved field significance. Background reflects the number of significant trends (green >20% positive, red >20% negative, and yellow >20% for both).

Canada Metrics	1977 - 2016 (40 yrs)	1957 - 2016 (60 yrs)	1937 - 2016 (80 yrs)	1917 - 2016 (100 yrs)
Jan	**27**/0 **(211)**	**28**/1 **(79)**	**38**/0 **(29)**	**47**/0 **(15)**
Feb	**25**/2 **(211)**	**27**/3 **(79)**	**36**/4 **(28)**	**40**/0 **(15)**
Mar	**28**/0 **(243)**	**36**/0 **(87)**	**37**/0 **(30)**	**40**/0 **(15)**
Apr	**18**/2 **(245)**	**31**/3 **(95)**	**30**/5 **(37)**	**33**/0 **(15)**
May	6/9 (245)	6/15 (96)	**8**/19 **(37)**	0/**29 (17)**
Jun	8/**11 (246)**	7/12 (95)	8/13 (38)	6/6 (17)
Jul	4/6 (248)	5/**8 (98)**	5/**5 (37)**	6/**12 (17)**
Aug	3/**12 (247)**	3/**17 (98)**	8/**13 (38)**	**12/18 (17)**
Sep	8/7 (246)	7/9 (99)	8/13 (38)	6/**18 (17)**
Oct	11/5 (243)	9/5 (95)	6/6 (36)	7/7 (15)
Nov	18/1 (217)	16/1 (89)	**25**/0 **(32)**	**40**/0 **(15)**
Dec	**24**/0 **(213)**	**24**/1 **(85)**	**33**/3 **(30)**	**53**/0 **(15)**
Annual	8/3 (227)	7/5 (83)	18/7 (28)	20/7 (15)
Max_julian	3/**10 (228)**	2/**16 (83)**	0/**24 (29)**	0/**13 (15)**
Min_julian	**11**/2 **(195)**	5/1 (76)	8/0 (26)	0/0 (15)
max_1	5/8 (227)	5/11 (83)	**11**/4 **(28)**	**7**/7 **(15)**
max_3	3/9 (238)	3/9 (104)	6/6 (34)	**6**/6 **(16)**
max_7	3/9 (232)	2/12 (102)	6/6 (33)	**6**/6 **(16)**
max_30	1/12 (223)	2/15 (95)	6/**16 (31)**	13/**27 (15)**
max_90	2/7 (224)	2/10 (94)	6/16 (32)	13/**13 (15)**
min_1	**18**/6 **(193)**	**17**/8 **(75)**	**15**/8 **(26)**	13/13 (15)
min_3	**19**/3 **(211)**	18/4 (92)	**12**/3 **(32)**	12/6 (16)
min_7	**20**/4 **(208)**	20/4 (91)	**16**/0 **(32)**	19/0 (16)
min_30	**23**/2 **(204)**	**22**/5 **(85)**	**19**/0 **(31)**	**20**/0 **(15)**
min_90	**25**/1 **(204)**	**24**/3 **(86)**	**26**/0 **(31)**	**33**/0 **(15)**
max_rise	6/10 (227)	4/13 (83)	**11**/7 **(28)**	**7**/7 **(15)**
max_fall	13/6 (227)	**22**/7 **(83)**	**25**/4 **(28)**	**20**/7 **(15)**
Annual_range	5/8 (195)	5/11 (76)	**12**/8 **(26)**	**7**/7 **(15)**

Patterns begin to emerge even in table format (Table 6): There are many increasing trends in the winter months (December-April) for all time periods and all are field significant; there are also a large number of trends in other months with most showing negative tendencies (specifically August) and only a couple showing field significance in the longer time periods; Annual mean flows show some trends, but none are field significant; Timing of maximum one day flow is usually earlier in the year and is field significant for all time periods; Timing of minimum one day flow is usually later with only one field significant time period; Maximum flows over different windows show inconsistent trends and few field significant time periods; There are many, mostly increasing, trends for the minimum flows over different windows and many are field significant; Difference-based metrics (maximum rise, maximum fall, and annual range) show some trends and some field significant longer time periods, but nothing consistent. There are generally more trends (as a percentage of available stations) in the longer time periods than the shorter ones.

The trend summary table for Canada minus SE stations (Table 8) shows very similar patterns to the table for Canada including SE stations (Table 6). May monthly mean at the 80 year analysis loses field significance due to the exclusion of a strong trend in an SE station. Minimum 3-day and 7-day flow at the 60 year analysis gains field significance due to the reduced threshold (fewer stations = lower P_{walker}). While the renewed RHBN list matched as close as possible the countrywide distribution, as the time period increases, the available stations skew southward and accumulates in some ecoregions (Table 7). This means the longer periods represent a more restricted area rather than the whole country.

Table 7. Distribution of stations in number and percentage at each time period. Colours show departure from initial distribution (red = less, green = more).

Ecoregions	Renewed RHBN	1977 - 2016 (40 yrs)	1957 - 2016 (60 yrs)	1937 - 2016 (80 yrs)	1917 - 2016 (100 yrs)
Desert	5 (1.5%)	4 (1.3%)	2 (1.5%)	2 (4.1%)	-
East Temperate	20 (5.9%)	20 (6.3%)	14 (10.6%)	7 (14.3%)	4 (22.2%)
Great Plains	23 (6.7%)	23 (7.2%)	11 (8.3%)	5 (10.2%)	1 (5.6%)
Hudson Plain	12 (3.5%)	11 (3.5%)	-	-	-
West Coast Mtns	16 (4.7%)	16 (5.0%)	9 (6.8%)	2 (4.1%)	1 (5.6%)
Tundra	14 (4.1%)	11 (3.5%)	1 (0.8%)	-	-
Taiga	70 (20.5%)	60 (18.9%)	13 (9.8%)	1 (2.0%)	-
Boreal	114 (33.4%)	107 (33.6%)	43 (32.6%)	18 (36.7%)	10 (55.6%)
Rockies	67 (19.6%)	66 (20.8%)	39 (29.5%)	14 (28.6%)	2 (11.1%)

Table 8. Table of results for renewed RHBN stations that do not display SE for 28 streamflow metrics and 4 evaluation periods. Shows percentage of positive significant trends/percentage of negative significant trends (number of stations that met data quality criteria). Field significance is shown by thick black boxes with bold numbers identifying the local tests that proved field significance. Background reflects the number of significant trends (green >20% positive, red >20% negative, and yellow >20% for both). "SE" is the number of stations removed in relation to Table 6.

Canada -26 (SE) Metrics	1977-2016 (40 yrs, 25 SE)	1957-2016 (60 yrs, 8 SE)	1937-2016 (80 yrs, 3 SE)	1917-2016 (100 yrs, 1 SE)
Jan	**30**/1 **(187)**	**31**/1 **(72)**	**42**/0 **(26)**	**50**/0 **(14)**
Feb	**27**/2 **(187)**	**29**/3 **(73)**	**40**/4 **(25)**	**43**/0 **(14)**
Mar	**30**/0 **(219)**	**38**/0 **(81)**	**41**/0 **(27)**	**43**/0 **(14)**
Apr	**19**/3 **(221)**	**31**/3 **(88)**	**26**/6 **(34)**	**29**/0 **(14)**
May	5/10 (221)	6/16 (89)	6/21 (34)	0/**31 (16)**
Jun	7/**11 (222)**	7/11 (88)	6/14 (35)	6/6 (16)
Jul	3/5 (223)	5/**8 (91)**	6/**6 (34)**	**6/12 (16)**
Aug	3/**12 (222)**	3/**17 (92)**	9/**14 (35)**	**12/19 (16)**
Sep	8/6 (221)	8/9 (91)	9/14 (35)	6/**19 (16)**
Oct	11/5 (219)	10/5 (88)	6/6 (33)	7/7 (14)
Nov	20/1 (193)	17/1 (82)	**28**/0 **(29)**	**43**/0 **(14)**
Dec	**26**/1 **(189)**	**26**/1 **(78)**	**37**/4 **(27)**	**57**/0 **(14)**
Annual	7/3 (206)	8/5 (77)	19/8 (26)	21/7 (14)
Max_julian	3/**10 (207)**	1/**16 (77)**	0/**22 (27)**	0/**14 (14)**
Min_julian	**10**/2 **(174)**	4/1 (70)	8/0 (24)	0/0 (14)
max_1	4/9 (206)	5/12 (77)	**12**/4 **(26)**	**7/7 (14)**
max_3	3/9 (213)	3/9 (97)	6/6 (31)	**7/7 (15)**
max_7	2/10 (207)	2/13 (95)	7/7 (30)	**7/7 (15)**
max_30	1/14 (199)	2/16 (89)	7/**18 (28)**	14/**29 (14)**
max_90	1/8 (200)	2/10 (88)	7/17 (29)	14/**14 (14)**
min_1	**20**/6 **(172)**	**19**/9 **(69)**	**17**/8 **(24)**	14/14 (14)
min_3	**20**/3 **(186)**	**20**/5 **(85)**	**14**/3 **(29)**	13/7 (15)
min_7	**22**/4 **(183)**	**21**/5 **(84)**	**17**/0 **(29)**	20/0 (15)
min_30	**24**/2 **(180)**	**24**/5 **(79)**	**21**/0 **(28)**	**21**/0 **(14)**
min_90	**27**/2 **(180)**	**25**/4 **(80)**	**25**/0 **(28)**	**29**/0 **(14)**
max_rise	5/9 (206)	4/13 (77)	**12**/8 **(26)**	**7/7 (14)**
max_fall	12/5 (206)	**18**/8 **(77)**	**23**/4 **(26)**	**14**/7 **(14)**
Annual_range	4/9 (174)	6/11 (70)	**12**/8 **(24)**	**7/7 (14)**

5.5 Trend Summaries for Ecoregions

Local trend tests are collected for all renewed RHBN flow stations in each ecoregion and ecoregion minus SE stations for the 40 year analysis as this had the largest number of stations. Table 9 shows the trend summary for ecoregions that did not have any SE stations and Table 10 shows trend summary for ecoregions that did have SE stations. Overall, trends are more unidirectional (either positive or negative) within ecoregions than country-wide, especially amongst the metrics that met field significance in Table 6. Tables 9 and 10 also reveal that the patterns found in the Canada group (Table 6) do not match those in some ecoregions, with some ecoregions showing opposing trends.

The Desert ecoregion has too few stations to show many trends, although the fact that half of the stations in the maximum fall metric show increasing trends could be important. The Eastern Temperate ecoregion (ET) has almost entirely increasing trends in monthly means (except a few in April, May, and June) with over half being field significant. The ET ecoregion also shows increasing trends for minimum flow over all windows with three being field significant (1, 3, and 90 day windows), and maximum one day fall is mostly decreasing and field significant. The Great Plains (GP) ecoregion shows most monthly means have more increasing trends in contrast to the annual mean that is mostly decreasing; the stations with decreasing annual means do not have any increasing monthly trends (regional summary in section 5.12). The GP ecoregion also has a few trends showing later timing of maximum flow, in contrast to all other ecoregions showing no trend or mostly earlier. The Hudson Plain (HP) ecoregion shows increasing monthly means and field significance only in winter months (November – February) and this may explain the field significant increasing annual mean. The HP ecoregion also shows the timing of minimum flow occurring later with field significance. For HP, the maximum flows over all windows are only decreasing with the 90-day window field significant; the minimum flows over all windows are only increasing with the 1-, 7-, and 90-day windows field significant. West Coast Mtns (WC) ecoregion shows only a few (positive and negative) trends for monthly means, except August with 6 out of 16 stations showing decreasing trends and field significance. The WC ecoregion shows a few trends for the maximums over all windows and the difference-based metrics, but no consistent direction. WC is also the only ecoregion to show decreasing minima over all windows; a significant ecological metric for plant and wildlife stress (Monk et al., 2011). WC trends for increasing max rise, decreasing minima, and increasing short maxima are all in the south of the region (trend maps for 1977-2016 in Appendix D).

Table 9. Summary results table in a similar format to Table 6 for ecoregions over the years 1977-2016 (40 years) that did not have any SE stations.

Metrics	Desert	East Temperate	Great Plains	Hudson Plain	West Coast Mtns
Jan	0/0 (4)	**40**/0 **(20)**	0/0 (1)	**36**/0 **(11)**	12/0 (16)
Feb	0/0 (4)	**20**/0 **(20)**	**100**/0 **(1)**	**9**/0 **(11)**	12/**6 (16)**
Mar	**25**/0 **(4)**	**25**/0 **(20)**	**37**/0 **(19)**	9/0 (11)	12/0 (16)
Apr	25/0 (4)	**30**/5 **(20)**	0/17 (23)	11/0 (9)	0/6 (16)
May	0/0 (4)	5/20 (20)	0/0 (22)	0/12 (8)	12/19 (16)
Jun	0/0 (4)	10/10 (20)	28/0 (18)	0/0 (8)	6/6 (16)
Jul	0/0 (4)	15/0 (20)	12/0 (16)	0/0 (8)	0/12 (16)
Aug	0/0 (4)	**15**/0 **(20)**	8/0 (13)	0/0 (8)	0/**38 (16)**
Sep	0/25 (4)	5/0 (20)	17/0 (12)	0/0 (9)	6/12 (16)
Oct	0/0 (4)	**15**/0 **(20)**	8/0 (13)	0/0 (11)	0/13 (15)
Nov	0/0 (4)	**25**/0 **(20)**	0/0 (1)	**45**/0 **(11)**	6/6 (16)
Dec	0/0 (4)	15/0 (20)	0/0 (1)	**45**/0 **(11)**	0/6 (16)
Annual	0/0 (4)	10/0 (20)	0/15 (20)	**14**/0 **(7)**	7/0 (15)
Max_julian	0/0 (4)	0/10 (20)	19/0 (21)	0/0 (7)	7/13 (15)
Min_julian	0/0 (4)	10/0 (20)	0/0 (0)	**29**/0 **(7)**	0/0 (15)
max_1	0/25 (4)	0/0 (20)	0/10 (20)	0/0 (7)	**7**/7 **(15)**
max_3	0/25 (4)	0/0 (20)	7/**13 (15)**	0/10 (10)	6/6 (16)
max_7	0/25 (4)	0/0 (20)	8/8 (13)	0/12 (8)	6/6 (16)
max_30	0/0 (4)	0/**10 (20)**	0/8 (12)	0/38 (8)	0/6 (16)
max_90	0/0 (4)	0/0 (20)	0/0 (12)	0/**12 (8)**	0/**6 (16)**
min_1	0/0 (4)	**5**/5 **(20)**	0/0 (0)	**14**/0 **(7)**	13/20 (15)
min_3	0/0 (4)	**5**/0 **(20)**	0/0 (0)	10/0 (10)	19/**19 (16)**
min_7	0/25 (4)	5/0 (20)	0/0 (0)	**12**/0 **(8)**	19/19 (16)
min_30	0/0 (4)	25/0 (20)	0/0 (0)	25/0 (8)	12/19 (16)
min_90	0/0 (4)	**35**/0 **(20)**	0/0 (0)	**25**/0 **(8)**	12/**19 (16)**
max_rise	0/25 (4)	15/0 (20)	5/**15 (20)**	0/0 (7)	**7**/7 **(15)**
max_fall	**50**/0 **(4)**	5/**25 (20)**	15/0 (20)	0/0 (7)	7/7 (15)
Annual_range	0/25 (4)	0/0 (20)	0/0 (0)	0/0 (7)	**7**/7 **(15)**

The ecoregions in summary Table 10 contain some SE stations so each is summarized in a group including these SE stations and another excluding these SE stations. There is only one important change between the full ecoregion group and that ecoregion without SE stations; the maximum rise for the Taiga ecoregion was field significant only due to a single positive trend that was from an SE station. Other field significance changes between full ecoregion group and the group without SE stations are due to decreases in the overall number of stations (fewer stations = lower P_{Walker}).

The Tundra ecoregion has too few stations to show many trends, but several are field significant anyway. The minimum flow is occurring earlier with field significance. Tundra minimum flows for all but the 1-day window as well as the maximum rise and fall show field significant increasing trends. The Taiga ecoregion shows a high number of increasing (and very few decreasing) trends with field significance for over half the monthly means (October – April); only some mixed trends for the other months although June is mostly decreasing and field significant. The minimum flow is occurring later with field significance. Taiga shows many increasing (no decreasing) trends with field significance for minimum flows over all windows. Taiga also shows a few mixed trends in difference-based metrics. The Boreal ecoregion has many increasing trends with field significance for the winter monthly means (December – April); some decreasing trends with field significance for summer monthly means (June – August). Boreal also shows earlier maximum flow timing with field significance. Curiously, Boreal is the only ecoregion that shows this trend which was also present in the full country summary (Table 6). The Boreal ecoregion shows few mixed trends and no field significance in minimum and maximum flows over all windows (mostly decreasing for maxima, mostly increasing for minima). The Rockies ecoregion also shows a high number of increasing trends with field significance in the winter monthly means (December – March); many decreasing trends with field significance in August. There are also a high number of increasing trends with field significance in the minima of all windows and the maximum fall.

The increasing trends in winter months are associated with the increasing trends in low flows for Taiga and Rockies ecoregions, but not the Boreal ecoregion (Table 10). As shown in the regime curves averaged over each ecoregion and normalized by drainage area in Figure 20, lowest flow consistently occurs in the winter months for Taiga and Rockies, but the Boreal ecoregion also has a potential minimum timing in the summer months.

Table 10. Summary results table in a similar format to Table 6 for ecoregions over the years 1977-2016 (40yrs) that have SE stations.

