Assessing the effect of Hydrologic Alteration on Alberta's Natural Flow Regime

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Executive Summary

Stream hydrology is thought to be a primary driver of riverine communities, impacting fish habitat quality and quantity, allocation of food, and selecting for life-history traits in fishes. There is considerable concern regarding the ecological impacts from hydrologic alteration due to climate and land-use change, and increasing water use extracted for industrial development. In many watersheds in Alberta (e.g., South Saskatchewan Basin), water use is fully allocated. This study will help satisfy current knowledge gaps by assessing patterns in stream hydrology from climate, precipitation and anthropogenic sources. The objectives of this project were to (1) determine how various ecologically relevant components of streamflow are changing across ecoregions in Alberta, (2) examine the similarities and differences between streamflow trends and climate trends, and (3) study the difference between trends in naturalized flow and measured flow. These objectives are intended to support and improve Alberta's policies that address in-stream flow needs, as well as set the stage for further research to determine the impact of the human activity and fish community structure in Alberta's streams. Stream gauge data was collected and assessed from across Alberta to develop trends across broad spatial and temporal scales. We describe trends from 1963-2012, which balanced the tradeoff with including a large number of stream gauges included in the analyses and the time period to detect change. We grouped hydrologic variables as: i) median monthly flows (group 1), ii) magnitude and duration of annual extreme conditions (group 2), iii) timing of annual extreme conditions (group 3), iv) frequency and duration of high and low pulses (group 4), and rate and frequency of change in water condition (group 5). Trends were assessed using non-parametric Mann-Kendall analyses. We used a detrending and pre-whitening approach to remove potential serial correlation in the data, which has been shown to be problematic when analyzing stream gauge data. There was large variation in flow conditions across eco-regions in Alberta. Overall, stream flows have decreased significantly across the province. For example, median monthly flows showed a strong decline throughout most of Alberta, although it was more pronounced in the foothills and boreal eco-regions. There was also a strong decline in maximum minimum extreme flow conditions across all variables (i.e. the 1-3-, 7-, 30- and 90-day maximum flow variables), most prominently in the Boreal and Rocky Mountain eco-regions. Overall, there was a "flattening" of hydrographs across the province. The rise rate, or the amount the flow increases from one day to the next decreased, as did the fall rate, or the amount the flow decreases from one day to the next. There were no trends in the timing of annual extreme flows or the number of high stream pulses. There was a broad increase in temperature throughout Alberta. Precipitation was significantly higher in the spring. Snow showed a significant decline across all of Alberta. These trends do not appear to be driven by climatic oscillations such as El Niño–Southern Oscillation or the Pacific Decadal Oscillation. This reports provides quantitative data on temporal and spatial trends of stream hydrology and climate across freshwater systems in Alberta to help aid in developing sustainable water extraction practices. The results indicate significant changes to Alberta's climate and stream systems, and suggest potential water scarcity issues in Alberta in the future.

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1.0 Project Description

1.1. Introduction

There is considerable and increasing concern about the sustainability of water use in Alberta given the effects of climate change and anthropogenic extraction. Unfortunately, there have been no systematic studies and there is a paucity of reliable, robust, and comprehensive data to study such impacts. The limited numbers of published studies have generated considerable media attention, bringing the environmental impacts of activities such as agriculture and water extraction under close scrutiny. These circumstances have led to considerable speculation, nationally and internationally, and a general anxiety by the public, about the possible environmental consequences and the significance of sustainable water in Alberta for both human and ecological health. And yet, there is very little retrospective information about the environmental impact of existing water extraction practices. Basic empirical information that would link hydrologic alteration to both climate and anthropogenic effects are needed. The study described here is intended to satisfy these important knowledge gaps, providing quantitative data on temporal and spatial trends of stream hydrology across freshwater systems in Alberta to help aid in developing sustainable water extraction practices.

1.2. Research Description

The objectives of this project was to: (1) determine how various ecologically relevant components of streamflow are changing across ecoregions in Alberta, (2) examine the similarities and differences between streamflow trends and climate trends, and (3) study the difference between trends in naturalized flow and measured flow. We examined trends in climate and stream hydrology by developing a meta-analysis of stream hydrology data (e.g., magnitude, frequency and duration of flooding). These data provided a long-term dataset to facilitate examination between climate and hydrologic alteration. Impacts of water extraction were modeled using well-established methods of indicators of hydrologic alteration, including the timing, duration and severity of floods and droughts, high peak flow, and skewness of daily flows. Because numerous indices of IHA exist, we screened numerous indices and time periods for their utility.

1.3. Approach

1.3.1.Literature Review

1.3.1.1. Impacts of Stream Hydrology on Aquatic Ecosystems

Human utilization of rivers for transportation, water supply, power generation and effluent discharge, combined with the watershed effects of land-use, have dramatically altered the hydrology of rivers around the world (Bakker, 2012; Gleick, 2002; Poff et al., 2010; Gordon, Peterson & Bennett, 2007). Hydrology is considered a primary driver of stream ecosystems, structuring physical habitat, providing connectivity, structuring aquatic communities, and at species level, selecting for life histories of aquatic organisms (Mims & Olden, 2012; Merritt et al., 2010; Poff et al., 2010; Anderson et al., 2006).

1.3.1.2. Life History Relationships and Stream Hydrology

Trade-offs among energetic investments in growth, reproduction, and survivorship have resulted in the evolution of life-history strategies that enable an organism to cope with ecological challenges (Statzner et al., 1997; Stearns, 1976; Winemiller, 2005; Andewartha & Birch, 1954). Indeed, evolutionary ecology recognizes a continuum of life-history strategies: ranging from those representing low investment, such as short-lived, small bodied individuals with high fecundity (i.e. referred to as r-strategists); to those with high investment, long-lived, large-bodied individuals with low fecundity (i.e. K strategists; (MacArthur & Wilson, 1967; Pianka, 1970; Stearns, 1976; Reznick, Bryant & Bashey, 2002)), and gradients in between (e.g. opportunistic, periodic, and equilibrium strategists; (Southwood, 1977; Southwood, 1988; Winemiller & Rose, 1992)). Ecological theory has acknowledged the role of disturbance as a fundamental process affecting the evolution of life-history strategies (Schlosser, 1990; Stearns, 1992; Winemiller, 2005). For example, it is widely recognized that a species' life-history strategy dictates, in large part, its response to environmental factors describing the variability, predictability, and seasonality of favorable conditions (Lytle, 2001; Resh et al., 1988; Murphy, 1968).

Understanding which species and what life-history characteristics are most vulnerable to changes in stream hydrology is a prerequisite for mitigating impacts and designing effective conservation strategies (Olden et al., 2010). Convergence of trait composition along hydrologic gradients has been demonstrated for freshwater invertebrates (Konrad, Brasher & May, 2008; Verberk, Siepel & Esselink, 2008) and freshwater fishes (Blanck, Tedesco & Lamouroux, 2007; Lamouroux, Poff & Angermeier, 2002; Logez, Pont & Ferreira, 2010; Mims et al., 2010; Poff & Allan, 1995), but empirical investigations that test predictions from life-history theory remain scant (but see (Mims & Olden, 2012; Reynolds, Webb & Hawkins, 2005; Paul, 2012)). Previous studies across the globe have found convergence of life-history characteristics of fishes in drainage basins along similar gradients of hydrologic variability, with an increasing prevalence of opportunistic strategists and a decreasing prevalence of periodic strategists concurrent with increasing hydrologic variability (Kennard et al., 2010; Mims et al., 2010; Mims & Olden, 2012; Southwood, 1988; Winemiller & Rose, 1992; Logez, Pont & Ferreira, 2010). Together, these studies provide support for the response of fish life-history strategies to hydrologic conditions.

1.3.1.3. Water Extraction as Hydrologic Alteration

Water extraction, for irrigation and industrial activity, represents an uncharacterized form of hydrologic alteration (Kennen *et al.*, 2008; Gordon, Peterson & Bennett, 2007). In Alberta, water is extracted at substantially high levels for use in agricultural irrigation and industry. For example, in southern Alberta irrigation accounts for 71% of water use, with some like the St. Mary’s, Oldman and Bow Rivers oversubscribed by irrigation use (Bjornlund, Nicol & Klein, 2007;

Schindler & Donahue, 2006). Likewise, in northern Alberta, industrial development of oil sands has reduced annual flows of streams and rivers (RSC, 2010; Squires, Westbrook & Dube, 2009). Between 349-370 million cubic meters of water is extracted yearly from the lower Athabasca River for oil sands development (CAPP, 2009; Griffiths, 2006). Although the total allocations represent roughly 2.2% of the total annual average river flow (CAPP, 2009), about 90% of that water is removed from the river for industrial use (Griffiths, 2006; Schindler & Donahue, 2006). Given current rates of consumption, future water extraction is expected to reduce the flow of the Athabasca River during critical low flow periods (September to April; (Schindler & Donahue, 2006)). As such, there are concerns regarding the impact, and timing of water extraction (Paul, 2012; Krimmer *et al.*, 2011), and the cumulative impact on fish populations (RSC, 2010). With increased demand for water for future agricultural and industrial use, the impacts of water extraction will produce or exacerbate water shortages around the Alberta, and may be limited by the availability of freshwater (RSC, 2010; Schindler & Donahue, 2006). Research is needed to ascertain the ecological impacts of water extraction and in particular whether different types of water extraction (e.g. agricultural versus industrial use) result in different impacts (e.g. duration, magnitude, frequency, seasonality), and timing (Paul, 2012; Krimmer *et al.*, 2011), how such impacts can be mitigated.

1.3.2.Experimental Procedures

The Water Survey of Canada (WSC) monitors streamflow at river stations across Canada. This data, measured as a daily median flow rate, is readily available online (www.wsc.ec.gc.ca). In Alberta, the WSC monitors 1063 stations across the province, but heavily concentrated in the southern watersheds. Figure 1 is a map illustrating the location of these stations.

These records are largely variable in their length and completeness of record. As a result, data was analyzed for a variety of analysis periods, consisting of anywhere from 40 years to 100 years in length, with all periods ending in 2012.