Metrics	Tundra	Tundra - 1 SE	Taiga	Taiga – 9 SE	Boreal	Boreal – 15 SE	Rockies	Rockies – 3 SE
Jan	0/0 (4)	0/0 (3)	**49**/0 **(47)**	**56**/0 **(39)**	**21**/0 **(92)**	**25**/0 **(77)**	**31**/2 **(61)**	**33**/2 **(58)**
Feb	0/0 (4)	0/0 (3)	**51**/0 **(47)**	**59**/0 **(39)**	**21**/2 **(92)**	**23**/1 **(77)**	**34**/3 **(61)**	**36**/3 **(58)**
Mar	25/0 (4)	33/0 (3)	**49**/0 **(49)**	**56**/0 **(41)**	**20**/1 **(106)**	**22**/0 **(91)**	**42**/0 **(66)**	**44**/0 **(63)**
Apr	**25**/0 **(4)**	**33**/0 **(3)**	**31**/0 **(49)**	**34**/0 **(41)**	**15**/0 **(104)**	**17**/0 **(89)**	23/2 (66)	22/2 (63)
May	0/0 (4)	0/0 (3)	18/2 (50)	17/2 (42)	0/15 (102)	0/17 (88)	9/3 (66)	8/3 (63)
Jun	25/12 (8)	29/14 (7)	8/**13 (53)**	7/**16 (45)**	2/**16 (102)**	0/**17 (88)**	9/5 (66)	8/3 (63)
Jul	0/0 (10)	0/0 (9)	2/5 (55)	2/7 (46)	4/**5 (103)**	1/**5 (88)**	2/8 (66)	2/6 (63)
Aug	0/0 (11)	0/0 (10)	2/7 (58)	2/6 (49)	2/**8 (101)**	0/**8 (86)**	3/**25 (65)**	3/**23 (62)**
Sep	0/0 (10)	0/0 (9)	19/4 (57)	23/4 (48)	4/5 (103)	2/6 (88)	14/12 (65)	15/10 (62)
Oct	0/0 (7)	0/0 (6)	**25**/4 **(55)**	**28**/4 **(47)**	4/4 (103)	5/5 (88)	15/9 (65)	16/6 (62)
Nov	0/0 (5)	0/0 (4)	**37**/0 **(51)**	**42**/0 **(43)**	10/1 (93)	12/1 (78)	16/2 (61)	**17**/2 **(58)**
Dec	0/0 (4)	0/0 (3)	**49**/0 **(49)**	**56**/0 **(41)**	**23**/0 **(92)**	**27**/0 **(77)**	**20**/2 **(61)**	**21**/2 **(58)**
Annual	0/0 (3)	0/0 (2)	14/5 (42)	14/6 (36)	8/2 (95)	6/2 (82)	6/3 (66)	6/3 (63)
Max_julian	0/0 (3)	0/0 (2)	0/10 (42)	0/11 (36)	2/**14 (95)**	1/**16 (82)**	3/9 (66)	3/8 (63)
Min_julian	0/**67 (3)**	0/**100 (2)**	**15**/3 **(39)**	**15**/3 **(33)**	11/1 (83)	10/1 (70)	10/2 (61)	10/2 (58)
max_1	0/0 (3)	0/0 (2)	5/2 (42)	3/3 (36)	7/7 (95)	5/9 (82)	3/12 (66)	3/13 (63)
max_3	12/0 (8)	14/0 (7)	0/6 (52)	0/7 (43)	4/7 (99)	4/8 (84)	0/13 (62)	0/12 (59)
max_7	12/12 (8)	14/14 (7)	0/6 (50)	0/7 (41)	3/8 (97)	2/10 (82)	0/13 (62)	0/12 (59)
max_30	0/0 (4)	0/0 (3)	0/9 (46)	0/11 (38)	3/13 (94)	2/15 (80)	0/13 (62)	0/14 (59)
max_90	0/0 (5)	0/0 (4)	0/9 (47)	0/10 (39)	5/7 (94)	2/9 (80)	0/8 (62)	0/7 (59)
min_1	0/0 (3)	0/0 (2)	**55**/0 **(38)**	**62**/0 **(32)**	6/7 (82)	7/7 (69)	**33**/5 **(61)**	**34**/5 **(58)**
min_3	**25**/0 **(4)**	**33**/0 **(3)**	**50**/0 **(48)**	**56**/0 **(39)**	7/3 (90)	8/4 (75)	**31**/2 **(61)**	**33**/0 **(58)**
min_7	**25**/0 **(4)**	**33**/0 **(3)**	**54**/0 **(46)**	**62**/0 **(37)**	7/3 (89)	8/4 (74)	**34**/2 **(61)**	**36**/2 **(58)**
min_30	**25**/0 **(4)**	**33**/0 **(3)**	**53**/0 **(43)**	**60**/0 **(35)**	10/0 (86)	12/0 (72)	**33**/2 **(61)**	**34**/2 **(58)**
min_90	**25**/0 **(4)**	**33**/0 **(3)**	**53**/0 **(43)**	**60**/0 **(35)**	17/0 (86)	18/0 (72)	**31**/0 **(61)**	**33**/0 **(58)**
max_rise	**33**/0 **(3)**	**50**/0 **(2)**	2/**21 (42)**	0/19 (36)	5/5 (95)	4/4 (82)	3/15 (66)	3/14 (63)
max_fall	**33**/0 **(3)**	**50**/0 **(2)**	17/5 (42)	**14**/3 **(36)**	9/5 (95)	**6**/5 **(82)**	**20**/0 **(66)**	**19**/0 **(63)**
Annual_range	0/0 (3)	0/0 (2)	3/3 (39)	3/3 (33)	8/8 (83)	6/10 (70)	2/11 (61)	2/12 (58)

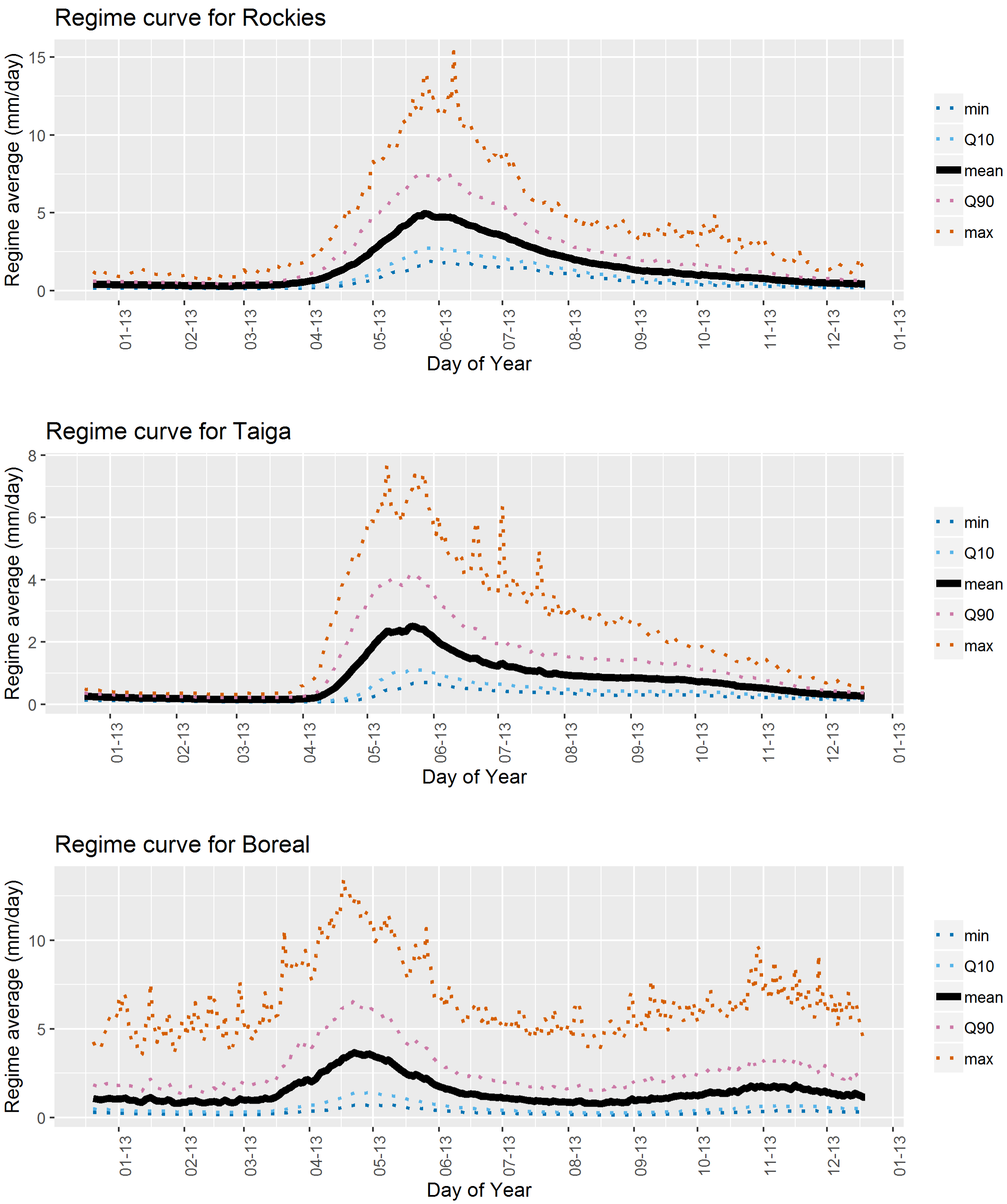


Figure 20. Regime curves averaged over ecoregions and normalized by drainage area (giving flows of mm/day). Top = Rockies, Middle = Taiga, Bottom = Boreal.

5.6 Geographic Distribution of Trends in Canada

Since trends may not cluster in the ecoregions presented thus far, Canada-wide maps for each trend metric and time period were produced (28 metric x 4 periods = 112 maps). A select few from the 40 year period (the period with the most stations) are presented below. Each map shows all stations that met quality criteria for the metric as well as all positive (orange "up" triangle) and negative (blue "down" triangle) significant local trends. To highlight the local tests that had stronger results than P_{walker} in each category, these are given a special accent on maps (black outline of triangle).

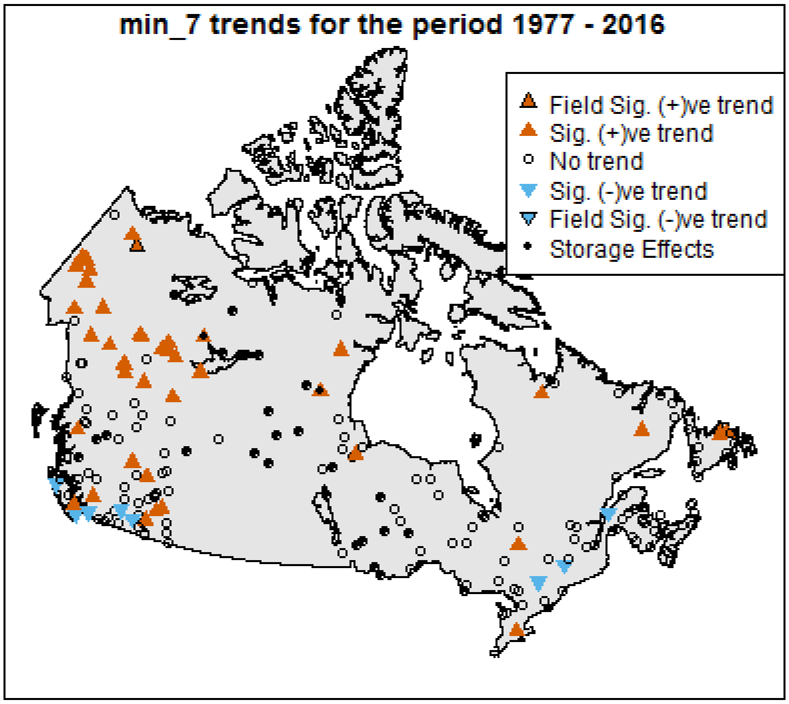


Figure 21. Local trends for renewed RHBN stations that met the quality criteria for calculating the Minimum flow averaged over 7 days.

Minimum flows of different lengths are important stressors for aquatic life; the time spent at low flow can lead to fish stress and die offs. Only two clusters show decreasing trends for the minima over 1-, 3-, and 7-day windows; a line for most of southern Ontario to the mouth of the St Lawrence River in Quebec, and the very south of British Columbia (Figure 21). The latter area shows decreasing trends over 30- and 90-day windows as well (Figure 22).

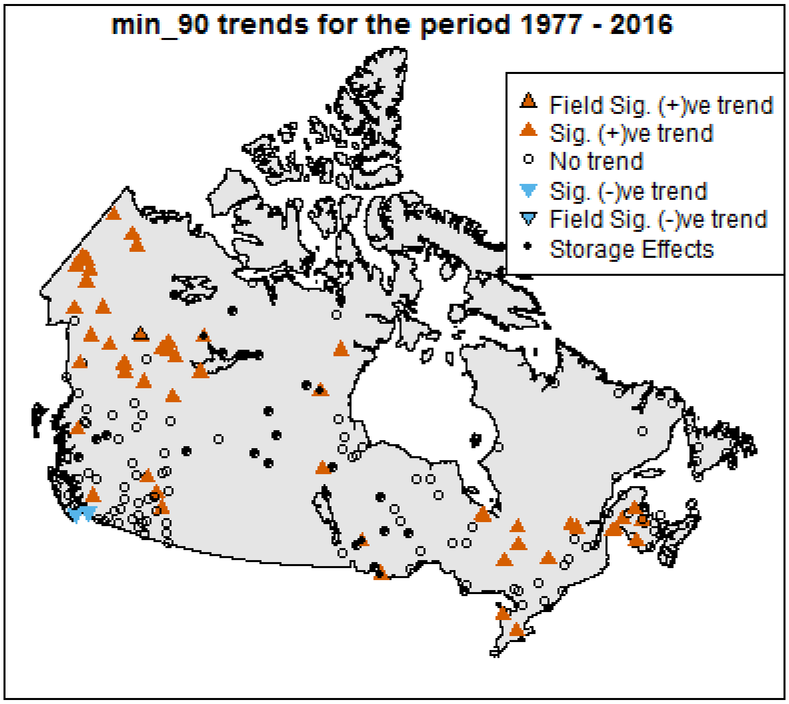


Figure 22. Local trends for renewed RHBN stations that met the quality criteria for calculating the Minimum flow averaged over 90 days.

Maximum flows averaged over 90 days show negative trend for almost all stations except three SE stations in the middle of the country (04GB004-SE indicator of 0.989, 05QE012-SE indicator of 0.972, 05UA003-SE indicator of 0.977) and two in the Atlantic region (Figure 23). The SE stations show trend due to more recent accumulations of storage; although this does not change the fact that longer flooding is more likely for these basins, it does mean that the trend for these stations is likely not solely controlled by annual weather patterns. The two Atlantic stations with trends are an example of trends in this area disagreeing with most of Canada (see also Figures 24 and 25); Atlantic trends will be covered in more detail in section 5.11.

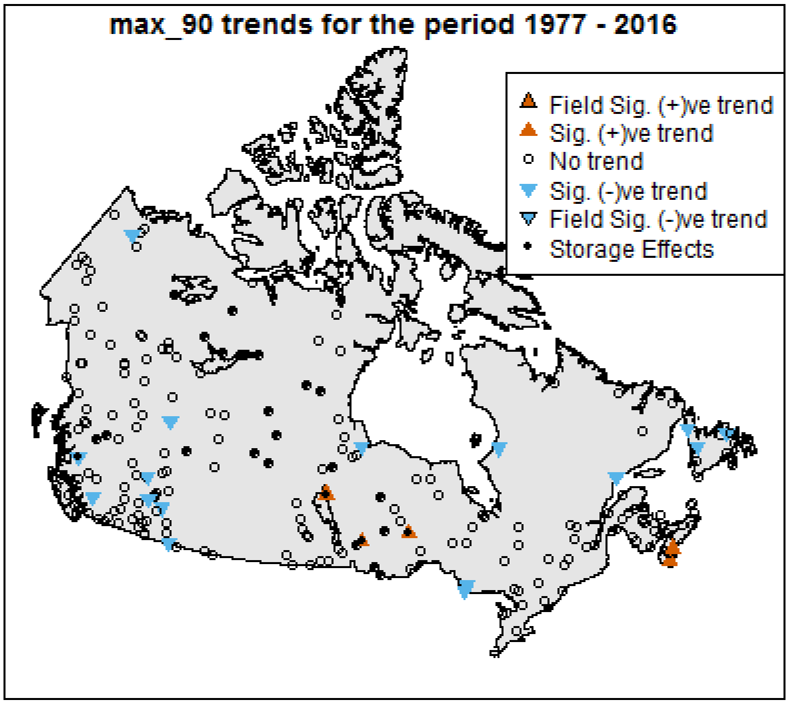


Figure 23. Local trends for renewed RHBN stations that met the quality criteria for calculating the Maximum flow averaged over 90 days.

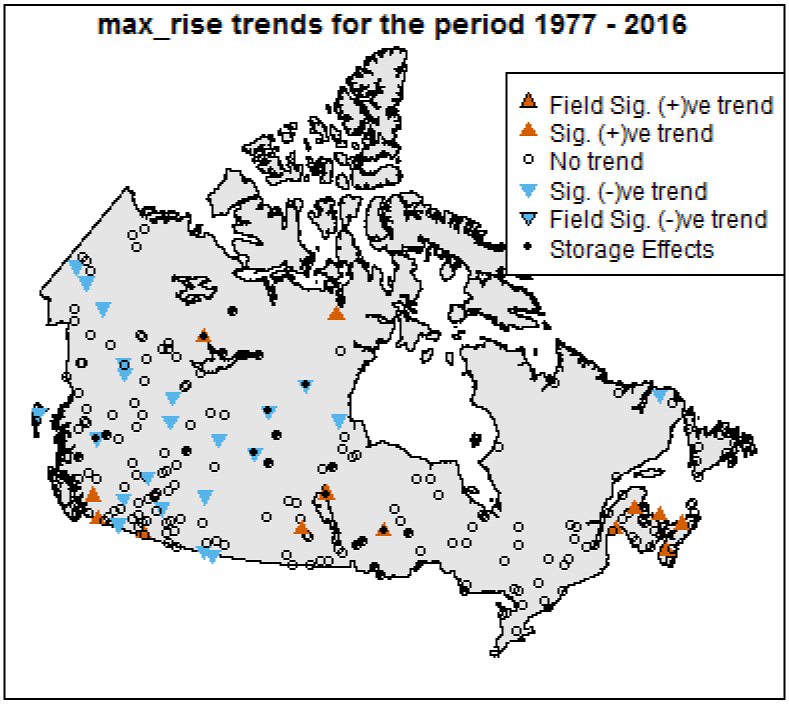


Figure 24. Local trends for renewed RHBN stations that met the quality criteria for calculating the Maximum one day rise in flow.

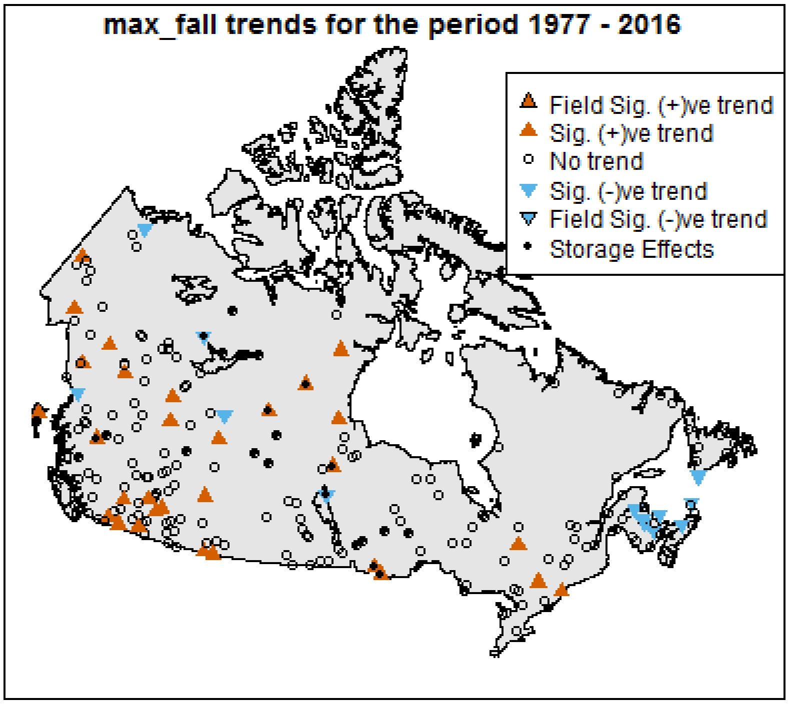


Figure 25. Local trends for renewed RHBN stations that met the quality criteria for calculating the Maximum one day fall in flow.

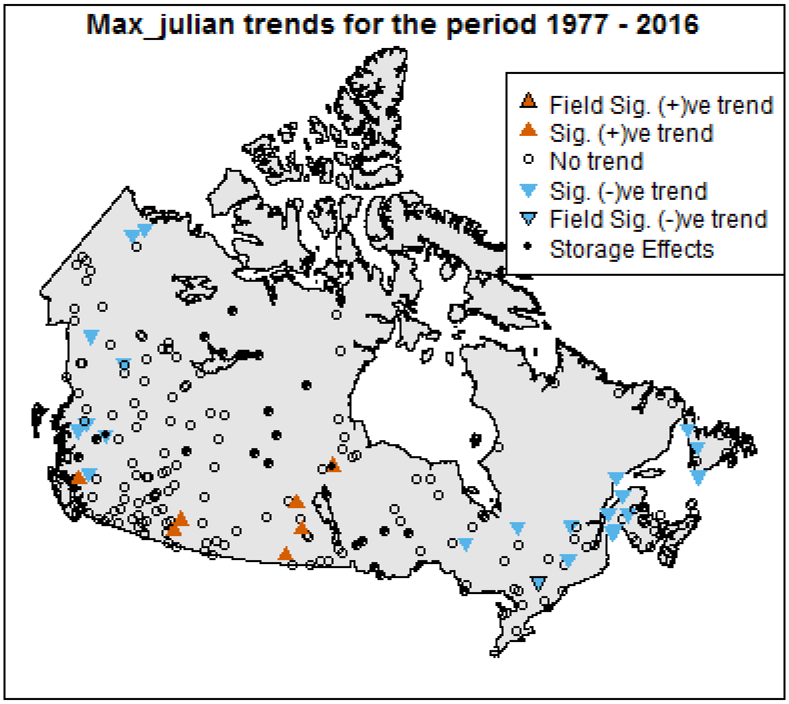


Figure 26. Local trends for renewed RHBN stations that met the quality criteria for calculating the Date of Maximum one day flow (increasing = later, decreasing = earlier).