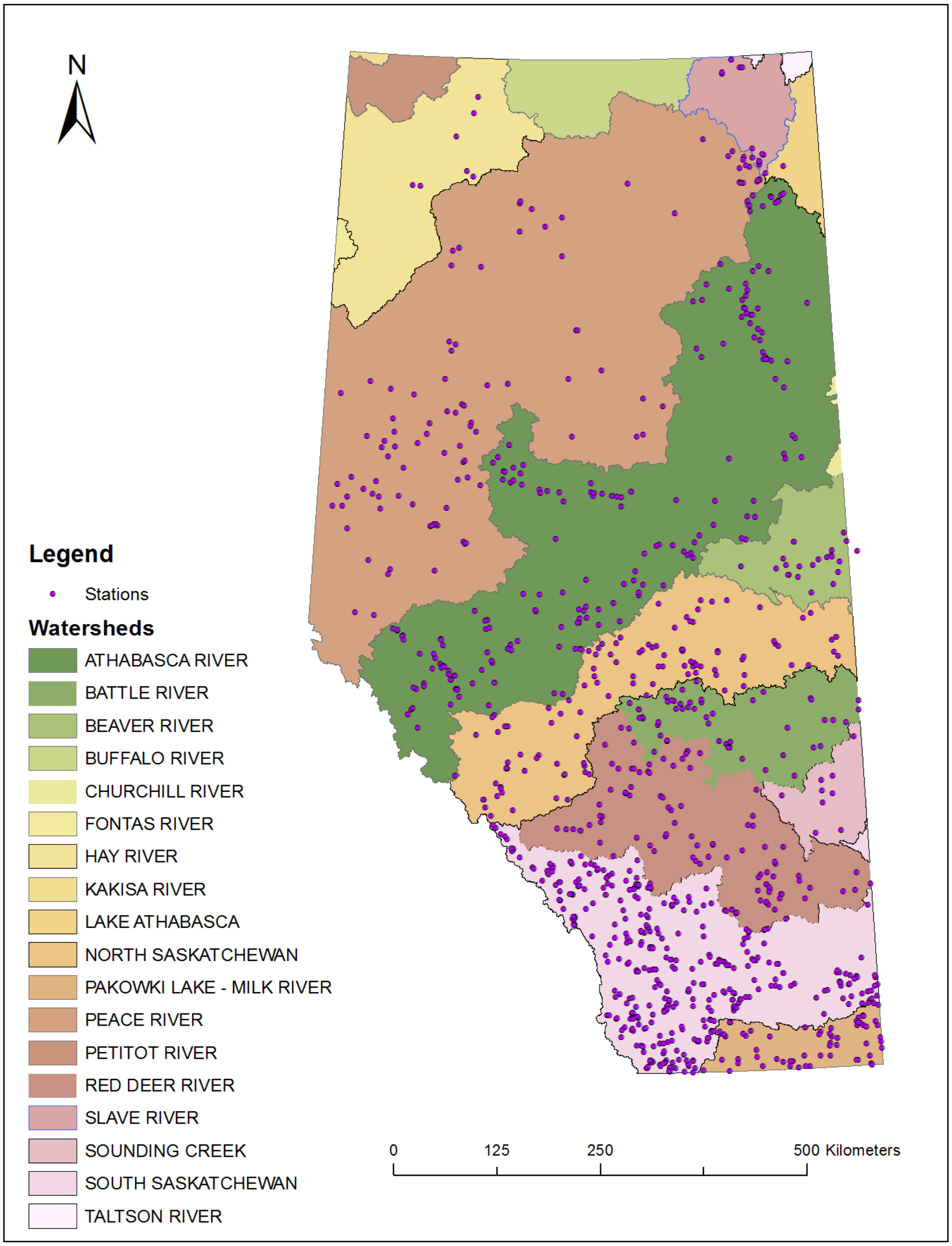


Figure 1: Water Survey of Canada stream gauge locations across the various watersheds in Alberta.

We used a similar to the approach used by Burn et al., 2008. That study focused on stations that were missing no more than four years of data over 30, 35, and 40 year periods. Our study analyzes longer periods. For example, only stations that contained a minimum of 90% of the years within a particular period were analyzed for that period (e.g. for a 70 year period, only stations with at least 63 years of data were analyzed). This was done to keep the sample size high enough for statistical methods. The total number of stations analyzed for each period is listed in Table 1. Note that the seasonal nature of the daily streamflow data collection may reduce the number of stations available for analysis.

Table 1: Number of Stations Available for Trend Analysis

Time Period for Analysis	Total Number of Stations Available for Analysis
2003-2012	320
1993-2012	309
1983-2012	299
1973-2012	221
1963-2012	139
1953-2012	65
1943-2012	33

1.3.3.Hydrological variables

Richter et al. (1996) created a method that defined a series of ecologically-relevant parameters in which to analyze hydrologic alteration. This method calculates 31 parameters, measuring the five key hydrologic characteristics for fish life-history: magnitude, timing, duration, frequency, and rate of change.

Table 2. Hydrologic parameters analyzed with the Indicators of Hydrologic Alteration (IHA) methodology.

IHA Statistics Group	Hydrologic Regime Characteristics	Hydrologic Parameters
Group 1: Monthly magnitudes	Magnitude, Timing	Median value for each calendar month
Group 2: Magnitude and duration of annual extreme conditions	Magnitude, Duration	Maximum and minimum of 1-, 3-, 7-, 30-, and 90-day means
Group 3: Timing of annual extreme conditions	Timing	Julian date of the annual maximum and minimum daily flow
Group 4: Frequency and duration of high and low pulses	Magnitude, Frequency, Duration	Number of high and low pulses each year Mean duration of high pulses and low pulses each year
Group 5: Rate and frequency of change in water conditions	Frequency, Rate of Change	Median of all positive and negative differences between consecutive daily flows Number of times streamflow rises one day and falls the next, or vice versa

Several other hydrologic indices have been developed over the years. Olden and Poff (2003) took a look at 171 indices that had been used in literature at that time and determined that the IHA method was adequate in calculating the major components of the flow regime. Note that the data was analyzed such that results are in reference to the water year (October to September) as opposed to the calendar year.

1.3.4.Climate variables

Climate data was generated using Climate NA software (Hamann *et al.*, 2013). This software calculates a variety of climate variables based on location latitude and longitude. Using this software, annual climate data was generated for all Alberta hydrometric stations. The list of climate variables generated can be found in Table 3.

The data set generated is a complete data set, spanning the years 1902 to 2012. No missing years are found in this data set.

Table 3. Climate variables analyzed for trends

Climate Variable	Abbreviation
Average temperature (°C)	Tave
Minimum Temperature (°C)	Tmin
Maximum temperature (°C)	Tmax
Precipitation (mm)	PPT
Precipitation as snow (mm) between August in previous year and July in current year	PAS

1.3.5.Trend analysis

1.3.5.1. Mann Kendall Trend Analysis

The Mann-Kendall non-parametric analysis (Mann, 1945; Kendall, 1975) has been commonly used to determine the presence of significant trends in hydrological data (Burn, Fan & Bell, 2008; Gan, 1998; Zhang *et al.*, 2001) and climate data (Gan, 1998). The Mann-Kendall test determines whether a variable of interest increasing or decreases with time. The nonparametric trait of the analysis is beneficial because it is suitable for non-normally distributed data series, with missing data (Hirsch & Slack, 1984). This is useful for hydrological data. However, this approach requires the data series to be serially independent. This may not occur with hydrological data. Certain hydrological time series characteristics, such as mean annual streamflows, frequently contain statistically significant serial correlation (Hirsch & Slack, 1984).

Yue et al. (2002) described potential biases when investigating trends in hydrologic data series: 1) the influence of the lag-1 serial correlation process (AR(1)) on Type 1 error; 2) the effect of a trend on serial correlation; and 3) the effect of AR(1) on trend.

Time series data with positive serial correlation have been shown to exhibit an increased probability that a significant trend will be found using the Mann-Kendall test (von Storch, 1999).

Several papers have looked at addressing autocorrelation when it comes to detecting trends (Yue *et al.*, 2002; Bayazit & Onoz, 2007; von Storch, 1999). von Storch (1999), addressed this problem by proposing a procedure called "pre-whitening". The objective of pre-whitening is to remove a serial correlation component from a time series data set (Kulkarni & von Storch, 1995) and has been used to reduce the impact of AR(1) of hydrological data in several studies, including Douglas et al. (2000) and Zhang et al., 2001.

The second consideration Yue et al. (2002) discussed was the possibility of a trend causing a false detection of an AR(1). This error would result in analyzing and interpreting the data series incorrectly. As a result, in data series that exhibit a trend, significant serial correlation could be detected, when in reality the data series does not contain serial correlation.

Conversely, the effect of an AR(1) on trend detection should also be considered. Yue et al. (2002) concluded that the variance of the slope estimates is altered by a positive AR(1) process.

Yue et al. (2002) proposed and tested a procedure. This procedure has been followed by other studies, including Burn et. al. (2008) and will be applied in this study. The first step is to estimate the slope of the data series. The slope of the trend is estimated using the Theil-Sen Approach (TSA) according to the following formula:

$$b = Median\left(\frac{X_j - X_l}{j - l}\right) \forall l < j \tag{1}$$

where b is the estimate of the slope and X_l is the l-th observation in the data series, X (Theil, 1950a; Theil, 1950b; Theil, 1950c; Sen, 1968). If b is approximately equal to 0, then no further analysis is required, as there is no trend present. However, if b is not equal to 0, then an assumption of linearity is made. The sample data are then "detrended" by:

$$X'_t = X_t - T_t = X_t - bt \tag{2}$$

where T_t is the identified trend (Yue *et al.*, 2002).