Two more instances of a contrary cluster of trends in the Atlantic region can be found in Figures 24 and 25. Maximum one day rise is an indication of the rate of change of flow at the beginning of a flood; an increasing trend in this metric shows more rapid floods. Maximum one day fall is an indication of the rate of change of flow after a flood; a decreasing trend in this metric shows a slower return to normal flows after a flood. This is investigated further in section 5.11.

The date of maximum one day flow is earlier for most of the country except a cluster roughly in the Prairies (Figure 26). This is investigated further in section 5.12. A map of the March monthly mean is presented in Figure 27 as an example of widespread increases in early spring flows. There is only one exception to an almost universal positive trend; station 06DA004 which is an SE station with an SE indicator of 0.905. As stated previously, SE stations may not show trends that are controlled by annual weather patterns and for this station the beginning of the period happens to be in a high storage (wet) period.

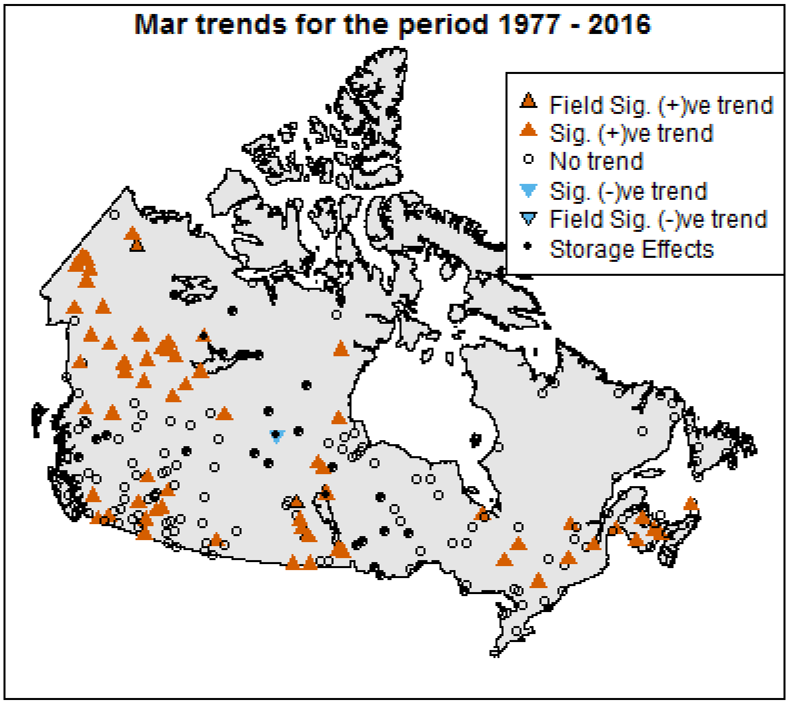


Figure 27. Local trends for renewed RHBN stations that met the quality criteria for calculating the March monthly mean flow.

5.7 Distribution of Trends against Watershed Size and Wetland Area

The distribution of significant trends over all metrics in relation to watershed size and wetland area reveals no skew nationally (Figure 28). Figure 29 shows that decreasing trends in August mean flow skew towards lower wetland area. Similar figures to Figure 29 were created for each ecoregion, but likewise did not reveal any skew.

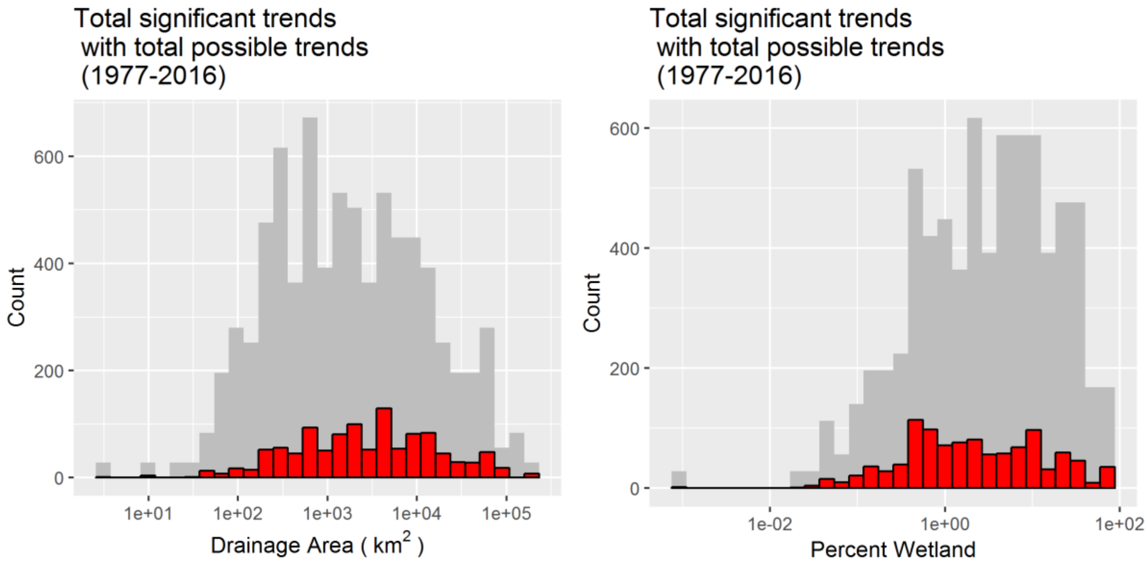


Figure 28. Total significant trend counts in red, total possible trend count in grey (28 metrics at each station). Drainage area in km^2 to the left, percent wetland to the right (log10 scale).

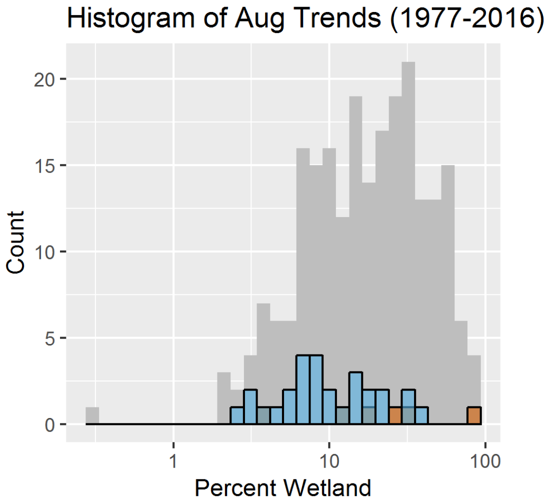
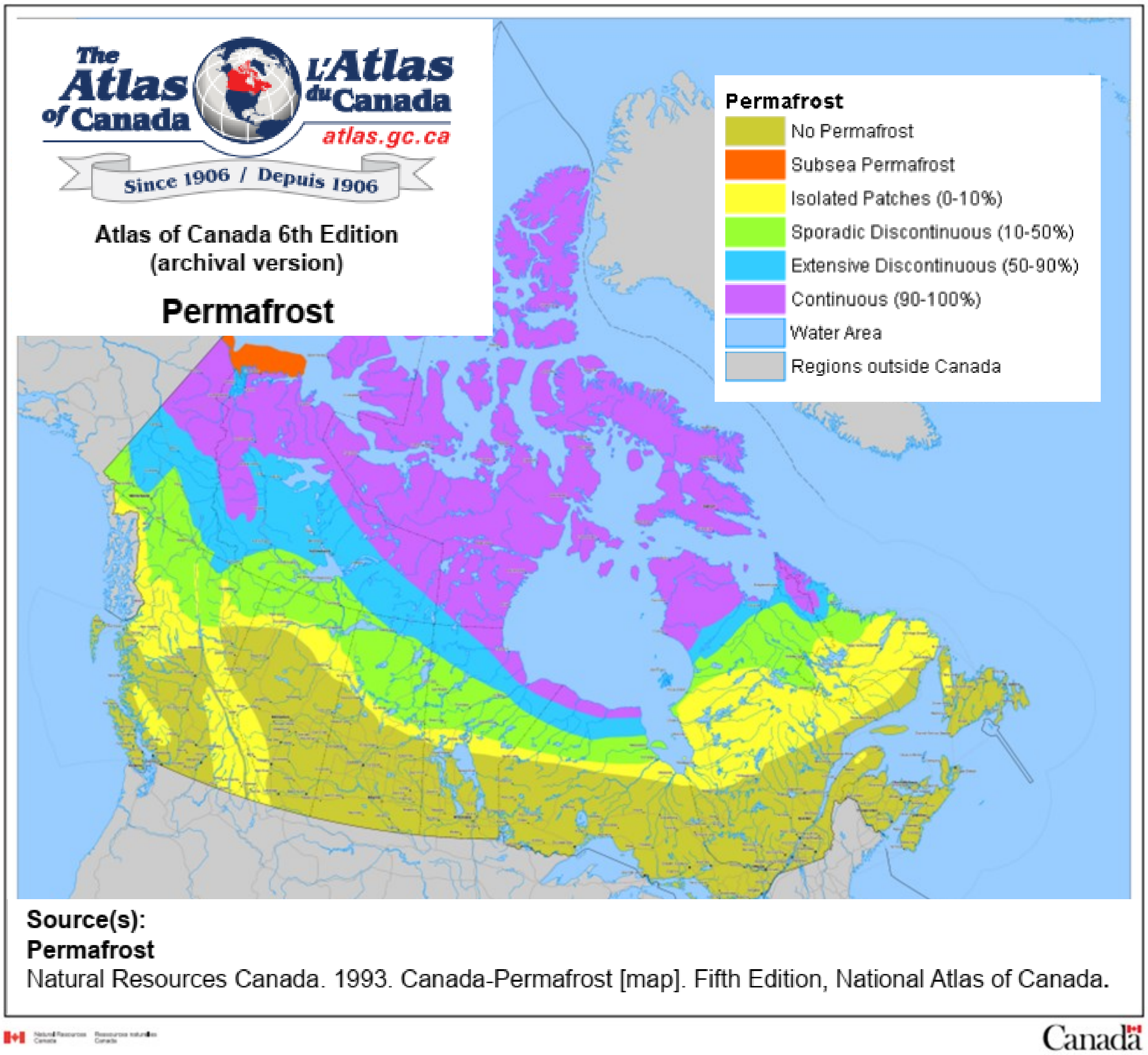


Figure 29. Histogram of significant August trends (negative in blue, positive in orange) versus percent wetland.

5.8 Canada: increasing winter flows discussion

Increasing winter/spring monthly flows (December - April) are significant on a national scale; most ecoregions also show this trend with the exception of the West Coast Mountains and Tundra ecoregions which show one or two months of increase in spring, Desert which shows none, and Great Plains which does not have sufficient winter data. Taiga has the strongest positive trends with 49-59% of stations showing local significance from December to March. Previous studies have found increasing monthly winter flows over periods ranging up to 70 years (Khaliq et al., 2008; Monk et al., 2011; Burn et al., 2012; Rood et al., 2017).



Source(s):
Permafrost
Natural Resources Canada. 1993. Canada-Permafrost [map]. Fifth Edition, National Atlas of Canada.

Figure 30. Permafrost in Canada, modified from Atlas of Canada 6th edition.

Most studies have pointed to permafrost thaw (St. Jacques and Sauchyn, 2009; Rood et al., 2017; Janowicz, 2011; Brabets and Walvoord, 2009; Bring et al., 2016) and increased groundwater connectivity (Connon et al., 2014) as the main cause of increasing winter flows in the north, although this trend is also found in areas that do not have any permafrost (Figure 30 showing extent of permafrost, Figure 31 showing January trends). Areas that would be expected to show trends related to permafrost thaw, do not show any trends (north-central Canada); perhaps this is related to the multiyear storage at these mostly SE stations or the thin overburden over the Canadian Shield (covering the central-east Canadian North).

Spence et al. (2011) found evidence of an alternative hypothesis in a study of four stations in the Taiga ecoregion; they found a change from nival to mixed regime and attribute increased winter flows to autumn rainfall events. Connon et al. (2014) show that permafrost thaw caused changes from storage to runoff generating terrains and increased seasonal thaw depth which allowed shallow subsurface flow during winter. Spence et al. (2014) likewise find with an isotope study of a small Taiga watershed that increased winter streamflow is not long-term groundwater baseflow, but extended runoff from autumn rainfall and suggest that winter rainfall could also be supplementing winter streamflows in larger watersheds. Indeed, Vincent et al. (2015) show increasing fall-winter precipitation that falls increasingly as rain in the north of Canada as well as increasing temperatures which could allow more rainfall events to replenish shallow groundwater before seasonal ground freeze. Assani et al. (2012) attribute increasing winter flows in southern Quebec to aquifers recharged in spring. Vincent et al. (2015) show an increasing proportion of winter precipitation is falling as rain in southern ON-QC over 1900-2012. Earlier spring freshet and peak flows in Eastern Canada have been widely reported (Figure 26 this thesis, as well as Déry et al., 2009; Rood et al., 2008; Burn and Whitfield, 2018; Déry et al., 2011; Cunderlik and Ouarda, 2009; Burn and Whitfield, 2016) and could help explain the widespread increases in early spring flows (March and April). Increasing winter monthly flows in the Atlantic are not continuous across the season and are discussed further in section 5.11.

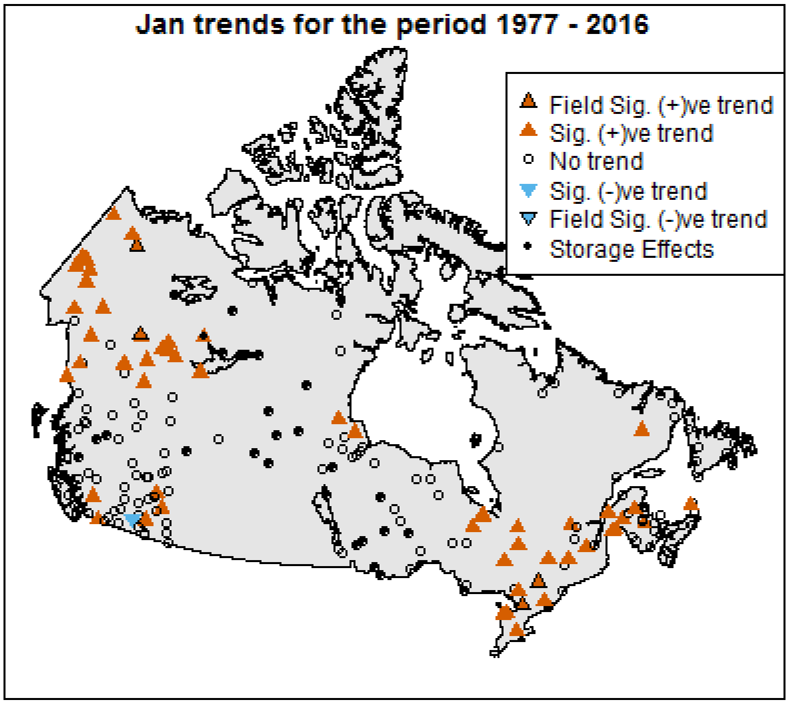


Figure 31. Local trends for renewed RHBN stations that met the quality criteria for calculating the January monthly mean flow.

5.9 Canada: increasing minimum flows discussion

Increasing minimum flows over all windows (1-, 3-, 7-, 30-, and 90-day) are significant on a national scale; Eastern Temperate, Hudson Plain, Rockies, Tundra and Taiga all show increasing minima with Taiga again having the strongest case (over 50% of stations showing local significance for all minimum windows). The exception areas, where minimum flows are decreasing, are very specific: QC-ON along the St Lawrence River valley and south coastal BC. Figure 32 shows the number of minimum trends at each station and highlights the specific areas where negative trends are found. While there are several cases of only a few minima trends at one location (similar to Khaliq et al., 2008), there were no cases of a single location with both increasing and decreasing trends. Studies of at least 40 years that use various minimum flows and baseflow have found increasing trends in certain areas and seasons; Rivard et al. (2009) for baseflow above 55° North, Burn et al. (2012) for winter 7-day minimum, St. Jacques and Sauchyn (2009) for winter baseflow. Several studies (Burn et al., 2012; Monk et al., 2011; Burn et al., 2010; Khaliq et al., 2008) show mixed trends in various minimum metrics using current RHBN stations, but largely similar spatial distribution: decreasing trends are clustered in south coastal BC, a general area from Newfoundland to Lake Erie, and sometimes a couple in central Canada (that correspond to SE stations in this thesis). Percentages of negative and positive trends in these studies are affected by the current RHBNs lack of northern stations and seem to overstate the importance of these decreasing trends. Trends affecting all minima windows are likely to be changes to baseflow and are clustered in the north (positive), possibly related to permafrost thaw (St Jacques and Sauchyn, 2009; Connon et al., 2014; section 5.8), and south coastal BC (negative), perhaps related to reported increases in temperature (Vincent et al., 2015; O'Neil et al., 2016; DeBeer et al., 2016).

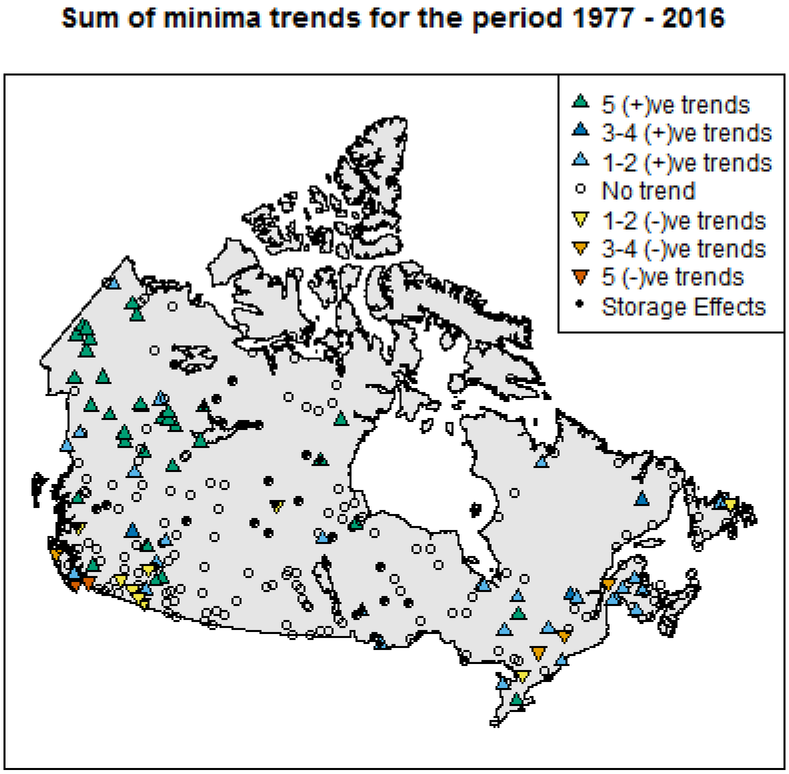


Figure 32. Sum of local trends for minima (1, 3, 7, 30, and 90 day) in renewed RHBN stations that met their respective quality criteria.

5.10 Canada: minimum flow trends associated with timing

Most ecoregions that showed increasing winter flows also showed increasing minimum flows with the exception of the Boreal ecoregion. The apparent correlation is due to the timing of minimum flows; stations with increasing minimum flow trends typically occurred in the winter and those with decreasing minimum flows typically occurred in the late summer and fall (Figure 33). There are two different mechanisms for these low flows; baseflow/groundwater supply in winter when there is little/no liquid precipitation, or low precipitation and/or high evapotranspiration in summer (flows are also generally reliant on groundwater here, but there are ecological abstractions in this case).