The second step takes the detrended data set and removes the AR(1) component. First, the lag-1 serial correlation coefficient is removed by:

$$r_1 = \frac{\frac{1}{n-1}\sum_{t=1}^{n-1}[X_t - E(X_t)] \cdot [X_{t+1} - E(X_t)]}{\frac{1}{n}\sum_{t=1}^{n-1}[X_t - E(X_t)]^2} \tag{3}$$

$$E(X_t) = \frac{1}{n}\sum_{t=1}^{n} X_t \tag{4}$$

where r_1 is the lag-1 correlation coefficient of the sample data, X_t, $E(X_t)$ is the mean of the data series and n is the sample size (Yue *et al.*, 2002). r_1 is then used to remove the AR(1) using:

$$Y'_t = X'_t - r_1 \cdot X'_{t-1} \tag{5}$$

This “trend-free pre-whitening” (TFPW) procedure results in a data series, Y'_t, that is independent (Yue *et al.*, 2002).

The third step blends the trend component of the sample data, T_t, and the residual, AR(1)-free component, Y'_t using the following:

$$Y_t = Y'_t + T_t \tag{6}$$

Finally, the Mann-Kendall test is applied to the blended data series, Y_t. As the above steps maintain the true trend of the data, while removing the AR(1) component, violations of serial correlation are no longer a concern.

The non-parametric Mann-Kendall trend analysis tests a null hypothesis that states the probability of variable Y increasing as time, T, increases is equal to 0.5, as shown in equation 7 (Helsel & Hirsch, 2002).

$$H_0: \quad Prob\left[Y_j > Y_i\right] = 0.5, where\ time\ T_j > T_i \tag{7}$$

Kendall’s S statistic is calculated using the Y,T data pairs. In order to reject the null hypothesis, S must be significantly different from zero. A monotonic trend in Y over time occurs when the null hypothesis is rejected (Helsel & Hirsch, 2002)

1.3.5.2. Generalized Least Squares Models

Trends were also analyzed using a Generalized Least Squares method. This method was employed in St Jacques, Sauchyn, & Zhao, 2010, and allows us to determine the factors driving each trend.

1.3.6.The Influence of Climate Oscillation Patterns

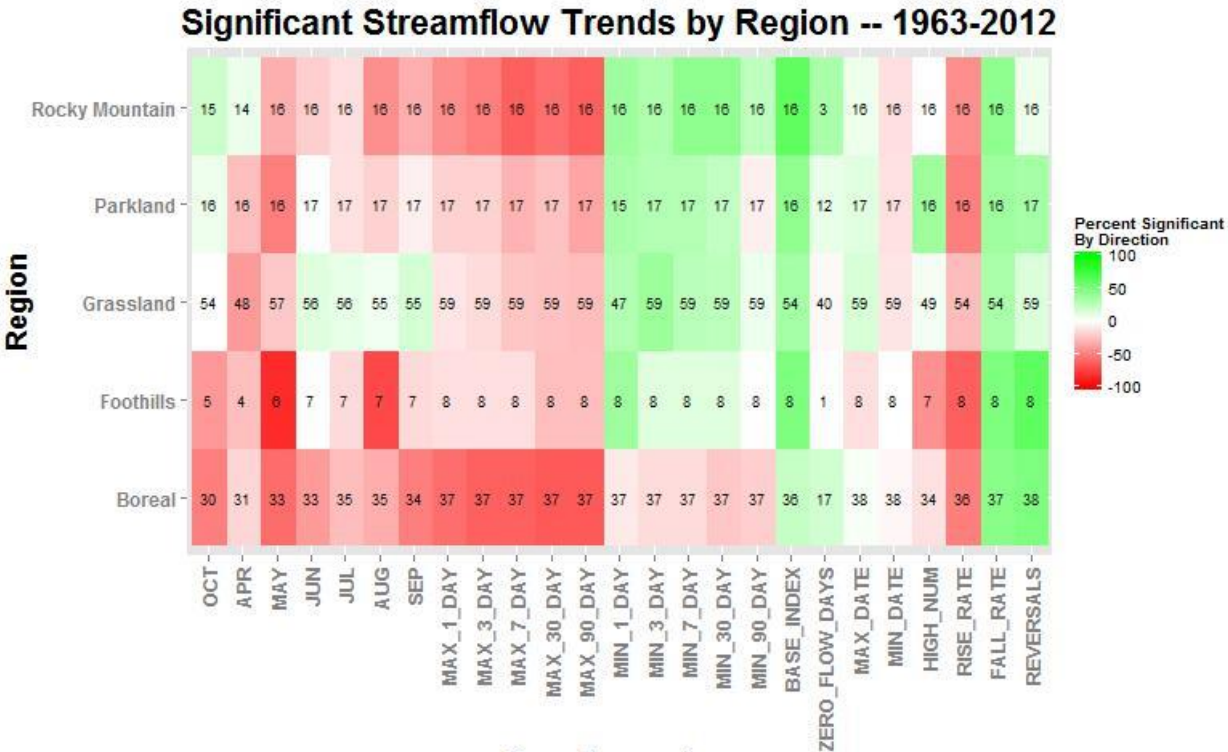
Another issue to consider with the Mann-Kendall trend analysis is the influence of climate oscillation patterns, such as the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Burn, Fan & Bell, 2008; St Jacques, Sauchyn & Zhao, 2010). Significant trends can be artificially detected, while the data is actually being influenced by climate variability patterns. von Storch and Zwiers (1999) discussed a composite analysis approach that examines the link between two sets of variables.

In this case, a subset of the data is taken of the years associated with the ten largest and ten smallest values of ENSO and PDO indices, respectively. The hydrologic indices associated with the largest values and smallest values of each index are then compared to the series mean using a t-test to determine if the mean of the subset is significantly different than the series mean of the whole data set (Burn, Fan & Bell, 2008).

1.4. Results

1.4.1. Mann Kendall Trend Analysis Results

Trends were analyzed across a variety of periods. In order to address the objectives of this study in an adequate yet concise manner, the focus of the results and discussion will be on addressing the data over the 50-year period (1963-2012). It was felt that a 50 year period strikes the right balance between having sufficient data to analyze trends with confidence, having enough stations eligible for analysis to allow for spatial conclusions to be drawn, and to properly assess the influence of the climate oscillation patterns on hydrologic variables, and any subsequent trends found. Figure 3 highlights the overall trends in stream flow variables across eco-regions in Alberta. Spatial trends are shown in Appendix 1.



Region	OCT	APR	MAY	JUN	JUL	AUG	SEP	MAX_1_DAY	MAX_3_DAY	MAX_7_DAY	MAX_30_DAY	MAX_90_DAY	MIN_1_DAY	MIN_3_DAY	MIN_7_DAY	MIN_30_DAY	MIN_90_DAY	BASE_INDEX	ZERO_FLOW_DAYS	MAX_DATE	MIN_DATE	HIGH_NUM	RISE_RATE	FALL_RATE	REVERSALS
Rocky Mountain	15	14	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	3	16	16	16	16	16	16
Parkland	16	16	16	17	17	17	17	17	17	17	17	17	15	17	17	17	17	16	12	17	17	16	16	16	17
Grassland	54	48	57	56	56	55	55	59	59	59	59	59	47	59	59	59	59	54	40	59	59	49	54	54	59
Foothills	5	4	6	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	1	8	8	7	8	8	8
Boreal	30	31	33	33	35	35	34	37	37	37	37	37	37	37	37	37	37	36	17	38	38	34	36	37	38

Figure 2- Trends in streamflow variables across eco-regions in Alberta from 1963-2012. Shown are the percentage of significant ($p < 0.05$) Mann Kendall results from stream gauges by direction (e.g. positive = green, negative = red). The number of stations showing a significant trend are overlaid on each cell.

Note that many hydrologic variables were not measured at a sufficient number of stations. This paper will only address the variables that were measured at least 10% of stations across the province for a given period. These variables include: November, December, January, February, March, High Pulse Length, Low Pulse Length and Low Pulse Number.

1.4.1.1. Monthly Median Streamflow (Group 1)

The monthly magnitude flow variables showed large decreases province wide (Table 2). All seven months analyzed showed negative trends , with the highest proportion of significant negative results occurring with May streamflow magnitude at nearly 50% of stations.

Table 2: Trends in Monthly Flow Magnitudes

Monthly Magnitude Variables	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
		Positive	Negative
October	121	18%	30%
April	114	13%	37%
May	129	9%	48%
June	130	18%	25%
July	132	14%	22%
August	131	14%	32%
September	130	18%	31%

The percentage of stations showing positive trends ranged from 0-33% for all regions for monthly magnitude variables, while the percentage of stations showing negative trends ranged from 7-61%. Five circumstances occurred where a particular region had at least 50% of its stations with a significant negative trend (Table 3). The Rocky Mountain region was the sole region without a majority of stations exhibiting significant negative trends.

Table 3: Regions where 50% of stations showed significant negative trends for monthly magnitude variables.

Monthly Magnitude Variables	Region	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Negative Trends
October	Boreal	30	53%
April	Grassland	48	50%
May	Boreal	33	61%
May	Parkland	16	50%
September	Boreal	34	50%

Figure 3 shows spatial variation is evident across Alberta's region. All regions experienced overall negative trends in April and May streamflows. However, more variation was experienced in summer and fall months, where the Grassland region experienced an overall positive trend, whereas the other four regions experienced various levels of overall negative trends.