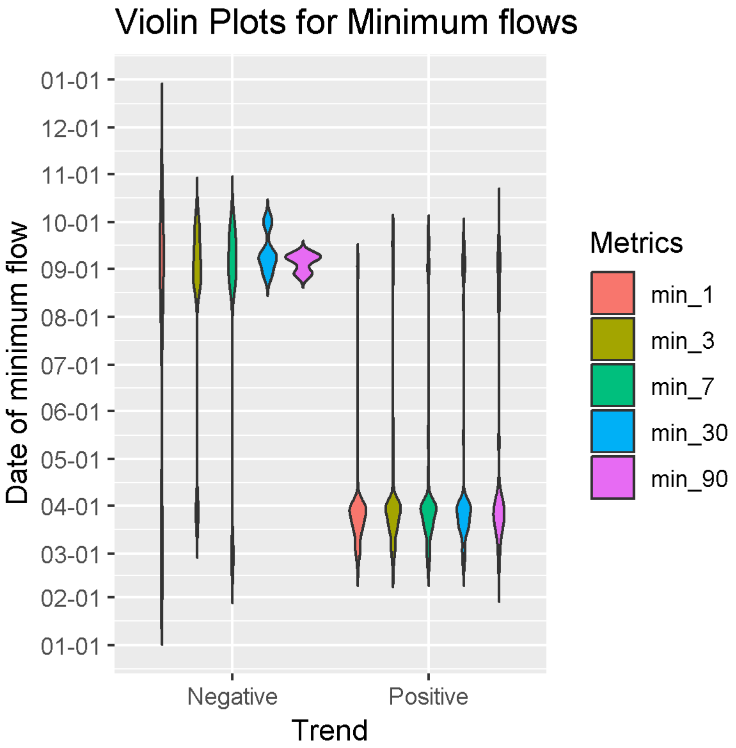


Figure 33. Violin plot of negative and positive trend distributions against the date of regime minimum of the corresponding station.

Min_julian trends (based on min1) are almost all later in the year, similar to Monk et al. (2011) over 1970-2005. Ehsanzadeh et al. (2010) and Burn et al. (2010) examined timing of 7-day minimum flow and found mostly earlier timing, and almost all winter low flows showed earlier timing over 1957-2006 for Burn et al. (2010). Perhaps minimum timing trends in this thesis disagree because the timing is based on min1 instead of min7; min1 timing trends would potentially have more scatter and indeed not many trends were identified, even in the longer periods (significant trends for 40 year period shown in Figure 34; 4 later, 1 earlier for 60 year; 2 later for 80 year; none in 100 year).

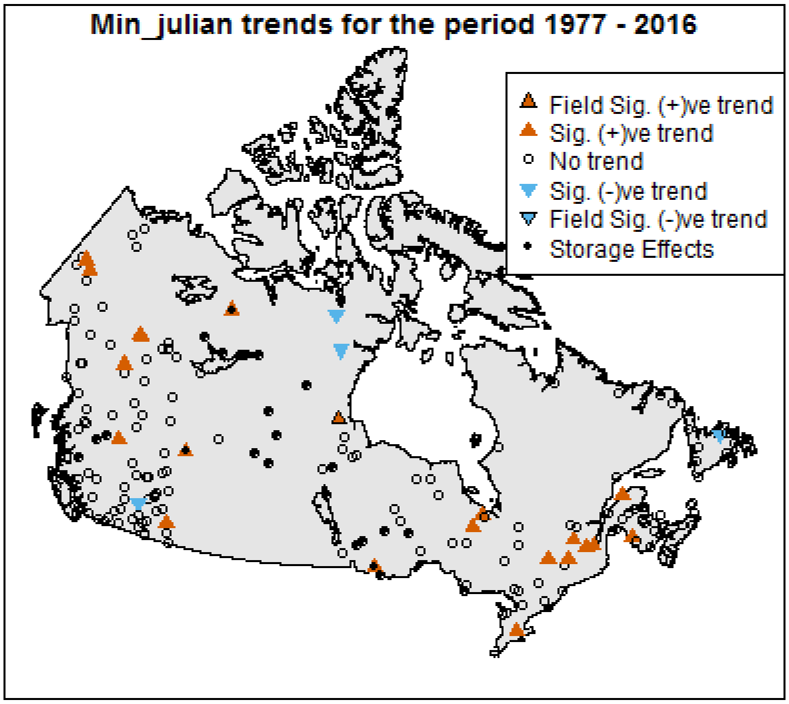


Figure 34. Local trends for renewed RHBN stations that met the quality criteria for calculating the date of annual minimum flow (Min_julian). Positive trend means later timing. Negative means earlier timing.

5.11 Atlantic Region

The Atlantic region showed contrary trends to most of Canada in several categories: decreasing max fall, increasing max over 30 and 90 days, increasing min over 90 days (trend maps for 1977-2016 in Appendix D). This cluster does not seem to agree with the ecoregion divisions in the area (convoluted division between Boreal and Eastern Temperate, Figure 2) but may be explained by the generally higher and nearly seasonally uniform precipitation in the area due to the Atlantic Ocean (Figure 35).

Results have been recompiled into new summary tables for the Atlantic region for the 40, 60, 80, and 100 year periods ending in 2016 (Tables 11 and 12). The Atlantic region contains 11 weak annual pattern stations according to the SE indicator (section 5.3, Figure 18) and so Table 12 displays the results for only strong annual pattern stations.

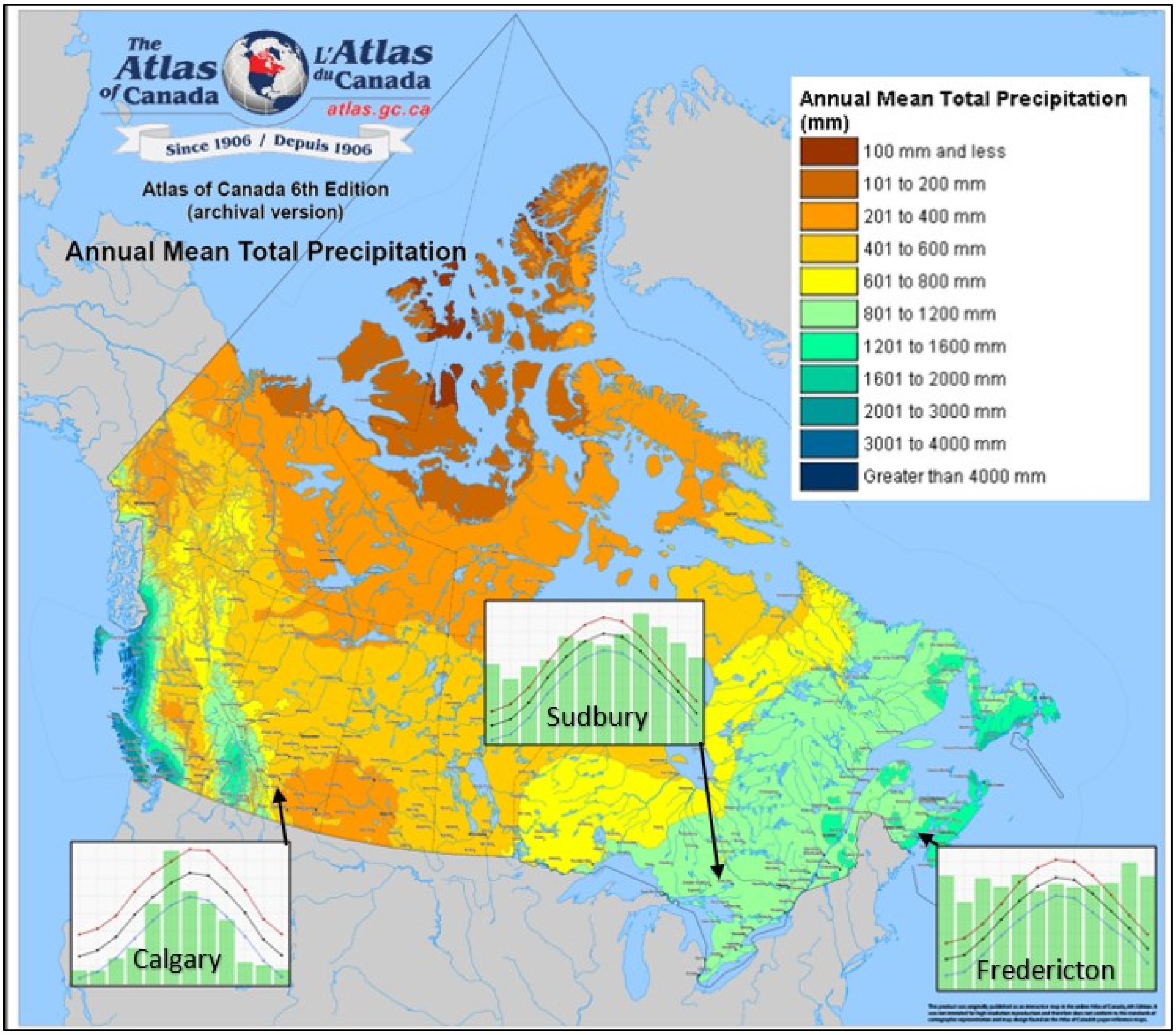


Figure 35. Annual mean total precipitation modified from Atlas of Canada 6th edition. Insets are local monthly precipitation norms (1981-2010).

Table 11. Summary results table in a similar format to Table 6 for Atlantic region over four time periods (40, 60, 80, and 100 years).

Atlantic Metrics	1977-2016	1957-2016	1937-2016	1917-2016
Jan	13/0 (38)	12/0 (24)	0/0 (9)	14/0 (7)
Feb	5/3 (38)	8/0 (24)	22/0 (9)	14/0 (7)
Mar	13/0 (38)	21/0 (24)	33/0 (9)	43/0 (7)
Apr	**29**/3 **(38)**	**42**/0 **(24)**	**33**/11 **(9)**	**29**/0 **(7)**
May	0/24 (38)	0/17 (24)	0/**22 (9)**	0/**29 (7)**
Jun	0/**16 (38)**	0/**17 (24)**	0/**22 (9)**	0/0 (7)
Jul	8/0 (38)	8/0 (24)	**11**/0 **(9)**	**14**/0 **(7)**
Aug	3/3 (38)	**4**/4 **(24)**	**11**/0 **(9)**	**14**/0 **(7)**
Sep	3/0 (38)	4/0 (24)	0/0 (9)	0/0 (7)
Oct	8/0 (38)	8/0 (25)	0/0 (9)	0/0 (7)
Nov	11/0 (38)	8/0 (25)	22/0 (9)	**29**/0 **(7)**
Dec	13/0 (38)	20/0 (25)	**44**/0 **(9)**	**57**/0 **(7)**
Annual	5/0 (37)	8/0 (24)	11/0 (9)	14/0 (7)
Max_julian	0/14 (37)	0/21 (24)	0/**22 (9)**	0/0 (7)
Min_julian	3/3 (37)	0/4 (24)	0/0 (9)	0/0 (7)
max_1	**5**/5 **(37)**	4/4 (24)	0/0 (9)	0/0 (7)
max_3	3/3 (38)	0/4 (25)	0/0 (9)	0/0 (7)
max_7	0/3 (38)	0/4 (25)	0/0 (9)	0/0 (7)
max_30	3/**8 (38)**	4/**8 (25)**	11/**11 (9)**	14/**29 (7)**
max_90	5/8 (38)	8/**12 (25)**	22/11 (9)	29/0 (7)
min_1	0/3 (37)	0/0 (24)	0/0 (9)	0/0 (7)
min_3	3/0 (38)	4/0 (25)	0/0 (9)	0/0 (7)
min_7	5/0 (38)	12/0 (25)	11/0 (9)	14/0 (7)
min_30	8/0 (38)	12/0 (25)	11/0 (9)	14/0 (7)
min_90	**13**/0 **(38)**	**16**/0 **(25)**	**11**/0 **(9)**	**14**/0 **(7)**
max_rise	11/0 (37)	0/0 (24)	0/0 (9)	0/0 (7)
max_fall	0/**22 (37)**	0/**25 (24)**	0/11 (9)	0/14 (7)
Annual_range	5/5 (37)	4/4 (24)	0/0 (9)	0/0 (7)

Table 12. Summary results table in a similar format to Table 6 for only strong annual pattern Atlantic region stations over four time periods (40, 60, 80, and 100 years).

Atlantic (strong annual pattern) Metrics	1977-2016	1957-2016	1937-2016	1917-2016
Jan	17/0 (29)	**20**/0 **(15)**	0/0 (5)	25/0 (4)
Feb	7/3 (29)	13/0 (15)	**40**/0 **(5)**	**25**/0 **(4)**
Mar	17/0 (29)	33/0 (15)	**60**/0 **(5)**	**75**/0 **(4)**
Apr	**31**/0 **(29)**	**53**/0 **(15)**	**60**/0 **(5)**	**50**/0 **(4)**
May	0/24 (29)	0/**13 (15)**	0/**20 (5)**	0/**25 (4)**
Jun	0/14 (29)	0/13 (15)	0/**20 (5)**	0/0 (4)
Jul	7/0 (29)	**7**/0 **(15)**	**20**/0 **(5)**	**25**/0 **(4)**
Aug	3/0 (29)	**7**/0 **(15)**	**20**/0 **(5)**	**25**/0 **(4)**
Sep	0/0 (29)	0/0 (15)	0/0 (5)	0/0 (4)
Oct	3/0 (29)	6/0 (16)	0/0 (5)	0/0 (4)
Nov	10/0 (29)	6/0 (16)	20/0 (5)	**25**/0 **(4)**
Dec	14/0 (29)	**25**/0 **(16)**	**60**/0 **(5)**	**75**/0 **(4)**
Annual	0/0 (28)	0/0 (15)	0/0 (5)	0/0 (4)
Max_julian	0/11 (28)	0/20 (15)	0/**20 (5)**	0/0 (4)
Min_julian	4/0 (28)	0/0 (15)	0/0 (5)	0/0 (4)
max_1	**7**/4 **(28)**	7/0 (15)	0/0 (5)	0/0 (4)
max_3	3/0 (29)	0/0 (16)	0/0 (5)	0/0 (4)
max_7	0/0 (29)	0/0 (16)	0/0 (5)	0/0 (4)
max_30	0/3 (29)	0/0 (16)	0/0 (5)	0/25 (4)
max_90	3/3 (29)	6/6 (16)	20/0 (5)	25/0 (4)
min_1	0/4 (28)	0/0 (15)	0/0 (5)	0/0 (4)
min_3	3/0 (29)	6/0 (16)	0/0 (5)	0/0 (4)
min_7	3/0 (29)	12/0 (16)	20/0 (5)	**25**/0 **(4)**
min_30	7/0 (29)	12/0 (16)	20/0 (5)	25/0 (4)
min_90	**17**/0 **(29)**	**25**/0 **(16)**	**20**/0 **(5)**	**25**/0 **(4)**
max_rise	14/0 (28)	0/0 (15)	0/0 (5)	0/0 (4)
max_fall	0/**29 (28)**	0/**40 (15)**	0/20 (5)	0/25 (4)
Annual_range	7/4 (28)	7/0 (15)	0/0 (5)	0/0 (4)

Trends in monthly means and timing of maximum flow are consistent with an earlier spring melt (increasing early spring months, decreasing late spring months, and earlier maximum) that has been reported by several studies (Déry et al., 2009; Rood et al., 2008; Déry et al., 2011; Burn and Whitfield, 2018; Cunderlik and Ouarda, 2009; Burn and Whitfield, 2016). These trends, if correlated in time with the decreasing maximum fall, could indicate more long-lasting flooding associated with an earlier spring freshet. Curiously, increasing trends in November and December do not continue in other winter months, indicating that increased flows are due to a short-term change, perhaps due to increasing autumn average and maximum precipitation (Vincent et al., 2015; Tan et al., 2017). The few increasing annual trends are from weak annual pattern (pluvial) stations (present in Table 11, absent in Table 12) and may be an extension of the northeastern US region of increasing annual flows reported in Rice et al. (2015) for 1940-2009, again, likely related to increasing precipitation found for spring through autumn (Vincent et al., 2015).

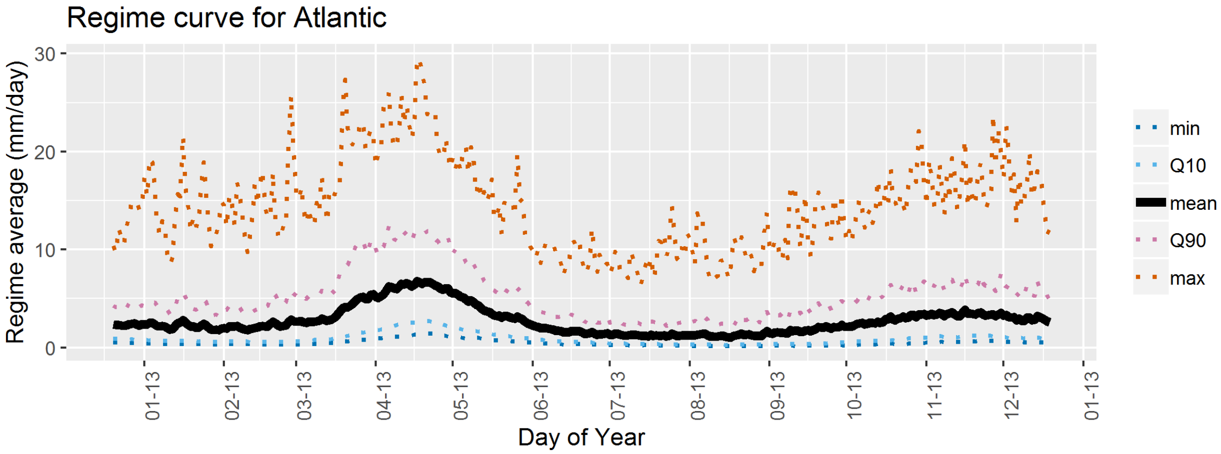


Figure 36. Regime curves averaged over Atlantic region and normalized by drainage area (giving flows of mm/day).

Trends found in max30 and max90 (both increasing and decreasing) without trends in smaller maximum windows appear to be related to weak annual pattern (pluvial) stations (present in Table 11, absent in Table 12). Although they could reflect changes in spring freshet (the primary sustained high flow period), they are more likely related to rainfall changes in the secondary regime peak in late fall (Figure 36) and confirmed increasing maximum precipitation events in autumn (Tan et al., 2017). Information on the timing of the larger window maximums would help answer this question. Increasing trends in min90 are likewise not mimicked in lower minimum windows but are present in both tables indicating this is not an issue with weak annual pattern (pluvial) stations. This precludes a widespread increase in minimum flow (which would be present in all minimum windows) and must be caused by more frequent and/or higher magnitude rainfall events in the summer/early fall (low flow season for Atlantic region, see Figure 36). This is confirmed by increasing autumn maximum precipitation (Tan et al., 2017) and increasing average precipitation in spring through autumn (Vincent et al., 2015).

5.12 Great Plains Region

The inconsistency between decreasing annual flow and increasing monthly flow trends reported in section 5.5 may be resolved by subdividing the group. Using CEC Level II ecoregions (as opposed to Level I) would divide the Great Plains into the Semi-Arid Prairies to the West with a mean annual precipitation of 250-550 mm, and the Temperate Prairies to the East with a mean annual precipitation of 450-700 mm (Wiken et al. 2011, Figure 37). Using these divisions generally would better cluster trends, however Annual trends are still separated into two groups (Figure 37). In addition to the two Level II ecoregions mentioned above, Figure 37 shows a small mountainous area in southern AB-SK called Cypress Uplands. This area collects more precipitation than the surrounding prairies (325-450 mm annually) and contains flora associated with the Rockies to the west (Wiken et al. 2011). Currently, Cypress Uplands is included in the Rockies Level I ecoregion, but due to its relatively low annual precipitation, perhaps it is better grouped with the Temperate Prairies. MacCullough and Whitfield (2012) grouped Great Plains stations based on streamflow characteristics only and found three groups; (1) in the foothills of the Rockies, (2) generally the West Prairies, and (3) the East Prairies grouped with Cypress Uplands. Using MacCullough and Whitfield (2012) groups 2 and 3 would cluster the decreasing April and Annual means together in the West; increasing monthly means in the East. Presumably those in the West are subject to the rain shadow effect from the Rocky Mountains and those in the East have other acting precipitation mechanisms.