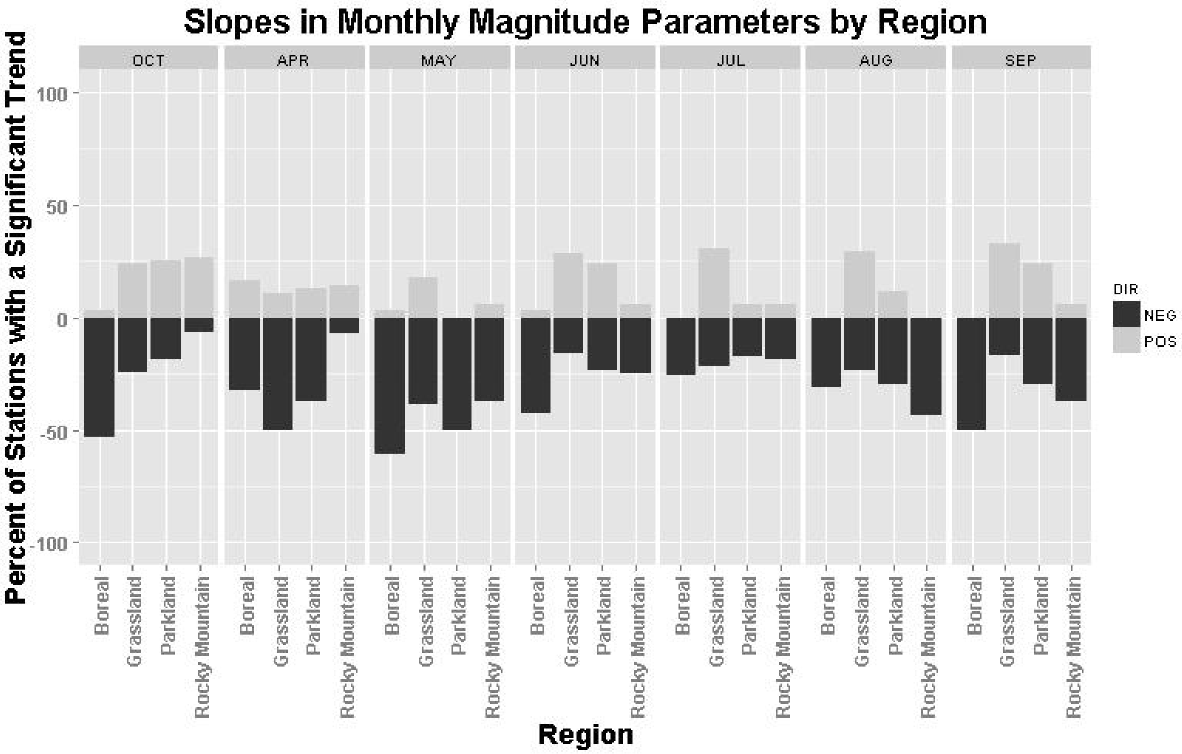


Figure 3: Trends in monthly median streamflow (Group 1) across eco-regions in Alberta from 1963-2012. Shown are the percentage of significant ($p < 0.05$) Mann Kendall results from stream gauges by direction (e.g. positive = grey, negative = black).

1.4.1.2. Magnitude and Duration of Annual Extreme Conditions (Group 2)

The overall provincial results are found in Table 4. The results for all maximum were consistent with one another, with the percentage of stations exhibiting a positive trend ranging from 6% to 11%, while the percentage of stations showing negative trends ranged from 39% to 50%. The opposite was found for minimum flow condition variables, with 29-39% of stations showing significant positive trends and 17-28% of stations showing significant negative trends.

Table 4: Trends in Annual Extreme Conditions

Annual Extreme Streamflow Condition Variables		Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
			Positive	Negative
Maximum	1-Day Flow	138	11%	39%
	3-Day Average Flow	138	8%	40%
	7-Day Average Flow	138	6%	44%
	30-Day Average Flow	138	8%	47%
	90-Day Average Flow	138	8%	50%
Minimum	1-Day Flow	124	35%	15%
	3-Day Average Flow	138	39%	17%
	7-Day Average Flow	138	36%	18%
	30-Day Average Flow	138	36%	21%
	90-Day Average Flow	138	29%	28%

Regional results for significant trends in the various maximum and minimum extreme flow conditions were largely consistent across all variables (ie. the 1-day maximum flow for stations in the Boreal region were similar to those of the 3-, 7-, 30- and 90-day maximum flow variables). Figure 4 and Table 5 depict the decreasing nature of the maximum flow condition variables and the largely increasing attribute of the minimum flow conditions.

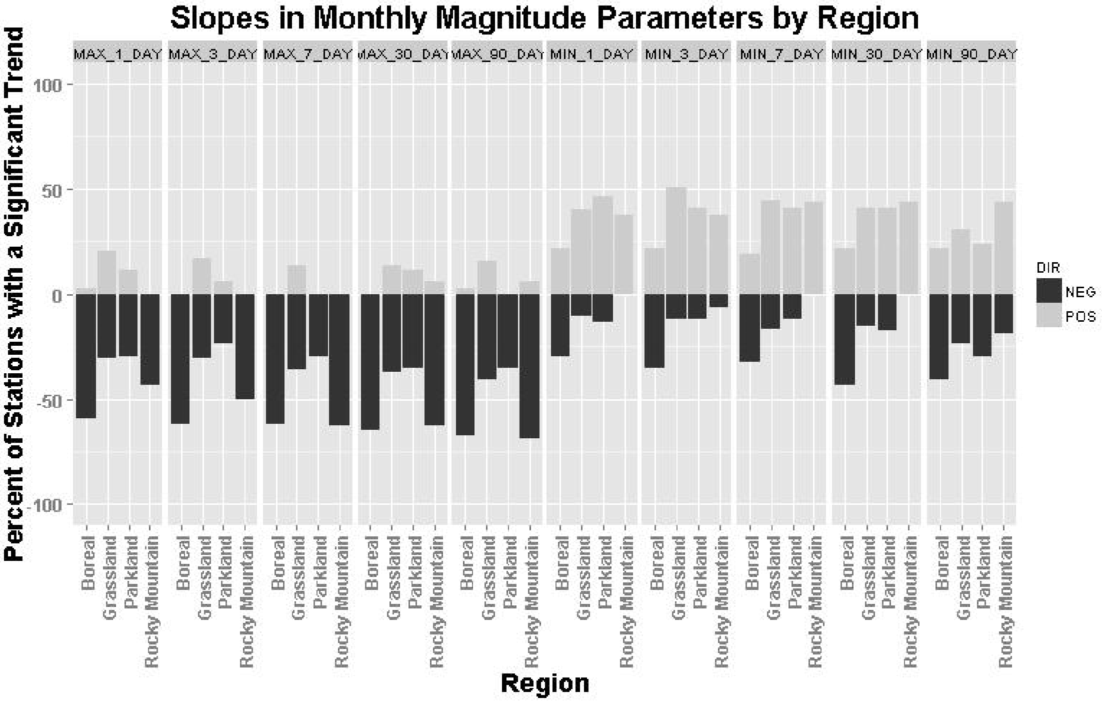


Figure 4: Trends in magnitude and duration of extreme conditions (Group 2) across eco-regions in Alberta from 1963-2012. Shown are the percentage of significant ($p < 0.05$) Mann Kendall results from stream gauges by direction (e.g. positive = grey, negative = black).

The Boreal and Rocky Mountain regions were found to have a greater percentage of stations exhibiting negative significant trends, averaging 63% and 58%, respectively. Comparatively, the average percentage of stations with significant negative stations for maximum flow conditions in the Foothills, Grassland and Parkland regions ranged from 18-35%. Most regions also exhibited positive trends; however the proportion of stations exhibiting negative trends was far higher in all regions. The opposite was generally found for minimum flow condition variables. Four of the five regions experienced higher percentage of stations showing positive trends than negative trends, with the exception of the Boreal region. This reflects the overall provincial trend results found in Table 6.

Table 5: Average proportion of stations showing significant trends across all extreme flow condition variables.

Group 2 Variables	Boreal		Foothills		Grassland		Parkland		Rocky Mountain	
	P	N	P	N	P	N	P	N	P	N
Maximum Flow Variables	1%	63%	0%	18%	16%	35%	6%	31%	3%	58%
Minimum Flow Variables	21%	36%	28%	13%	41%	16%	39%	17%	41%	5%

1.4.1.3. Timing of Annual Extreme Conditions (Group 3)

The overall provincial results for the trends in timing of annual extreme flow events are found in Table 6. Only 29% of stations had a significant trend for the date of the annual maximum daily flow, while 37% had a significant trend for the date of the annual minimum daily flow. In general, the Julian date of the maximum flow is increasing, meaning the 1-day maximum daily flow is occurring later in the year. However, the opposite was found for the Julian date of the minimum flow. Slightly more stations experienced a negative trend than a positive trend. As a result, on average, the 1-day minimum daily flow earlier in the year.

Table 6: Trends in Timing of Annual Extreme Streamflow Conditions

Timing of annual extreme conditions	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
		Positive	Negative
Date of the annual maximum daily flow	139	19%	10%
Date of the annual minimum daily flow	139	15%	22%

Regional results are slightly variable. As illustrated in Figure 5 and Table 7, the Boreal region is relatively evenly split between significant positive and negative trends for both the date of the maximum flow and the date of the minimum flow. However, the Grassland, Parkland and Rocky Mountain regions are all showing different trends between the two parameters, which reflect the findings illustrated in Table 8. That is, all three regions are showing more positive trends than negative for the date of the maximum flow, and vice-versa for the date of the minimum flow.

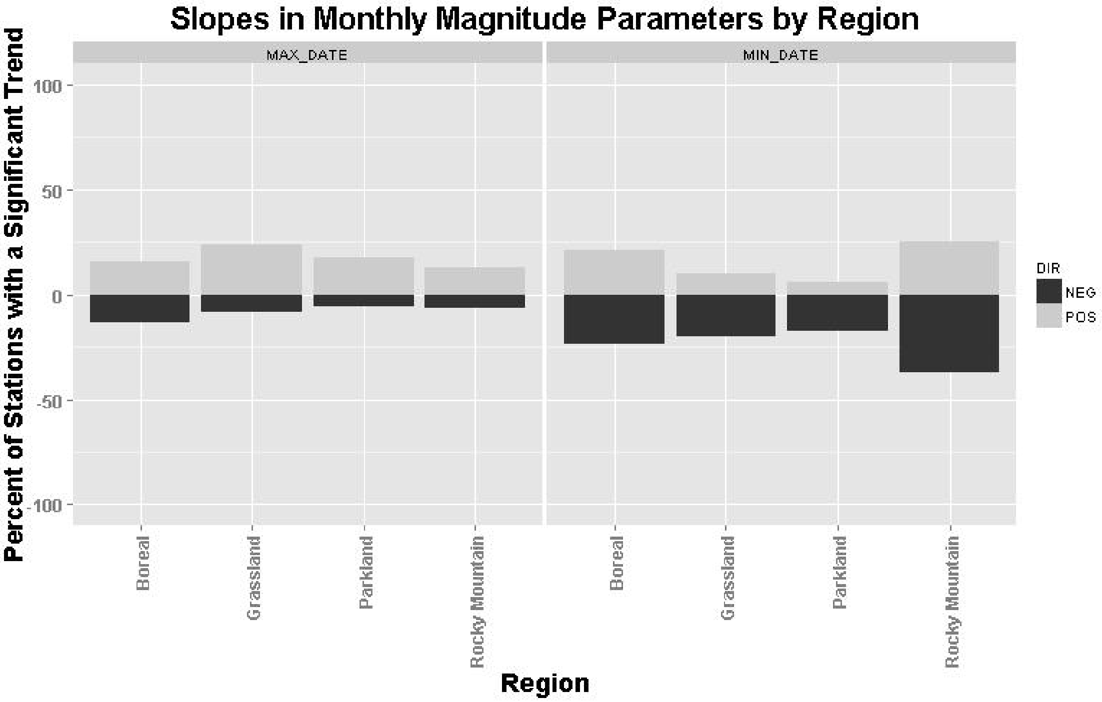


Figure 5: Trends in timing of extreme conditions (Group 3) across eco-regions in Alberta from 1963-2012. Shown are the percentage of significant ($p < 0.05$) Mann Kendall results from stream gauges by direction (e.g. positive = grey, negative = black).

Table 7: Regional Results for Group 3 parameters.

Timing of annual extreme conditions	Region	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
			Positive	Negative
Date of the annual maximum daily flow	Boreal	38	16%	13%
	Grassland	59	24%	8%
	Parkland	17	18%	6%
	Rocky Mountain	16	13%	6%
Date of the annual minimum daily flow	Boreal	38	21%	24%
	Grassland	59	10%	20%
	Parkland	17	6%	18%
	Rocky Mountain	16	25%	38%

1.4.1.4. Frequency and Duration of High and Low Pulses (Group 4)

Only one of the four variables within this group was eligible for analysis: the high number of streamflow pulses. 123 stations were eligible for analysis for this variable. 17% showed significant positive trends, while 16% showed significant negative trends. Table 10 illustrates the variation displayed across Alberta's regions. The Parkland and Grassland regions included more stations displaying positive trends than negative, while the opposite was true for the Boreal region.

Table 8: Regional results for Group 4 variables.

Frequency and Duration Variable	Region	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
			Positive	Negative
Number of High Pulses	Boreal	34	6%	18%
	Grassland	49	24%	20%
	Parkland	16	38%	0%
	Rocky Mountain	16	6%	6%

1.4.1.5. Rate and Frequency of Change in Water Conditions (Group 5)

The trend results reflect a "flattening" of hydrographs across the province. The rise rate, or the amount the flow increases from one day to the next is decreasing, while the fall rate, or the amount the flow decreases from one day to the next is also decreasing. However, the number of reversals, or the number of times streamflow went from increasing to decreasing or vice-versa, increased over the same time period. In other words, streamflow across the province is changing more frequently, but in smaller increments.

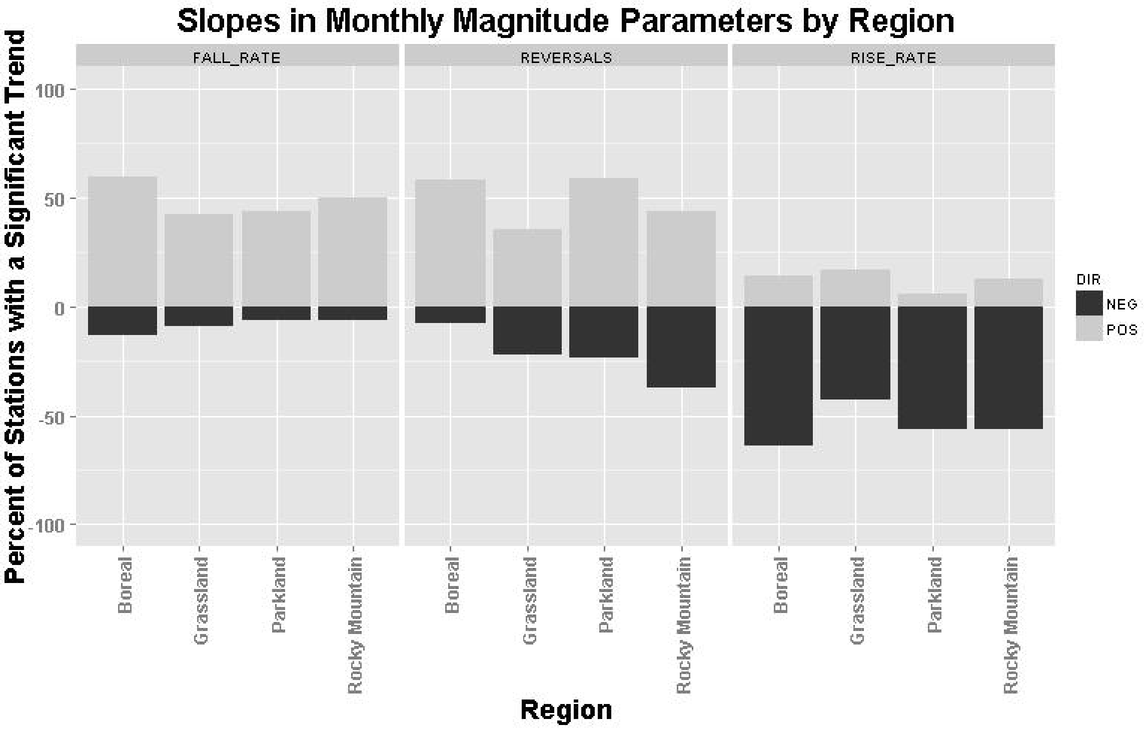


Figure 6: Trends in monthly magnitude (Group 5) across eco-regions in Alberta from 1963-2012. Shown are the percentage of significant ($p < 0.05$) Mann Kendall results from stream gauges by direction (e.g. positive = grey, negative = black).

Table 9: Trends in Streamflow Rate Parameters

Rate and Change Frequency Variables	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
		Positive	Negative
Rise Rate	131	14%	53%
Fall Rate	132	10%	48%
Number of Streamflow Reversals	139	47%	19%

All regions follow this pattern as well. They all experienced a higher level of negative trends than positive trends for rise rate, and vice-versa for fall rate (Figure 6).

1.4.1.6. Climate Parameters

Seasonal variation was evident for all five climate parameters analyzed (Table 10). Temperatures were found to be increasing throughout Alberta in all seasons. The majority of stations showed an increasing winter temperature, while the trends for all the temperature variables for other seasons ranged from 18-34%. There was also a notable decrease in winter precipitation.

Table 10: Trends in Seasonal Climate Variables

Climate Variable	Season	Total Number of Stations Eligible for Analysis	Percentage of Stations with Significant Trends	
			Positive	Negative
Precipitation as Snow (PAS)	Fall	133	0%	20%
	Winter	119	0%	95%
	Spring	129	3%	9%
	Summer	102	0%	0%
Precipitation (PPT)	Fall	133	1%	2%
	Winter	119	0%	95%
	Spring	133	14%	1%
	Summer	134	26%	0%
Average Temperature (Tave)	Fall	139	32%	0%
	Winter	139	76%	0%
	Spring	139	34%	0%
	Summer	139	29%	1%
Maximum Temperature (Tmax)	Fall	139	27%	0%
	Winter	139	76%	0%
	Spring	139	18%	0%
	Summer	139	29%	0%
Minimum Temperature (Tmin)	Fall	139	31%	4%
	Winter	139	78%	0%
	Spring	139	34%	0%
	Summer	139	27%	40%

The patterns seen in Table 10 largely remain the same. All regions experience relatively little change in fall precipitation followed by significant decreasing winter precipitation. Spring precipitation remained relatively constant as well, with only the Boreal region showing significant change, with 37% of stations showing significant positive trends. Summer precipitation ranged from 0% (Grassland) to 61% (Boreal) of stations showing increasing trends.

Figures 7 illustrates the regional variation for precipitation and average temperature.

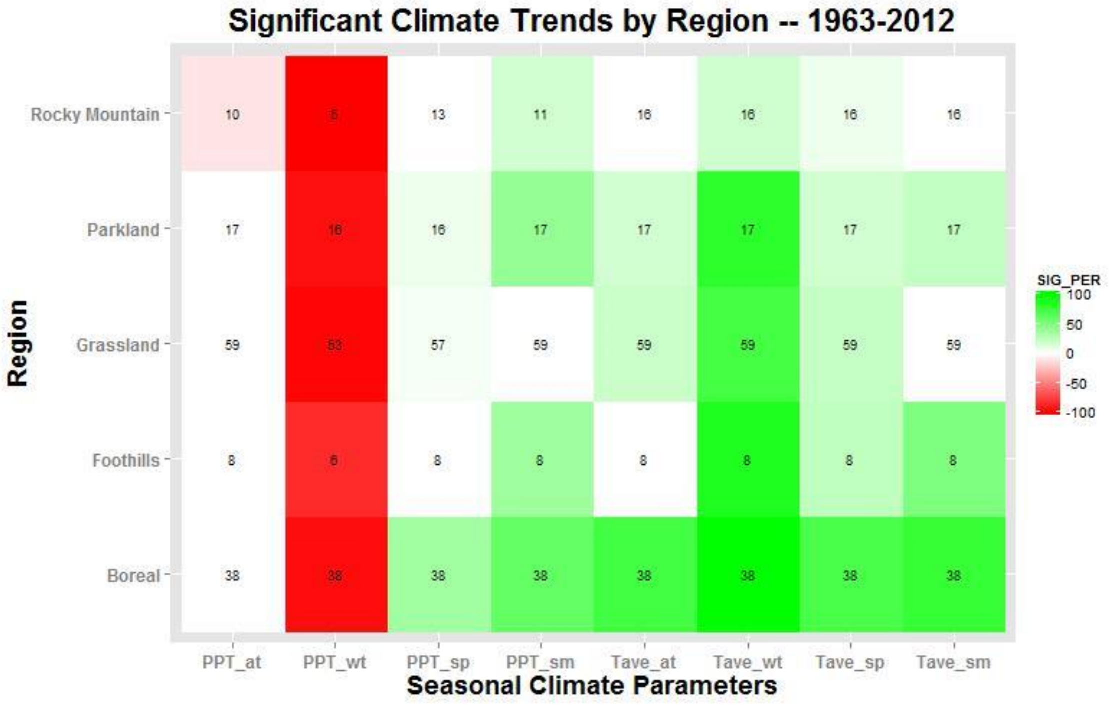


Figure 7 - Trends in climate variables across eco-regions in Alberta from 1963-2012. Shown are the percentage of significant ($p < 0.05$) Mann Kendall results from stream gauges by direction (e.g. positive = green, negative = red). The number of stations showing a significant trend are overlaid on each cell.