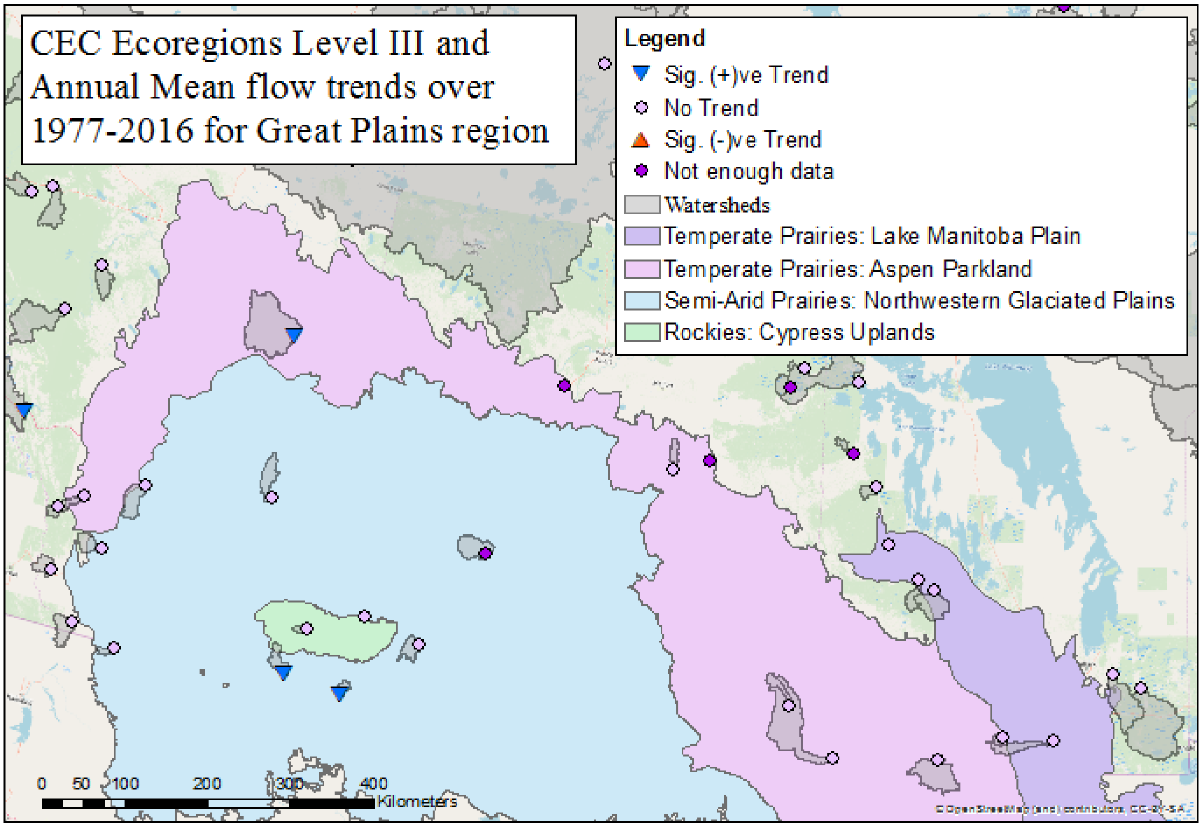


Figure 37. CEC Level III ecoregions and local mean annual flow trends for stations meeting quality criteria between 1977-2016.

Vincent et al. (2015) and DeBeer et al. (2016) show strong decreasing winter precipitation in the West and increasing precipitation in the East (MB and ON) for Spring-Autumn. Likewise, Tan et al. (2017) show increased maximum precipitation in the East (MB and ON) for Spring-Autumn.

A large part of the Great Plains region is characterized by features called Prairie Potholes and characterized by semi-permanent and seasonal wetlands that may be part of the non-contributing area (Shook and Pomeroy, 2011). McKenna et al. (2017) find evidence of ecohydrological shift in a North Dakota example of the Prairie Pothole region. They suggest the landscape is potentially at the maximum saturation seen this century with higher groundwater level, increased spring runoff, faster runoff response, and significant increases in ponded area. However, this may not be found in watersheds affected by agriculture; Dumanski et al. (2015) found that farmers have increased drainage efforts in recent wet years to improve agricultural yield and have sharply reduced the number of ponds.

5.13 Mountainous West Region

Previous research on the western mountains of Canada has shown differing responses of watershed with or without glaciers (Stahl et al., 2006; Stahl and Moore, 2006; Moore et al., 2009). As such, stations within BC and YT (mostly Rockies ecoregion with some Taiga and Boreal), excluding watersheds entirely within the West Coast ecoregion, were collected into glacier and non-glacier groups based on reported glacier presence from Paznekas and Hayashi (2016) and Atlas of Canada (2010) for a summary table (Table 13).

The Glacier group shows several consistent trends. Decreasing summer flows are consistent with previous studies (Déry et al., 2009; Rood et al., 2008) and stronger decreases in glacier compared to non-glacier watersheds are consistent with Stahl et al. (2006). Summer decreases may be attributed to widespread glacier decline (Ommanney, 2002; Moore et al., 2009) that had previously supplemented summer low flows (Moore et al., 2009; Marshall et al., 2011). Increasing summer trends in the shortest summer period may simply be an indication of the stage of glacier decline where warm and dry conditions related to recent positive PDO (since around 1977) would initially increase summer flows with faster glacier melt before ultimately decreasing (Moore et al. 2009; Whitfield et al., 2010). Moore et al. (2009) state that most watersheds have passed the initial stage of decline, except perhaps those in NW BC and Yukon, where no August decreases are evident over 1977-2016 (Figure in Appendix D). Decreasing maxima over all windows are almost all field significant for the Glacier group while there is little consistent trend for the No Glacier group, indicating that glacial flows must be contributing to maximum flows. Increasing minima over all windows are associated with winter increases for both groups (sections 5.8-5.10). The three difference-based metrics indicate reduced flow range, less reactive floods, and a slower flood recession for the Glacier group and more mixed results for the No Glacier group.

Table 13. Summary results table in a similar format to Table 6 for Mountainous West region stations with and without glaciers over three time periods (40, 60, and 80 years).

	Glacier			No Glacier		
Metrics	1977-2016	1957-2016	1937-2016	1977-2016	1957-2016	1937-2016
Jan	**39**/0 **(18)**	**29**/0 **(7)**	**50**/0 **(2)**	**33**/1 **(67)**	**26**/4 **(23)**	17/0 (6)
Feb	**33**/0 **(18)**	14/0 (7)	0/0 (2)	**39**/3 **(67)**	**33**/4 **(24)**	0/**20 (5)**
Mar	**37**/0 **(19)**	**33**/0 **(9)**	**33**/0 **(3)**	**40**/0 **(81)**	**40**/0 **(25)**	**33**/0 **(6)**
Apr	26/0 (19)	38/0 (8)	**40**/0 **(5)**	**22**/5 **(82)**	**34**/7 **(29)**	12/12 (8)
May	**16**/0 **(19)**	**30**/0 **(10)**	20/0 (5)	8/4 (84)	**7**/10 **(29)**	**12**/12 **(8)**
Jun	6/0 (18)	**10**/0 **(10)**	0/0 (5)	7/**7 (89)**	10/3 (30)	11/0 (9)
Jul	6/11 (18)	0/20 (10)	0/**20 (5)**	0/6 (90)	0/6 (32)	0/0 (8)
Aug	11/**37 (19)**	0/**50 (10)**	0/**40 (5)**	0/10 (88)	0/15 (34)	0/**11 (9)**
Sep	16/**11 (19)**	10/**20 (10)**	0/**40 (5)**	11/9 (88)	**6**/12 **(34)**	11/22 (9)
Oct	26/5 (19)	0/10 (10)	0/25 (4)	14/8 (86)	7/13 (30)	0/12 (8)
Nov	**28**/0 **(18)**	11/0 (9)	0/0 (5)	23/1 (71)	10/3 (29)	**17**/0 **(6)**
Dec	17/0 (18)	12/0 (8)	0/0 (3)	**29**/1 **(69)**	**19**/4 **(27)**	0/**17 (6)**
Annual	6/6 (18)	0/14 (7)	0/**50 (2)**	9/4 (81)	0/9 (23)	0/20 (5)
Max_julian	6/6 (18)	0/14 (7)	0/0 (2)	2/9 (81)	0/13 (23)	0/20 (5)
Min_julian	0/6 (17)	0/0 (7)	0/0 (2)	14/0 (66)	0/0 (22)	0/0 (4)
max_1	0/33 (18)	0/**57 (7)**	0/**50 (2)**	5/7 (81)	4/**13 (23)**	20/0 (5)
max_3	0/**33 (18)**	0/**40 (10)**	0/**50 (4)**	0/8 (77)	0/6 (33)	0/0 (7)
max_7	0/**33 (18)**	0/**44 (9)**	0/**67 (3)**	0/9 (75)	0/12 (33)	0/0 (7)
max_30	0/**33 (18)**	0/**50 (8)**	0/**67 (3)**	0/8 (74)	0/12 (32)	0/**14 (7)**
max_90	0/**17 (18)**	0/**38 (8)**	0/**67 (3)**	0/5 (74)	0/6 (32)	0/14 (7)
min_1	**41**/6 **(17)**	**43**/14 **(7)**	**50**/0 **(2)**	**36**/3 **(64)**	**33**/0 **(21)**	0/0 (4)
min_3	**33**/0 **(18)**	**40**/0 **(10)**	**33**/0 **(3)**	**35**/1 **(68)**	**30**/0 **(30)**	0/0 (7)
min_7	**39**/0 **(18)**	**44**/0 **(9)**	**33**/0 **(3)**	**36**/3 **(67)**	**27**/3 **(30)**	0/0 (7)
min_30	**39**/0 **(18)**	**50**/0 **(8)**	**33**/0 **(3)**	34/1 (67)	**24**/3 **(29)**	0/0 (7)
min_90	**33**/0 **(18)**	**38**/0 **(8)**	**33**/0 **(3)**	**36**/0 **(67)**	**27**/0 **(30)**	0/0 (7)
max_rise	0/11 (18)	0/29 (7)	0/**50 (2)**	4/16 (81)	4/35 (23)	**20**/20 **(5)**
max_fall	**22**/0 **(18)**	**57**/0 **(7)**	**50**/0 **(2)**	**17**/4 **(81)**	**30**/0 **(23)**	60/0 (5)
Annual_range	0/35 (17)	0/**57 (7)**	0/**50 (2)**	3/6 (66)	5/**14 (22)**	**25**/25 **(4)**

Trends affecting both the Glacier and No Glacier groups could indicate a more widespread atmospheric influence. Both groups show increasing winter and spring monthly flows and minimum flows (Table 13), consistent with previous results table (Table 10 for Rockies, Taiga and Boreal; details in sections 5.8-5.10). This may be attributed to a restriction of the duration of typical winter conditions: precipitation is increasingly composed of rain (Vincent et al., 2015); annual temperature, especially during winter, has risen, with the most extreme increases in the north (Vincent et al., 2015 and DeBeer et al., 2016) and minimum summer temperature has increased (O'Neil et al., 2016); and snowcover duration has declined (Vincent et al., 2015 and DeBeer et al., 2016, amongst others).

Streamflow trends in this region have been shown to have a strong correlation to the ~60 year periodicity of the PDO (Whitfield et al., 2010; Rood et al., 2005; Burn et al., 2004; Burn, 2008; Brabets and Walvoord, 2009; St. Jacques et al., 2010). Care was taken in the above analysis to avoid the influence of changing PDO phase: atmospheric studies cited used a minimum of 60 years of data and streamflow trends from this thesis appear to be consistent between the 40, 60, and 80 year periods (Table 13).

Chapter 6 Conclusions and Recommendations

6.1 Conclusions and Recommendations

This thesis developed a new set of selection criteria based on a review of other RHNs (e.g., US, UK, Australia) to renew Canada's RHBN and improve its coverage of non-atmospheric factors affecting streamflow such as geographic location, ecological factors as represented by ecoregions, and watershed characteristics (e.g., watershed size). The renewed RHBN has more stations overall as well as more northerly stations, especially in underrepresented ecoregions such as the Tundra, the Taiga and the Hudson Plain. Justifications for membership decisions and limits of record years appropriate for climate studies may be found in Appendix A. The renewed RHBN continues to avoid anthropogenic influences and is thus appropriate for detecting climate-related changes in streamflow.

Climate-related trends in streamflow were identified using the renewed RHBN and aggregated nationally, by ecoregion, and by special groups identified when analyzing the results. A definition for SE is developed and used to modify national and ecoregion groups. Concurrent atmospheric and long-term ice trends are associated with identified trends.

Presented below are conclusions as well as recommendations collected over the course of this thesis for the renewed RHBN and the subsequent trend detection study.

6.1.1 Renewed RHBN

The final list of 279 renewed RHBN stations (Appendix A) is appropriate for climate trend studies. Every reasonable effort has been made to control for direct human impacts through land use maps, data quality screening, data consistency screening, and, where needed, historical searches. However, there are improvements to this list that would benefit from the institutional expertise and continuity of the Water Survey of Canada. Recommendations for the WSC are presented below.

6.1.1.1 Regional Vetting

While there was a quality control step in the development of the Renewed RHBN for possible historical direct human impacts (see section 3.3.1), this was only a brief search and only on those stations that had been flagged during the search for abrupt hydrometric changes (section 2.2.2.2.3). The regional Water Survey of Canada offices would have more complete knowledge of the possible human impacts on a watershed, as well as the local sources to confirm this impact. If this legacy information is lacking, perhaps FlowScreen could be used to help identify stations that require more research. A vetting period for the regional WSC offices is recommended.

6.1.1.2 Justifications

To increase confidence in the RHBN list, stations that apparently disregard basic rules of the RHBN (such as “no regulation”) need to have accessible justifications. Any recommended data limits would also need justification. The recommended “RHBN_start”, “RHBN_end”, and “Notes” columns presented in section 3.1 are given in Appendix A for the Renewed RHBN list from this thesis.

6.1.1.3 Dissemination to Researchers

An updated RHBN list is of no use if researchers and policy makers do not use it. There does not seem to be as much use of the current RHBN as there should be. To help with this, may we suggest a news box directly on the page where HYDAT is downloaded when these data are published. This page is visited by most water professionals and a small explanation of the RHBN could increase its use.

6.1.1.4 Scheduled RHBN renewal

Regular network renewal and re-evaluation is paramount to maintain the quality of the RHBN. To again take advantage of the land use maps created by Agriculture and Agri-Food Canada, RHBN renewal is recommended just after 2020, when the land use maps for that year are published.

6.1.1.5 Continuity

Although regular (perhaps every decade) renewal of the RHBN is recommended, emphasis must be placed on continuity of the current network. Trends may change with increasing record length when short-term processes (e.g., glacier wastage) or climatic oscillations (e.g., PDO) mask the long-term, climate-related, streamflow trends. Long-term streamflow records provide the context for more detailed basin-scale studies of hydrological processes.

6.1.1.6 Storage Effects

The storage effects noted in section 3.3.2 and 4.2.3 can violate the assumptions made in most trend studies, which tend to focus on annual values, as these may be artificially deflated or inflated by previous years’ storage. For example, the trend for peak flow after many years of storage accumulation in a station with strong ‘storage effects’ should not be compared to a trend in a station without; the former is responding to years of excess flows, while the latter is likely only responding to annual atmospheric or watershed changes. The scale of changes needed to effect trends in these two categories is different.

It is useful to identify stations that have multiyear storage effects before conducting trend studies. A simple automated screening for SE is presented (section 4.2.3) and can be used for subsequent trend studies. An appropriate place for this information would be the "Notes" column (section 3.1 and Appendix A), although whether or not this is the purview of the Water Survey of Canada is debatable and concerns about SE stations may be better left to researchers' discretion.

6.1.2 Trends

Streamflow data from a renewed RHBN over periods ranging from 40 to 100 years were analyzed using a MK BBS local test for trend and Walker's test for field significance. Local tests were grouped into country-wide and ecoregions, as well as groups without storage effect stations, for new field significance tests.

Increasing minimum flows occurred almost exclusively in the winter months and were consistent over all window lengths for northern stations subject to permafrost changes and possibly autumn rainfall. Trends of decreasing minimum flows were localized to southern BC and south ON-QC. Previous studies showed similar spatial distributions of these trends, but with the current RHBN's lack of northern stations, may have overstated the importance of decreasing minimum flows when expressed as percentage of streamflows with trend. Timing of streamflow metrics would help in interpretation (see section 6.1.2.3). SE stations generally did not show many trends and thus did not affect trend counts or field significance for most metrics (Table 10), however, weak annual pattern (pluvial) stations did show different trends (Table 11 and 12, section 5.11). Mountainous watersheds with glaciers show mostly declining streamflow (i.e. maximum windows and summer months), indicating that their glaciers have suffered so much wastage that they are no longer supplementing summer flows, a process described in Moore et al. (2009).

Presented below are recommendations for future trend detection studies.

6.1.2.1 Groups

Trend detection studies may further limit the number of factors affecting flow by grouping together similar watersheds. Where national trends were never unidirectional (increasing or decreasing, Table

6 and 8), CEC Level I Ecoregions largely provided groupings with consistent trend direction (section 5.5) with the exception of ecoregions with large precipitation differences (rain shadow on the Great Plains or the Atlantic Ocean in the East). Grouping stations based on similar ecohydrology is recommended; CEC Level I Ecoregions are acceptable, but additional groups such as Atlantic (section 5.11) and dividing the Great Plains (section 5.12) is advised. Identifying key watershed characteristics, such as the presence of glaciers, has also proven to be useful.

6.1.2.2 Oceanic Oscillations

Oceanic oscillations may have strong correlations with streamflow metrics (see Mortsch et al., 2015, for a Canadian summary). Chen and Grasby (2009) note that evaluation periods should not begin or end at an extreme of a correlated oscillation and would ideally cover three full oscillations. This thesis only based evaluation periods on the longest and most recent available data, not avoiding oscillation effects. It would be difficult to account for oscillations on a national scale, but this may be appropriate on a regional or group scale (suggested groups in section 6.1.2.1).

6.1.2.3 Metrics

Metrics should be chosen with the intention of allowing easy attribution. While there were some important insights from the chosen metrics, interpretation was sometimes hampered by ambiguous timing of events and the metrics did not cover some aspects of streamflow (e.g., frequency of high flows, recession curves, baseflow, etc.).

Minimum and maximum flows over different windows were assumed to respect the timing found in the regime curve (which may be ambiguous, see section 5.11). The timing of these flows should be recorded so changes may be associated with the proper seasonal effects (e.g., spring melt or fall rainfall for maxima, summer or winter ‘dry’ season for minima). Regime curves normalized by drainage area and averaged over similar groups (giving flows of mm/day, Figure 20 and 36) could be useful for establishing seasons that limit the processes affecting flow. For example, a peaks-over-threshold approach over the annual data excluding spring melt would yield important information about rainfall-driven events. Spring melt could potentially be defined as the date that runoff exceeds 1.5 times average of last 16 days (onset of spring freshet; Burn et al, 2004 – Liard River study, and Monk et al., 2012) and maintained for a minimum amount of time defined by the regime curve, before returning to this threshold value (the duration of this sustained flow perhaps providing more pertinent information).

Metrics not included in this thesis could have provided additional information: peaks-over-threshold shows the frequency of events, recession curves may show drainage rates or sensitivity to storage, and baseflow could indicate groundwater influences. Sensitivity to storage (Berghuijs et al., 2016) may be particularly useful for areas of Canada with SE stations, Prairie Potholes (where the contributing area varies significantly), or northern areas with many lakes (Spence et al., 2014).

6.1.2.4 Scale of Trends

While this thesis assessed the statistical significance of trends, an idea of their magnitude could provide useful information on the severity of streamflow changes. The Theil-Sen slope (section 1.5.1) is widely used (DeBeer et al., 2016, Rivard et al., 2009; Tan et al., 2017; Su et al., 2018) and is recommended.