Seasonal average temperatures were found to be increasing within most regions for all seasons. Only two regions experienced no change in average temperature in a particular season: the Grassland Rocky Mountain regions both experienced no changes in summer average temperature. The Boreal region consistently included the highest proportion of stations showing increasing trends, ranging from 71-100% and averaging 81% of stations.

1.4.2. Detecting the Impact of the Climate Oscillation Patterns

The influence of the ENSO and PDO patterns was analyzed to determine whether they influenced the detection of significant trends in the hydrologic variables. A composite analysis approach was used to determine if the hydrologic variables in years exhibiting low ENSO or PDO were significantly different from those in years exhibiting high ENSO or PDO metrics.

For the 30-, 40-, 50-, 60- and 70-year periods, only seven variables had at least 20% of stations across the province had significantly different data subsets for high and low PDO years: April, June, July, Max 90-day flow, base index, rise rate and fall rate (Table 11). Only one variable had greater than 30% of stations with significant results: June flow during the 70-year period.

Table 11: Composite Analysis results indicating the influence of PDO one various flow characteristics across a variety of periods.

Variable	Period	Percent of Stations with Significant Results	Total Number of Stations
April	1943-2012	21%	33
June	1943-2012	42%	33
June	1953-2012	30%	64
June	1963-2012	26%	138
July	1943-2012	24%	33
Maximum 90-Day Average Flow	1943-2012	27%	33
Fall Rate	1943-2012	27%	33
Rise Rate	1943-2012	27%	33
Rise Rate	1953-2012	23%	64

The regional results for the 1963-2012 period only had two circumstances where at least 50% of stations within a region were impacted by PDO at a significant level: the Rocky Mountain and Foothills regions for June streamflow.

Table 12: Regional composite analysis results for the 1963-2012 period.

Variable	Period	Region	Percent of Stations with Significant Results	Total Number of Stations
June	1963-2012	Foothills	75 %	8
June	1963-2012	Rocky Mountain	56 %	16

In comparison, only one variable for one year resulted in at least 20% of stations with significant results. Over the 70-year period, 21% of stations in Alberta measured July flows that were significantly different in high-ENSO metric years to those flow in low-ENSO metric years. No regions were found to have at least 50% of stations were significantly impacted by PDO for the 1963-2012 period.

1.5. Relevance and Impact

1.5.1.What do the project results mean for Albertans?

In Alberta, water extraction in conjunction with dramatic economic growth, increased human population, and changes in land-use, has led to serious concerns about the sustainability of water and groundwater resources (King, 2004; Milly et al., 2008). Consequently in the coming years, it is expected that many Alberta streams will face water shortages (Schindler & Donahue, 2006). With growing industrial demand for freshwater and long-term predictions of increased drought from climate change (RSC, 2010; King, 2004), these predictions are only likely to worsen. Understanding the ecological impacts of water extraction represents a key opportunity for research that can best address these looming water crises and to develop mitigation efforts.

There has been a dramatic decline in freshwater fish biodiversity globally, and this is true for Alberta (Ricciardi & Rasmussen, 2001; Abbitt & Scott, 2001; Ehrlich & Wilson, 1991; Hutchings & Festa-Bianchet, 2009; Jelks et al., 2008; Ricciardi & Rasmussen, 1999). Freshwater fish provide forage for other biota, drive ecosystem properties, and are indicators of aquatic ecosystem health (Jackson, Peres-Neto & Olden, 2001; Olden et al., 2010; Poff & Allan, 1995).

1.5.2.Do the project results inform a provincial strategy, policy, regulation or operational practice?

This research can help address concerns over provincial water apportionment and other transboundary agreements, with the potential to help improve Alberta's policies that address in-stream flow needs (IFN), and in particular inform the Water for Life Strategy, and the Regional Plan process(Wenig, Kwasniak & Quinn, 2006; Anderson et al., 2006).

The Water for Life Strategy was released 10 years ago to describe Alberta's commitment to the wise management of our province's water resources for the benefit of all Albertans. The strategy has three main goals: safe, secure drinking water; healthy aquatic ecosystems; and reliable, quality water supplies for a sustainable economy. These goals are to be met through knowledge and research, partnerships, and water conservation. This project has helped support the latter two goals through developing knowledge and research to understand the drivers of healthy aquatic ecosystems and their interactions between water use/withdrawals which allow understanding around the balance between environmental protection and a sustainable economy.

1.5.3.Qualitative and quantitative (where possible) discussion about the economic, environmental, and social benefits resulting from the completed project, including immediate benefits and potential future impacts.

Stream hydrology is closing link to the maintenance of freshwater biodiversity. Losses of freshwater fishes have important consequences to Albertans. Freshwater fish provide ~ 15% of animal protein to global diets, including an important component to Aboriginal peoples (FAO, 2010). Further, fisheries provide an enormous economic value to Alberta. For example, > 250,000 Albertans bought recreational fishing licenses, representing $171 million of direct annual expenditures into the Alberta economy, and $676 million worth of attributable purchases (DFO, 2010).

1.6. Overall Conclusions

There was large variation in flow conditions across eco-regions in Alberta. Overall, stream flows have decreased significantly across the province. For example, median monthly flows showed a strong decline throughout most of Alberta, although it was more pronounced in the foothills and boreal eco-regions. There was also a strong decline in maximum minimum extreme flow conditions across all variables (i.e. the 1-3-, 7-, 30- and 90-day maximum flow variables), most prominently in the Boreal and Rocky Mountain eco-regions. Overall, there was a "flattening" of hydrographs across the province. The rise rate, or the amount the flow increases from one day to the next decreased, as did the fall rate, or the amount the flow decreases from one day to the next. There were no trends in the timing of annual extreme flows or the number of high stream pulses. There was a broad increase in temperature throughout Alberta. Precipitation was significantly higher in the spring. Snow showed a significant decline across all of Alberta. These trends do not appear to be driven by climatic oscillations such as El Niño–Southern Oscillation or the Pacific Decadal Oscillation.

1.7. Next Steps

The results of this report will be used to develop a Master's thesis (expected in spring 2017) as well as two scientific publications.

1.8. Communication Plan

This research was and will continue to be communicated to the public and stakeholders through regional, national and international conferences, workshops, as well as meetings with stakeholders (e.g., industry, watershed councils, and other multi-stakeholder groups). The results of our research will also be communicated more broadly to suitable media (e.g., print newspapers, magazines), via the internet (e.g., UofA website), and through scientific publications.

1.9. Scientific Achievements

1.9.1.Publications

Neufeld, K., Watkinson, D., and **M.S. Poesch**. 2015. The effect of hydrologic alteration on capture efficiency of freshwater fishes in a highly modified Prairie stream: Implications for bio-monitoring programs. River Research and Applications. DOI: 10.1002/rra.2913.

Neufeld, K., Watkinson, D., Tierney, K. and **M.S. Poesch**. (In Review). Incorporating connectivity in measures of habitat suitability to assess impacts of hydrologic alteration to stream fish. Ecological Applications (EAP16-0673).

1.9.2.Presentations at scientific meetings, public events and media appearances

Neufeld, K., Watkinson, D., Tierney, K., and M.S. Poesch. Augmented flow may restrict the movement potential and habitat availability of the threatened Western Silvery Minnow (*Hybognathus argyritis*) in a prairie river. May, 2015, Regulated Rivers Conference, Castlegar, B.C.

Poesch, M.S. The impact of hydrologic alteration on freshwater fishes in Alberta. Alberta Innovates, Water Research Symposium, May 27, 2015, Calgary AB.

Neufeld, K., Watkinson, D., and M.S. Poesch. Incorporating Movement Potential with Habitat Suitability Models: Implications for the Threatened Western Silvery Minnow (*Hybognathus argyritis*) in an Augmented Prairie River. August 22, 2015, American Fisheries Society, Portland, Oregon.

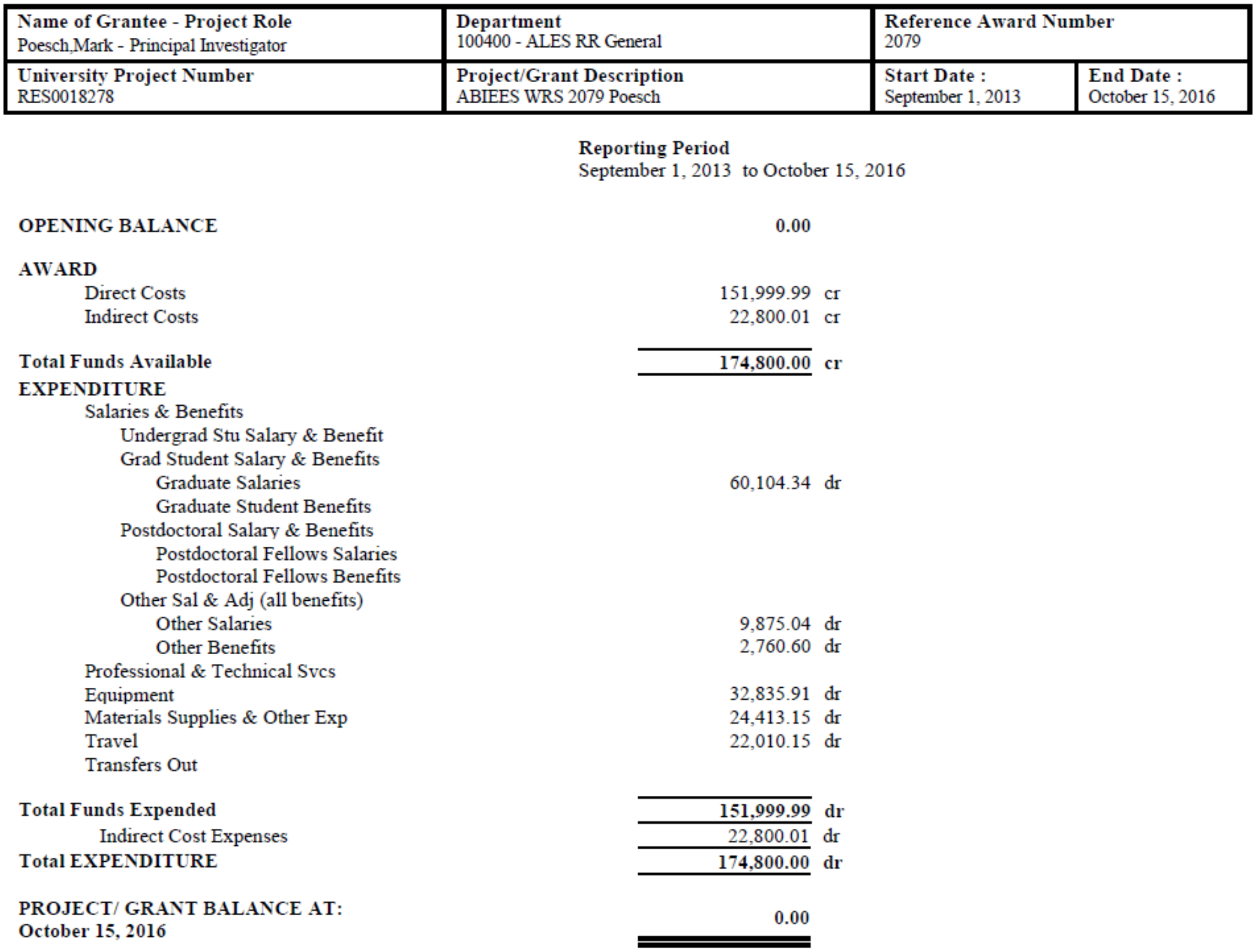
Hamilton, K., and M.S. Poesch**.** Assessing the Ecological Impacts of Water Extraction on Stream Hydrology and Alberta's Fish Community Structure and Function. FLOW 2015, Portland, Oregon.

Poesch, M.S. and W.K. Hamilton. Assessing the effect of hydrologic alteration on Alberta's natural flow regime. Alberta Water Innovation Forum. May 31, 2016, Edmonton, Alberta.

1.9.3. List of highly qualified personnel

1) Kyle Hamilton, MSc student (2014- Current)
2) Neufeld, Kenton, MS student (2013-2016)
3) Shubha Pandit, Post-doctoral fellow (2014-2015) – in-kind support for analyses

2.0 Financial Report



Name of Grantee - Project Role Poesch,Mark - Principal Investigator	**Department** 100400 - ALES RR General	**Reference Award Number** 2079	
University Project Number RES0018278	**Project/Grant Description** ABIEES WRS 2079 Poesch	**Start Date :** September 1, 2013	**End Date :** October 15, 2016

Reporting Period
September 1, 2013 to October 15, 2016

OPENING BALANCE	**0.00**	
AWARD		
Direct Costs	151,999.99	cr
Indirect Costs	22,800.01	cr
Total Funds Available	**174,800.00**	**cr**
EXPENDITURE		
Salaries & Benefits		
Undergrad Stu Salary & Benefit		
Grad Student Salary & Benefits		
Graduate Salaries	60,104.34	dr
Graduate Student Benefits		
Postdoctoral Salary & Benefits		
Postdoctoral Fellows Salaries		
Postdoctoral Fellows Benefits		
Other Sal & Adj (all benefits)		
Other Salaries	9,875.04	dr
Other Benefits	2,760.60	dr
Professional & Technical Svcs		
Equipment	32,835.91	dr
Materials Supplies & Other Exp	24,413.15	dr
Travel	22,010.15	dr
Transfers Out		
Total Funds Expended	**151,999.99**	**dr**
Indirect Cost Expenses	22,800.01	dr
Total EXPENDITURE	**174,800.00**	**dr**
PROJECT/ GRANT BALANCE AT: **October 15, 2016**	**0.00**	

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4.0 Appendices

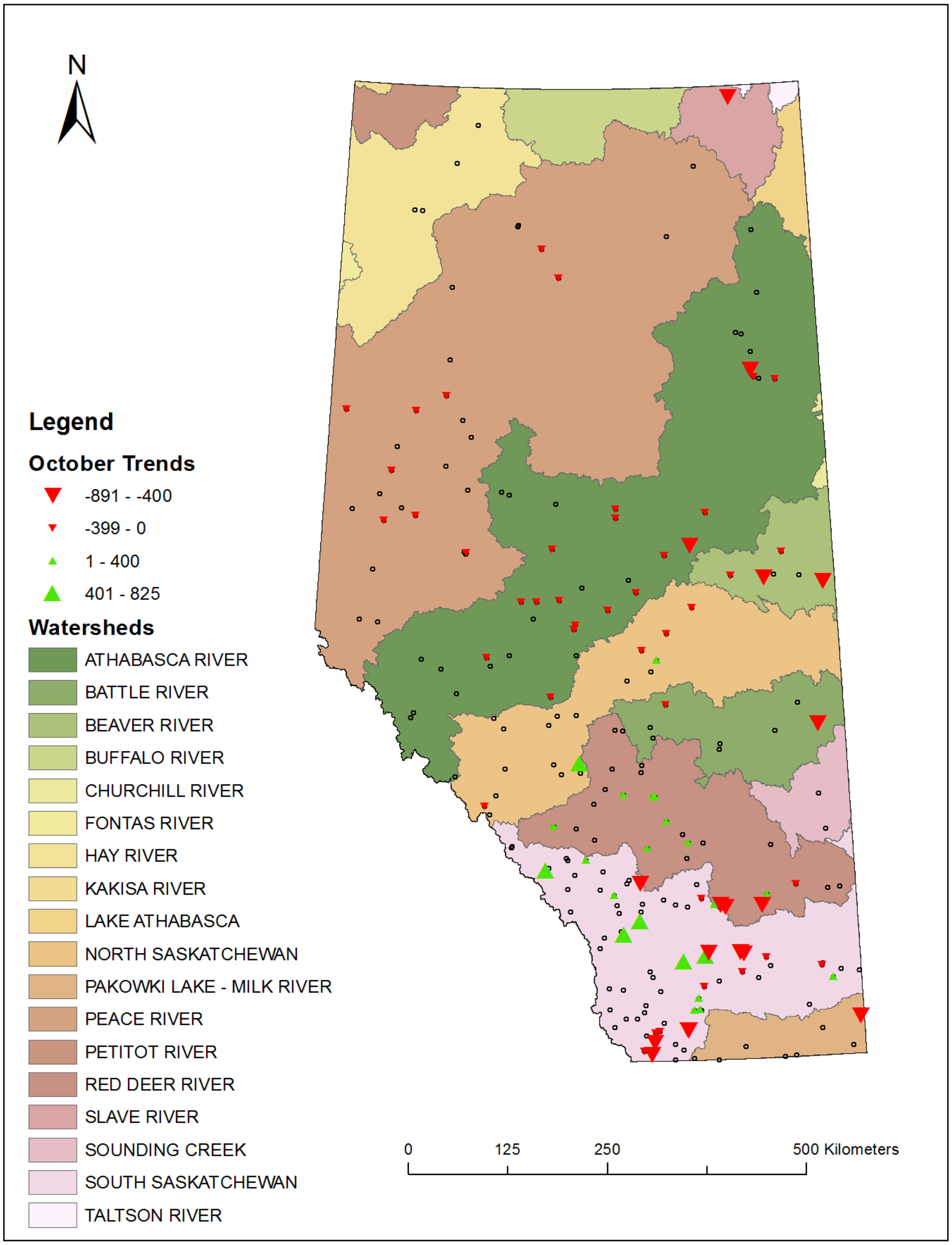

Figure 8: Trends for October median streamflow. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