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Appendix A: Renewed RHBN list

Station	**Notes**	**RHBN_start**	**RHBN_end**	**Rationale**
01AD002				
01AD003				
01AJ010				
01AK001				
01AP002				
01AQ001				
01BC001				
01BE001				
01BH005				
01BJ003				
01BL002				
01BO001				
01BP001				
01BQ001				
01BS001				
01BV006				
01CA003				
01DL001				
01DP004				
01EC001				
01ED005				
01ED007				
01EF001				
01EO001				
01FA001				
01FB001				
01FB003				
02AB014				
02AD010				
02BF002				
02CA002				
02CF011				
02DD015				
02EA005				

02EC002				
02FB007		1967		FlowScreen result: 6 CPs around 1967, significant increase in low and baseflows. Although there are several supposedly non-flood control dams in the watershed, I could not even find the years these were constructed. Recommend not using the data prior to 1967.
02FC001	Regulated, but included in previous RHBN. Regulation occurred before stream gauge record start; keep pending further study of impacts of regulation.			
02GA010				
02HL004				
02JC008				
02KB001	Regulated, but included in previous RHBN. Regulation occurred before stream gauge record start; keep pending further study of impacts of regulation.			
02LB007				
02LC043				
02LG005				
02NE011				
02NF003				
02PB006				
02PD002				
02QA002				
02QC009				
02RF001				
02RG005				

02UC002				
02VB004				
02WB003				
02XA003				
02XC001				
02YC001				
02YJ001				
02YL001				
02YQ001				
02YR001				
02YS003				
02ZB001				
02ZC002				
02ZF001				
02ZG001				
02ZG003				
02ZH001				
02ZK001				
02ZM006				
03AC004				
03BD002				
03BF001				
03ED001				
03FA003				
03KC004				
03MB002				
03NF001				
03QC001				
03QC002				
04AD002				
04CA002				
04DA001				
04DC001				
04DC002				
04FA001				
04FC001				
04GA002				
04GB004				

04JC002				
04KA001				
04LJ001				
04LM001				
04MF001				
04NA001				
05AA008				
05AB005				
05AD003				
05BB001				
05BL022				
05BL023				
05BM014				
05CK001				
05DA007				
05DA009				
05DA010				
05DC006				
05DE007				
05FB002				
05HA003	Regulated, but included in previous RHBN. Only data post-regulation should be used; keep pending further study of impacts of regulation.	1963		
05HE001				
05HH003				
05JB004				
05KJ014				
05LA003				
05LD001				
05LD003				
05LE010				
05LG004				
05LJ005				
05LJ007				

05LJ019	Regulated, but included in previous RHBN. Regulation occurred before stream gauge record start; keep pending further study of impacts of regulation.			
05MA020				
05NF002				
05NF010				
05OA007				
05OF014				
05OF017				
05PA006				
05PB014		1941		FlowScreen result: max Changepoints occurred in 1926, another with 7 CPs in 1941. Magnitude of change is significant. Could not rule out direct human impact.
05PH003				
05QE009				
05QE012				
05SA002				
05TD001				
05TF002				
05TG002				
05UA003	Possible multiyear storage effects.			
05UF004				
05UG001				
05UH001				
05UH002				
06AB002				
06BD001				
06CD002	Possible multiyear storage effects.			
06DA001				
06DA002				

06DA004				
06FA001				
06FB002				
06FC001				
06FD002				
06GD001				
06HB002				
06JC002		1984		FlowScreen: max changepoint occurred in 1984. HYDAT Remarks note that high flows should be used with discretion before this year (no explanation). Recommend not using data prior to 1984.
06KC003				
06LA001				
06LC001				
06MA006				
07AA001				
07AA002				
07AF002				
07AG003				
07AH002				
07BK001				
07CD001				
07DD002				
07EC002				
07EE009				
07FB001				
07FC003				
07GG001				
07HC001				
07JC001				
07KE001				
07LE002				
07OB001				
07OB004				
07OB006				
07OC001				
07RD001				

07SA002				
07SB010	Possible multiyear storage effects.			
07SB013				
07TA001	Possible multiyear storage effects.			
08CD001				
08CE001				
08CG001				
08DA005				
08EB004				
08ED001				
08EE004				
08EE008				
08FB006				
08GD004				
08HA001				
08HA003				
08HB002				
08HB025				
08HE006				
08HF004				
08JB002				
08JE001				
08KA009				
08LA001				
08LD001		1931		FlowScreen: max Changepoint occurred in 1931, and 5 CPs occurred in 1980. Prior to 1931 the data is particularly choppy due to early logging activities in this watershed; flumes and a "splash dam".
08LG016				
08MA002				
08MB006				
08ME025				
08MG005				
08MH006				
08MH016				

08NB005				
08NC004				
08ND013				
08NE006				
08NE077				
08NF001				
08NH005				
08NH016				
08NH084				
08NH130				
08NJ130				
08NL007				
08NL070				
08NM171				
08NM174				
08OA002				
08OB002				
09AA012				
09AC001				
09AE003				
09BA001				
09BC001				
09DD003				
09DD004				
09EA003				
09EA004				
09FC001				
09FD002				
10AA001				
10BE001				
10BE004				
10BE007				
10CB001				
10CD001				
10CD003				
10CD004				
10CD005				
10EA003				

10EB001				
10ED001				
10ED003				
10FA002				
10FB005				
10GA001				
10GB006				
10GC003				
10JC003	Possible multiyear storage effects.			
10KB001				
10LA002				
10LC003				
10LC007				
10MC002				
10NC001				
10ND002				
10PB001				
10QA001				
10QD001				
10RA002				
10RC001				
10TF001				
10UH001				
11AA026				
11AA032				
11AB075				
11AB117				

Appendix B: Current RHBN excluded from Renewed RHBN

Station	**Notes**
01AJ004	<- Not Natural
01AP004	<- Not Natural
01BU002	<- Not Natural
01CB004	<- Regulated + regulation starts during period of record.
01DG003	<- Not Natural
01EG002	<- Discontinued
02AA001	<- Discontinued
02AB008	<- Not Natural
02CF008	<- Not Natural
02LH004	<- Discontinued
02OE027	<- Not Natural
02PJ007	<- Not Natural
02RD002	<- Discontinued
02VC001	<- Discontinued
02YA001	<- Discontinued
02YN004	<- Does not meet minimum length of record
03MD001	<- Did not meet one of the data quality criteria: After excluding years with more than 5% missing data, there are only 19 years of record prior to our baseline (2010).
03NG001	<- Discontinued
05AA023	<- Discontinued
05AD005	<- Regulated + regulation starts during period of record.
05AD025	<- Did not meet one of the data quality criteria: After excluding years with more than 5% missing data, there are only 6 years of record prior to our baseline (2010).
05BA002	<- Regulated + dataset is fragmented and not useful for trend detection.
05HC005	<- Regulated + very small flows that would be heavily impacted by regulation.
05LE011	<- Not Natural

05LH005	<- Not Natural
05LL027	<- Not Natural
05MG004	<- Regulated + Unknown start date to regulation.
05NF006	<- Not Natural
05PD023	<- Discontinued
06JB001	<- Did not meet one of the data quality criteria: After excluding years with more than 5% missing data, there are only 17 years of record prior to our baseline (2010).
07OB003	<- Middle nest with 07OC001 and 07OB001, both of which are continuous (this one is seasonal): redundant.
08GA010	<- Regulated + Unknown start date to regulation.
08GA061	<- Not Natural
08HB008	<- Regulated + regulation starts during period of record.
08NH131	<- Discontinued
08NN015	<- Heavily managed by the South East Kelowna Irrigation District, there are several man-made reservoirs and diversions. Could not determine at this time when these structures were built and if the management practice has changed over time.
09AA001	<- Did not meet one of the data quality criteria: After excluding years with more than 5% missing data, there are only 9 years of record prior to our baseline (2010).
09AA006	<- Max Changepoint occurred in 1988, and 6 more CPs in 1998. Historical and continued placer gold extraction in Atlin, BC. The absence of historical or future regulation cannot be guaranteed with so much mining activity.
10FB006	<- Regulated + regulation is from the Peace River, considerably upstream, but site not likely useful for trend analysis.
10KD001	<- Regulated + site not likely useful for trend analysis.

Appendix C: Additional references for R code

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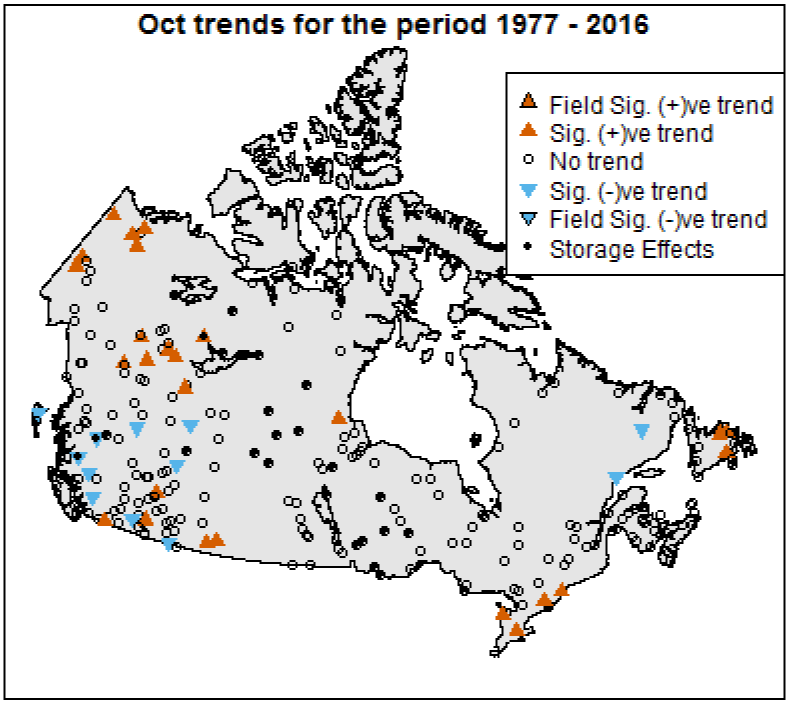
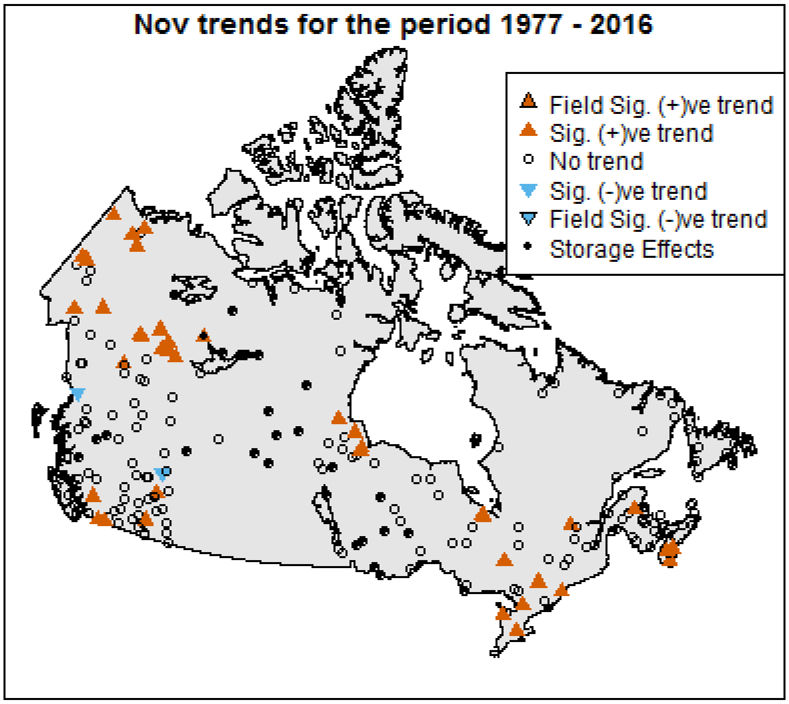
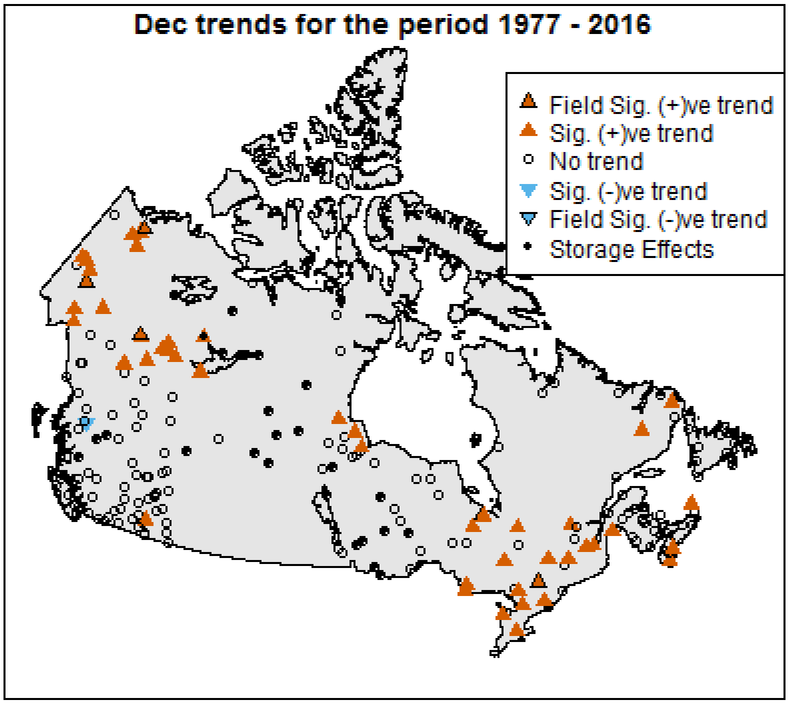
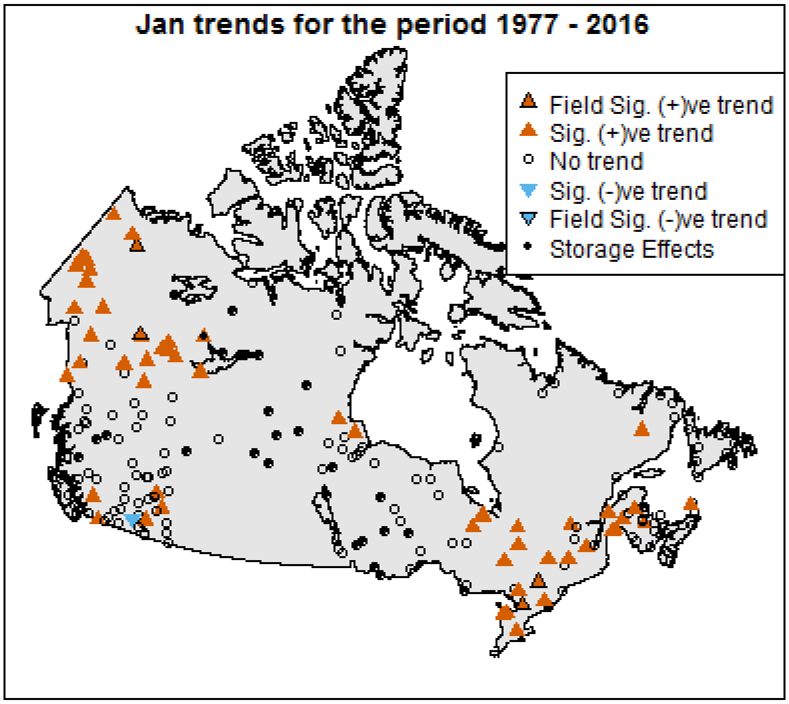
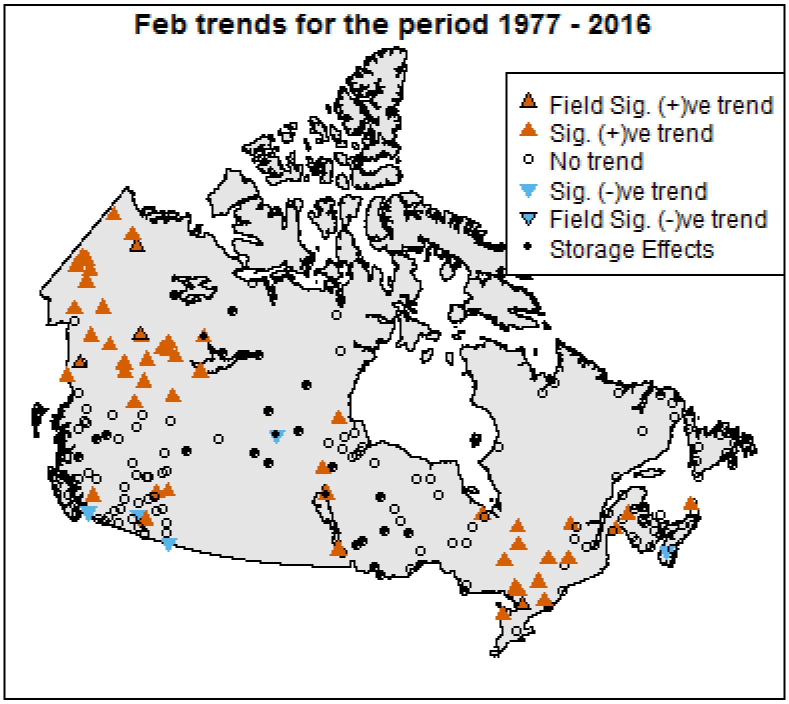
Appendix D: All Monthly Trend Results Maps for the period 1977-2016






Dec trends for the period 1977 - 2016


Jan trends for the period 1977 - 2016


Feb trends for the period 1977 - 2016
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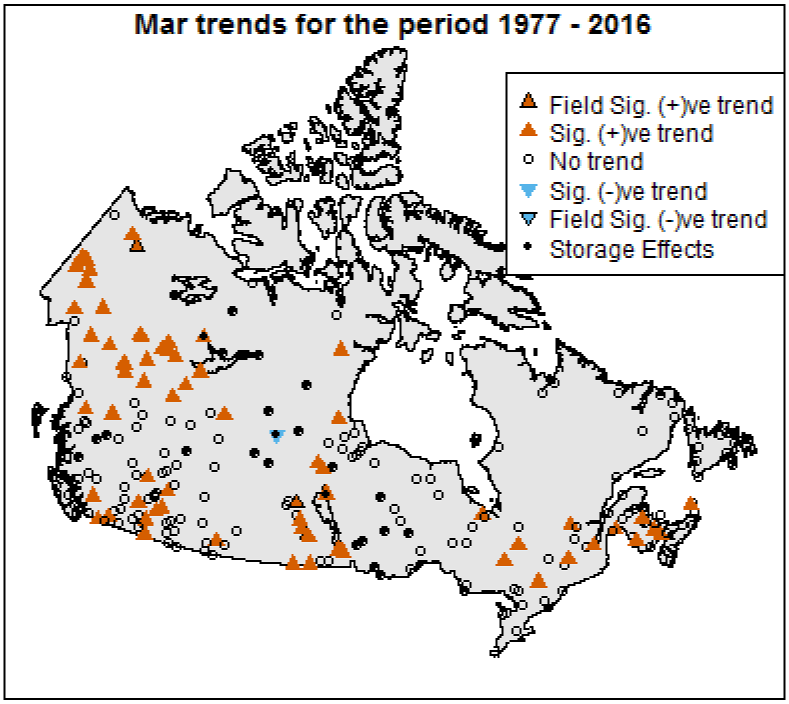
Sig. (+)ve trend
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects


Mar trends for the period 1977 - 2016
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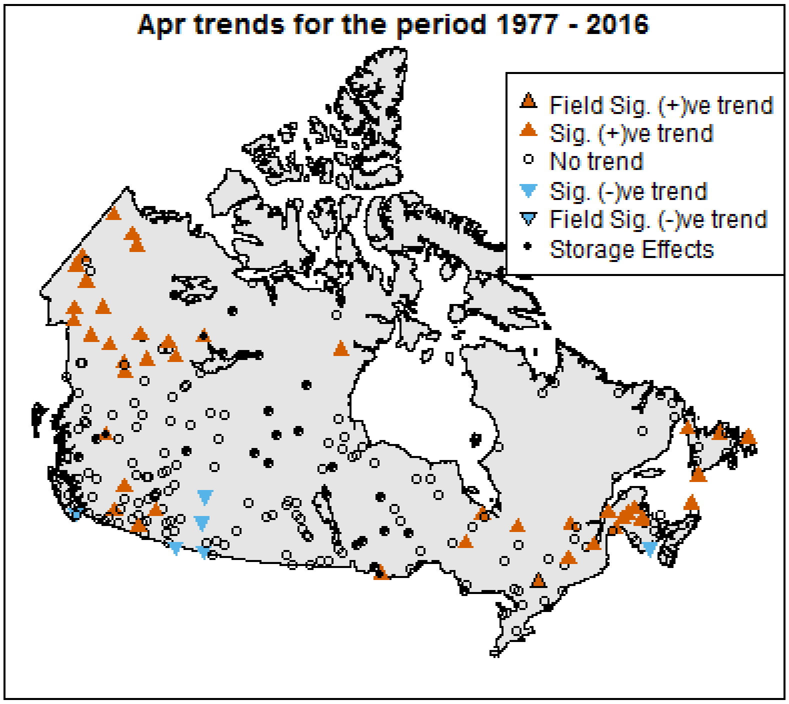
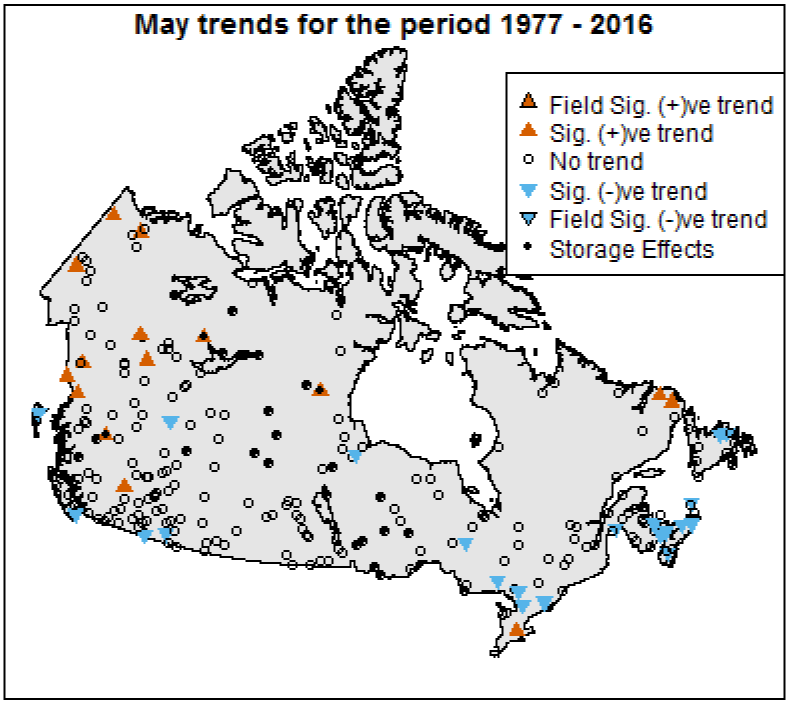
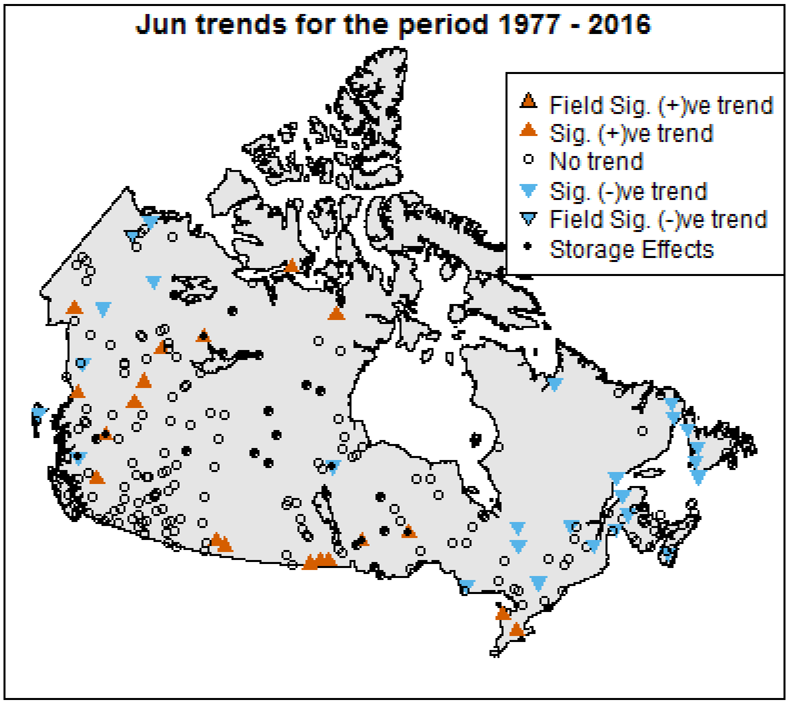
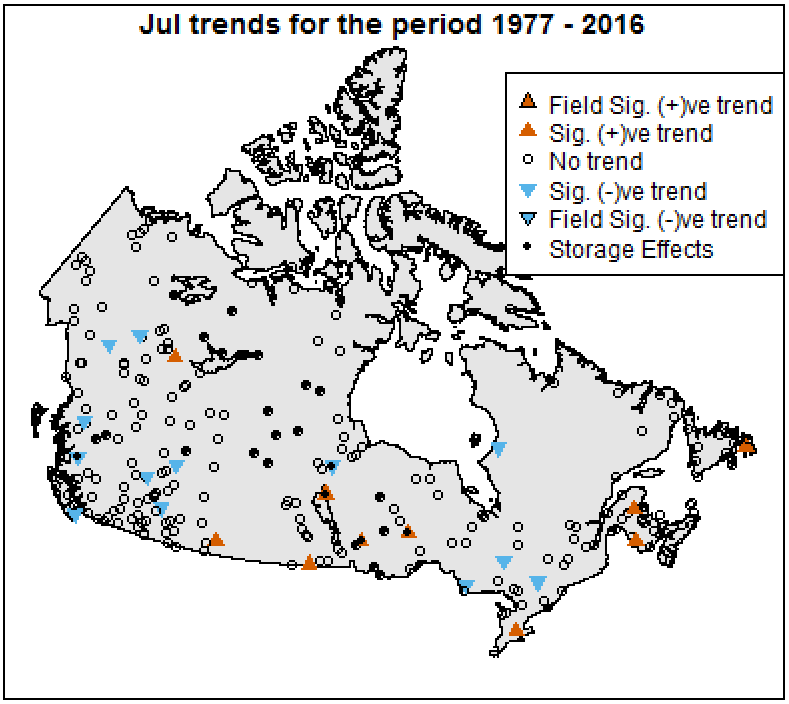
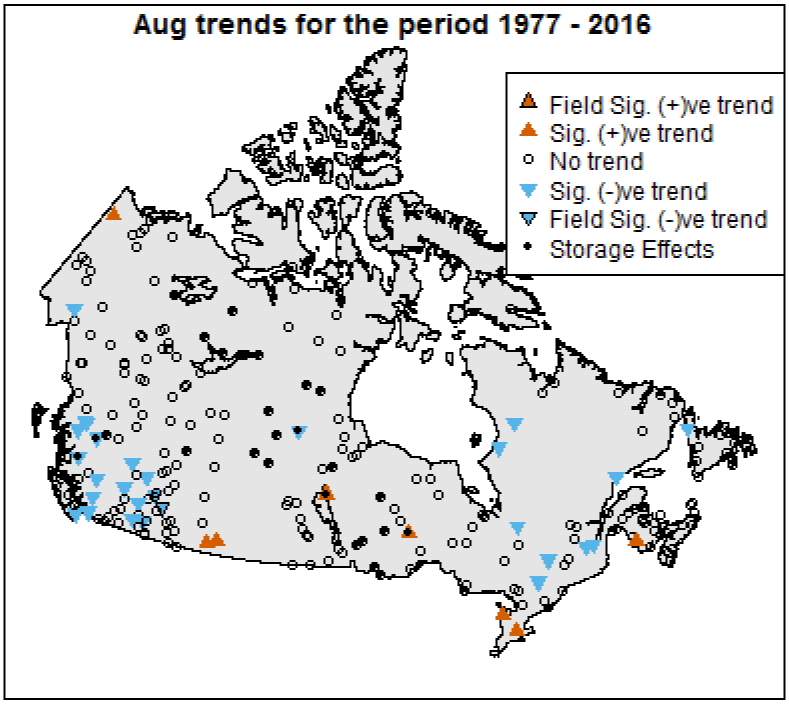
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects


Apr trends for the period 1977 - 2016
Field Sig. (+)ve trend
Sig. (+)ve trend
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects


May trends for the period 1977 - 2016
Field Sig. (+)ve trend
Sig. (+)ve trend
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects


Jun trends for the period 1977 - 2016
Field Sig. (+)ve trend
Sig. (+)ve trend
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects


Jul trends for the period 1977 - 2016
Field Sig. (+)ve trend
Sig. (+)ve trend
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects


Aug trends for the period 1977 - 2016
Field Sig. (+)ve trend
Sig. (+)ve trend
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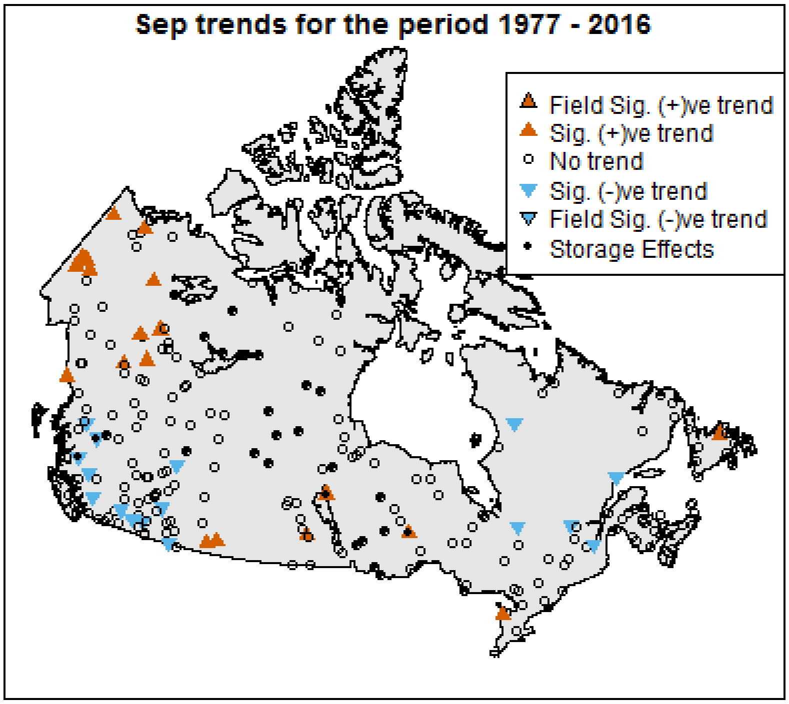
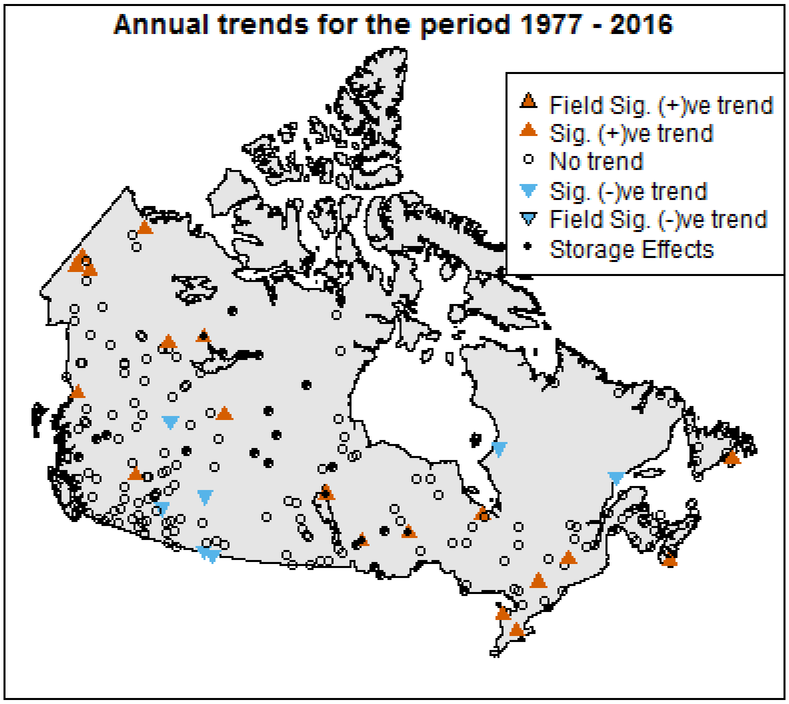
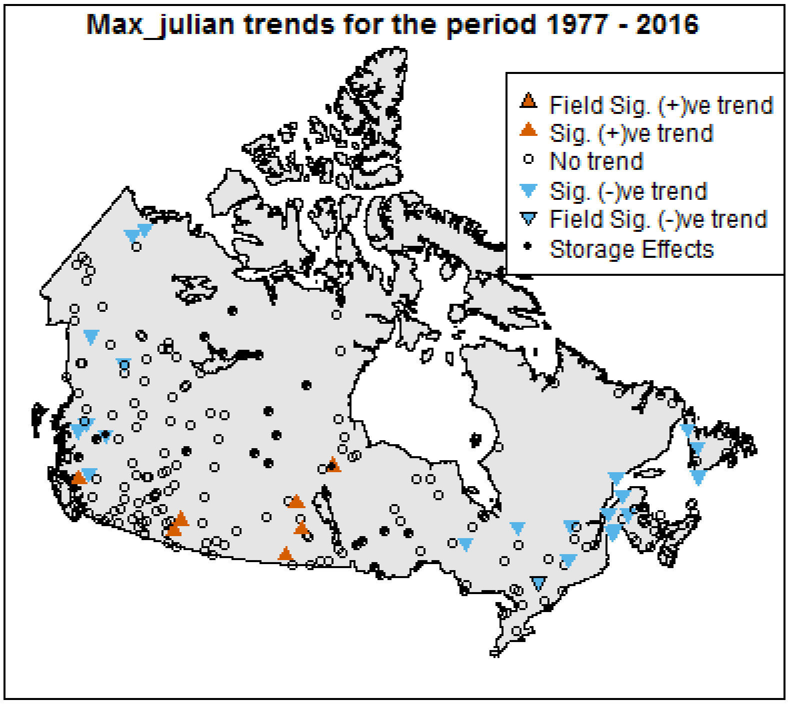
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects

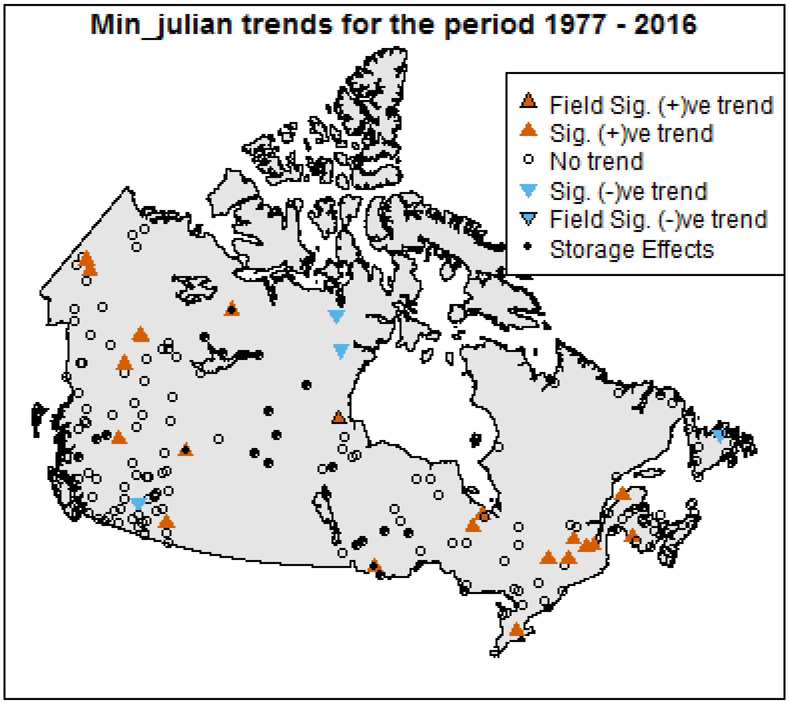

Sep trends for the period 1977 - 2016
Field Sig. (+)ve trend
Sig. (+)ve trend
No trend
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects



Annual trends for the period 1977 - 2016



Max_julian trends for the period 1977 - 2016


Min_julian trends for the period 1977 - 2016
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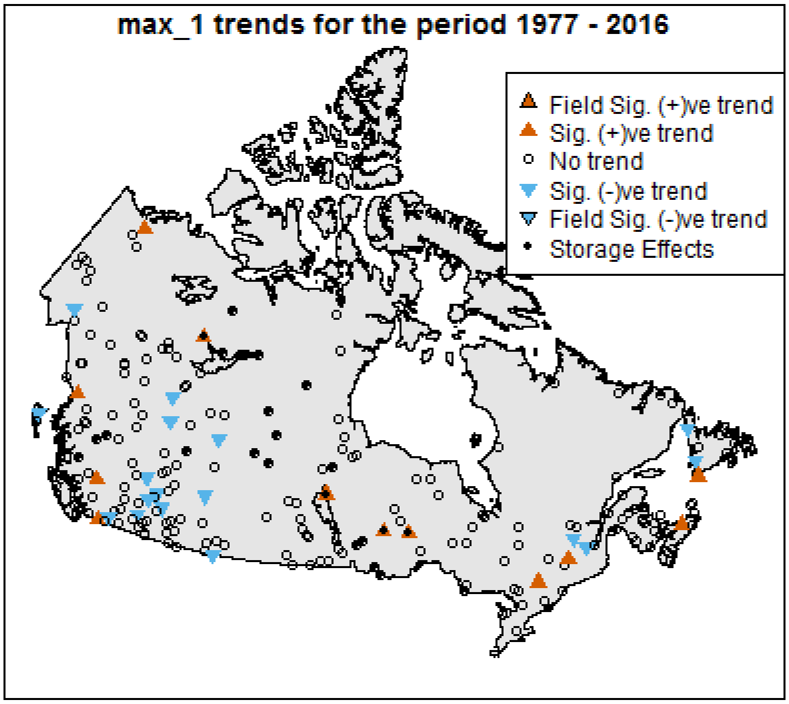
Field Sig. (-)ve trend
Storage Effects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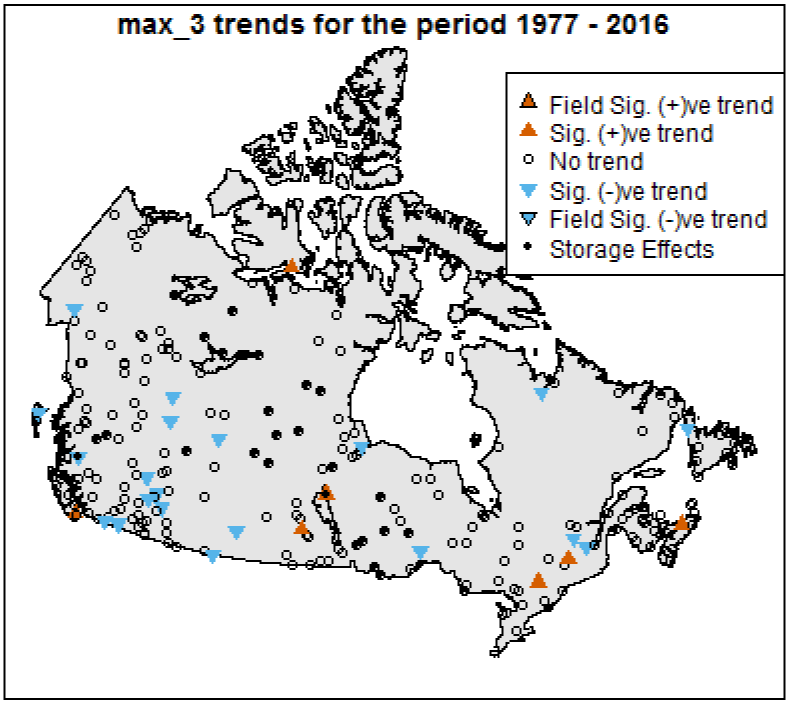
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects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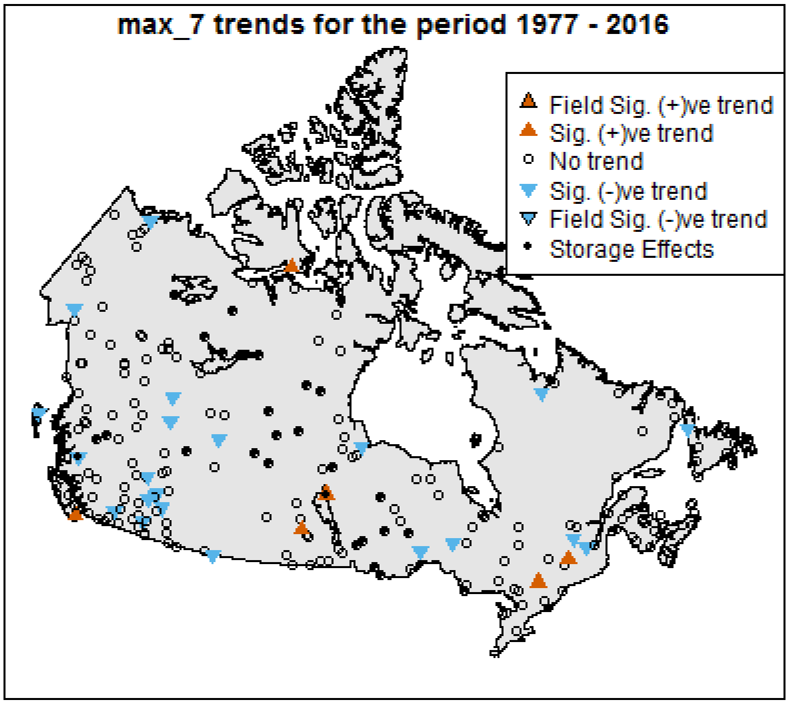
Sig. (-)ve trend
Field Sig. (-)ve trend
Storage Effects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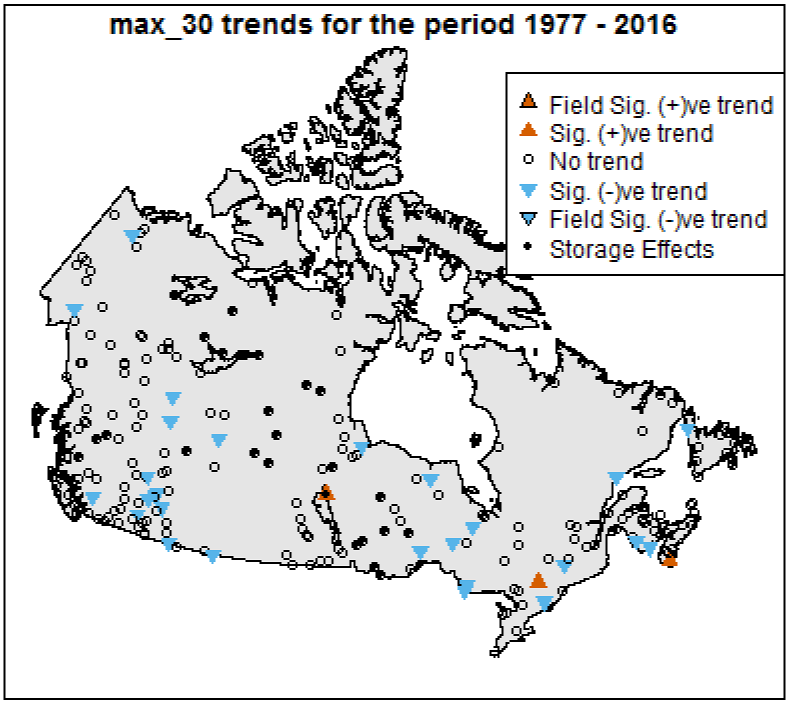
Field Sig. (-)ve trend
Storage Effects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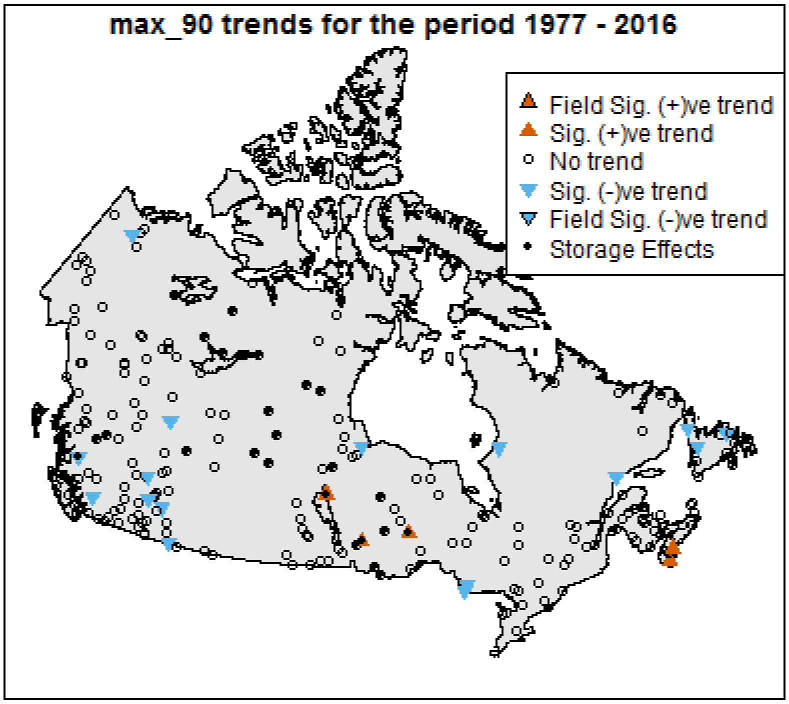
Field Sig. (-)ve trend
Storage Effects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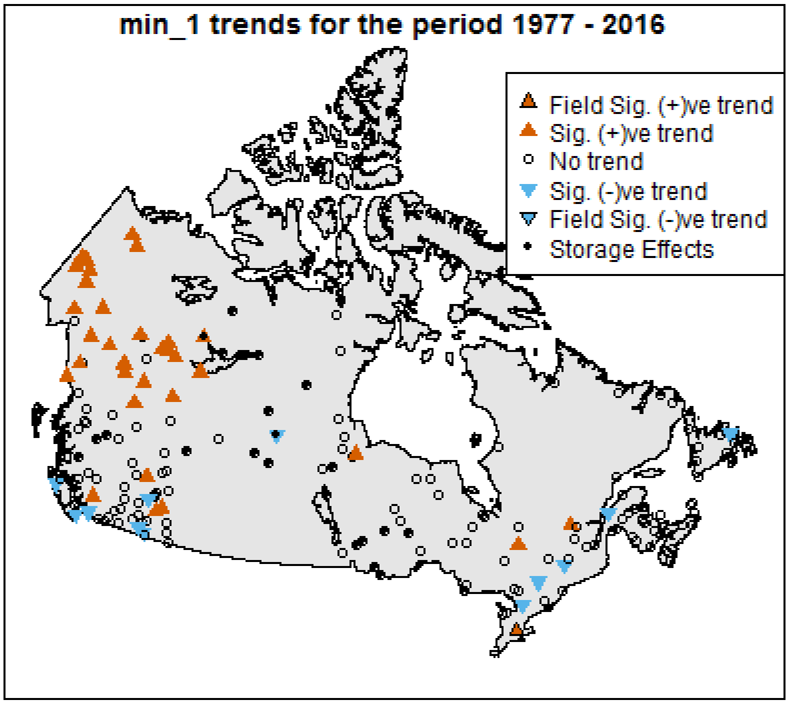
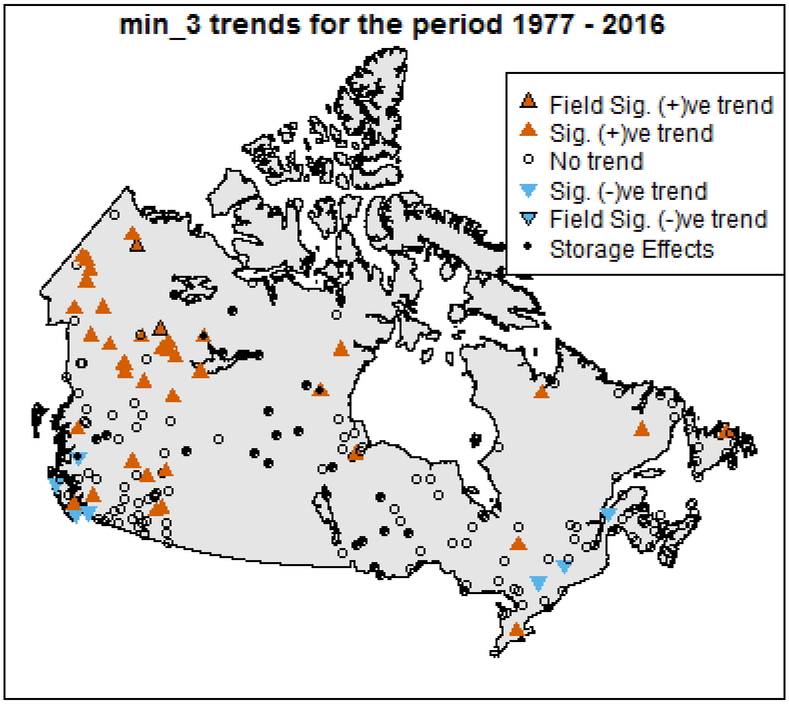
Storage Effects



min_1 trends for the period 1977 - 2016



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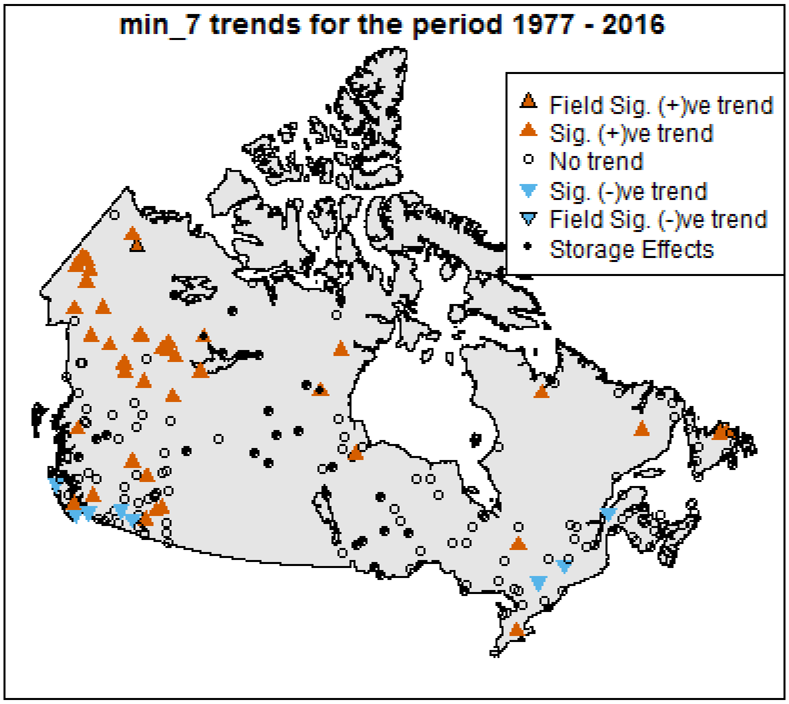
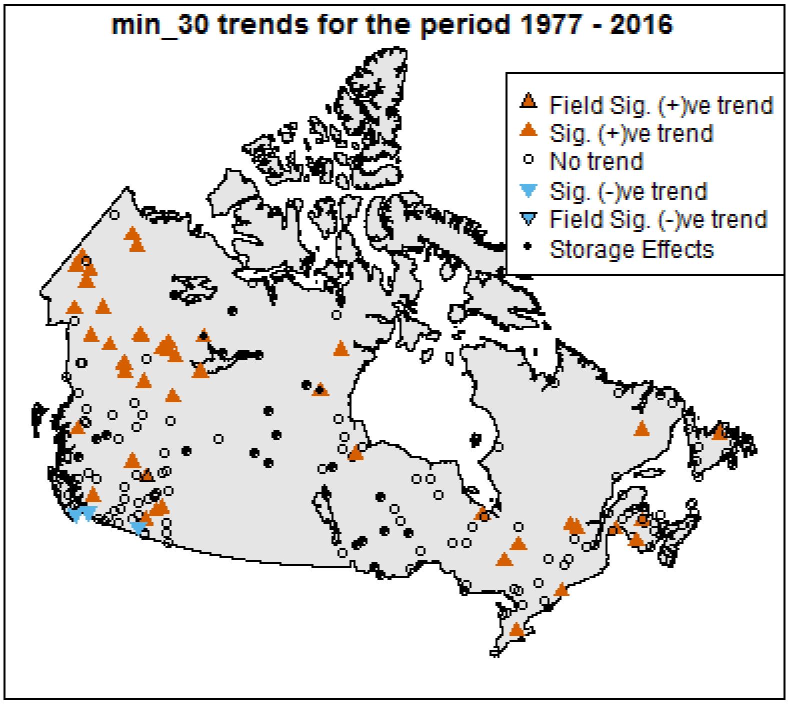

min_7 trends for the period 1977 - 2016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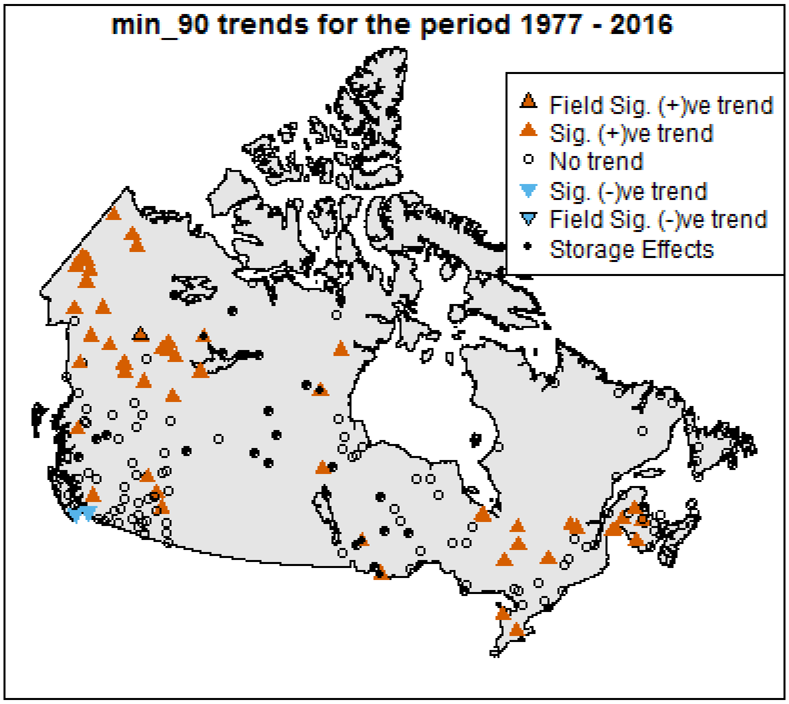
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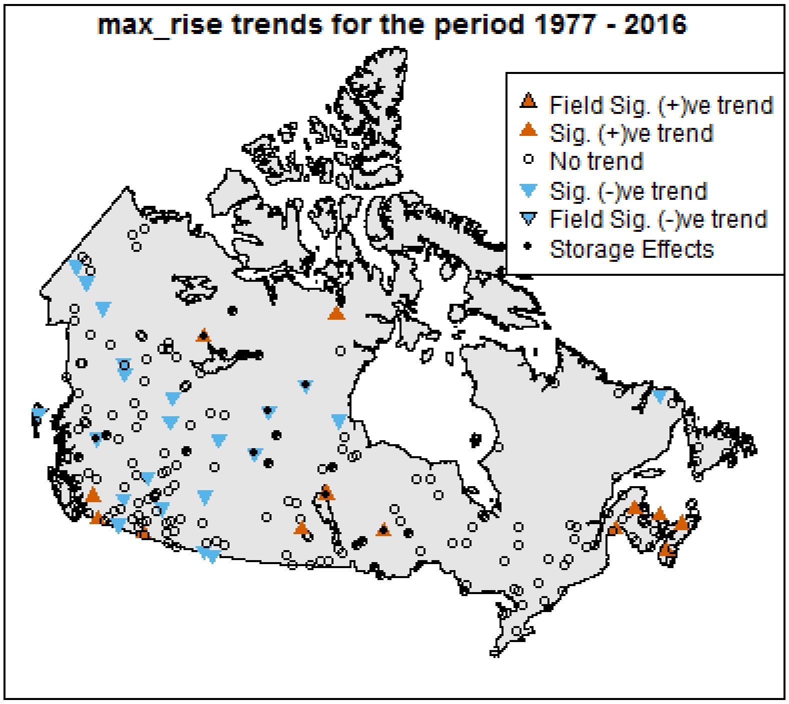
Field Sig. (-)ve trend
Storage Effects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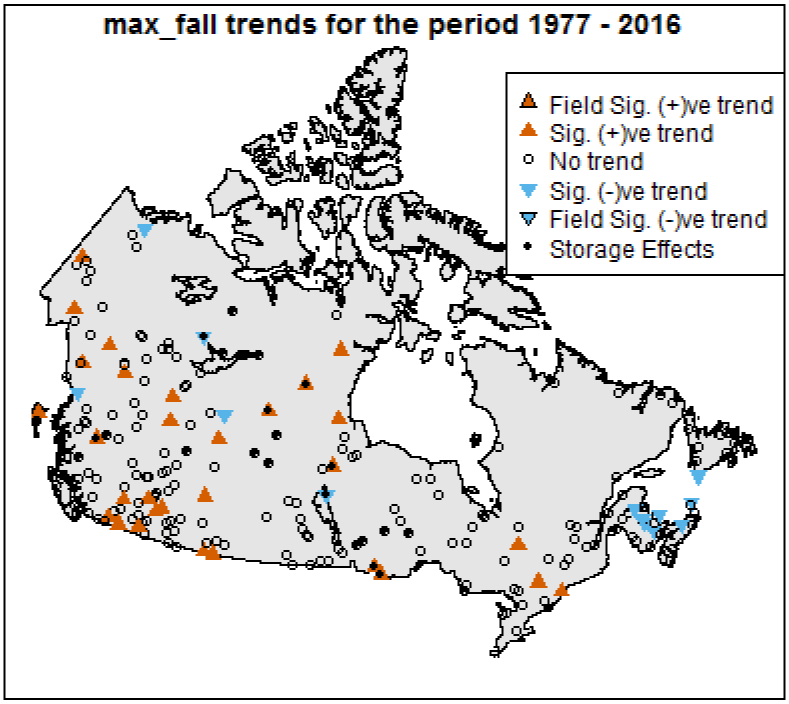
Storage Effects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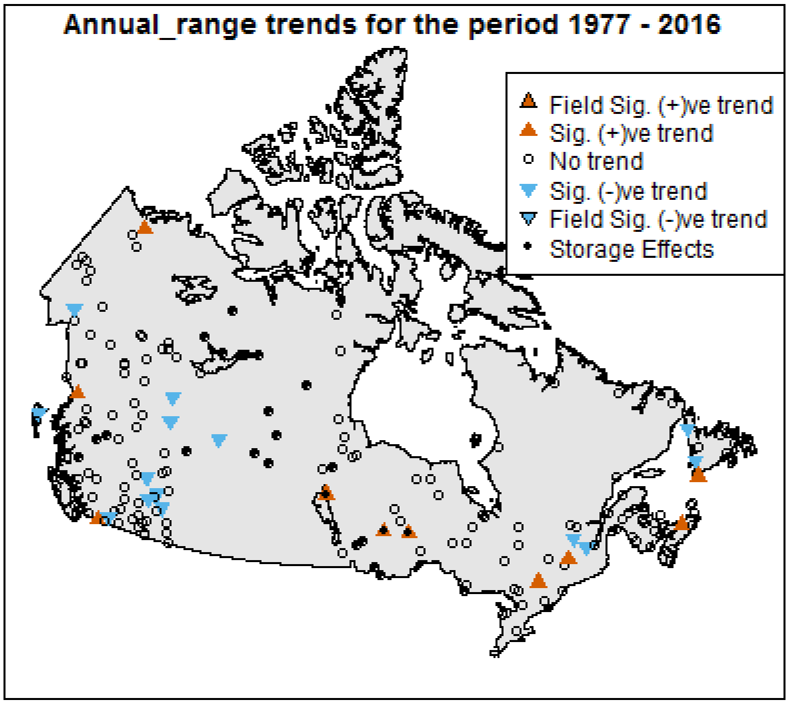
Storage Effects


Annual_range trends for the period 1977 - 2016
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No trend
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Field Sig. (-)ve trend
Storage Effects