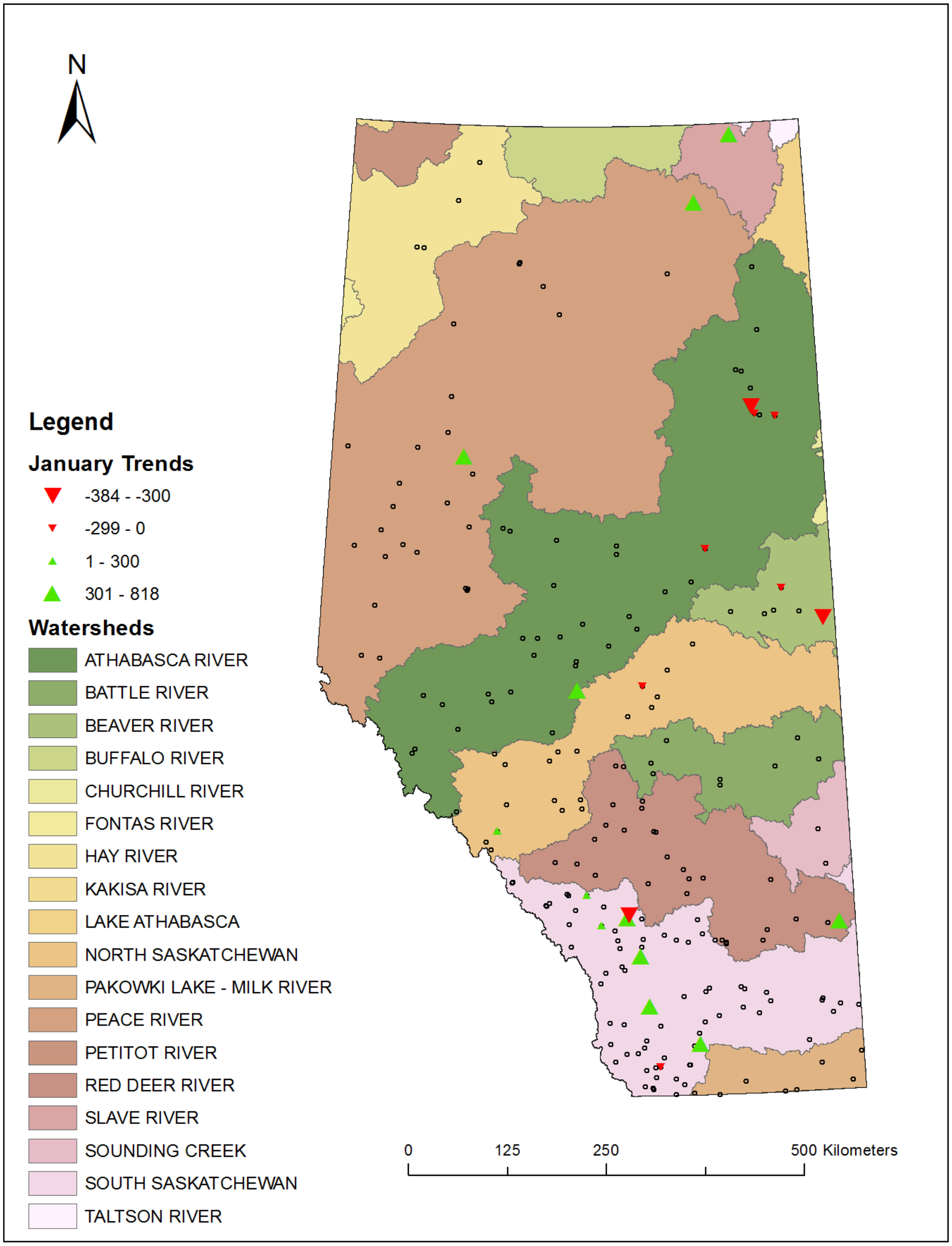

Figure 9: Trends for January median streamflow. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

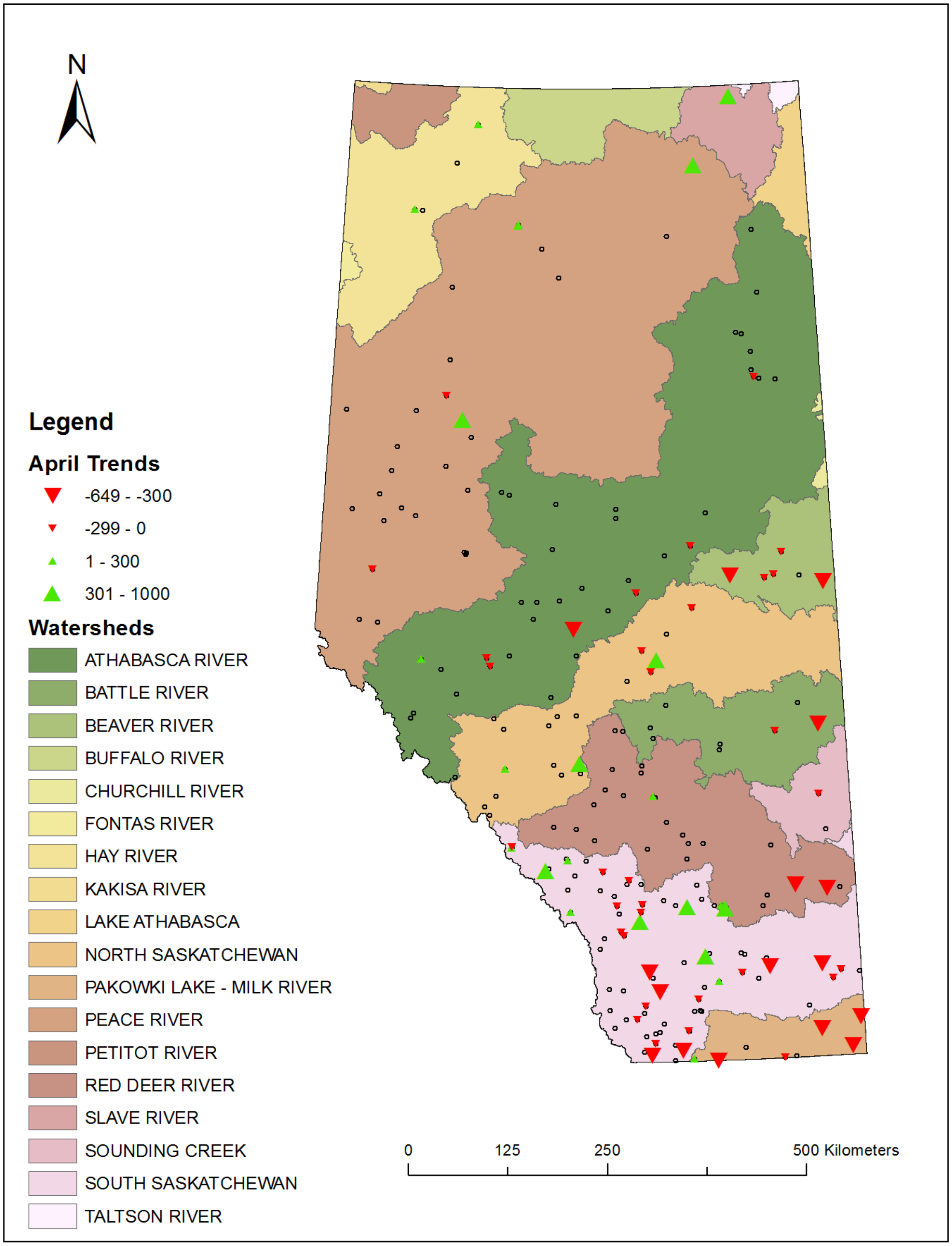

Figure 10: Trends for April median streamflow. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

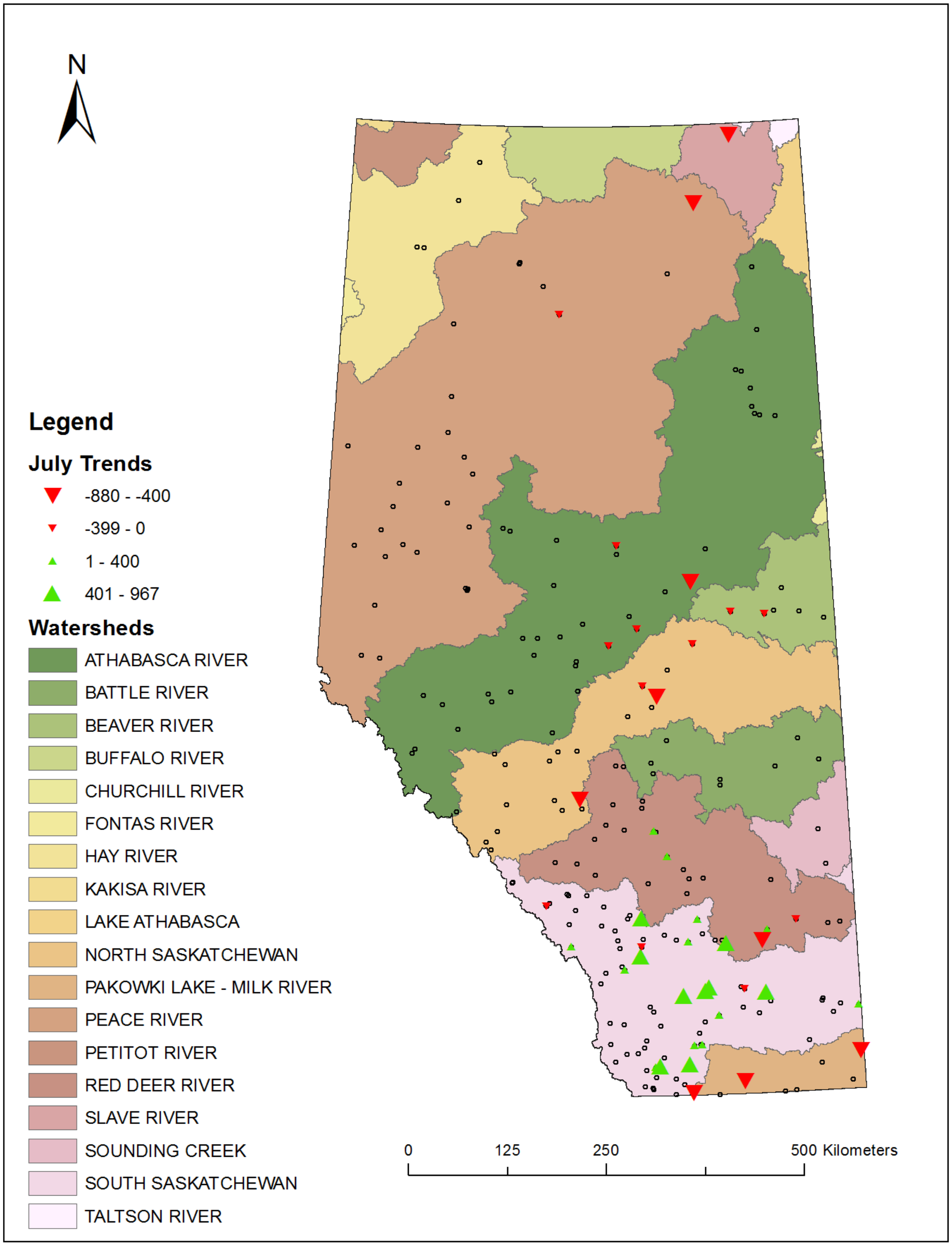

Figure 11: Trends for July median streamflow. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

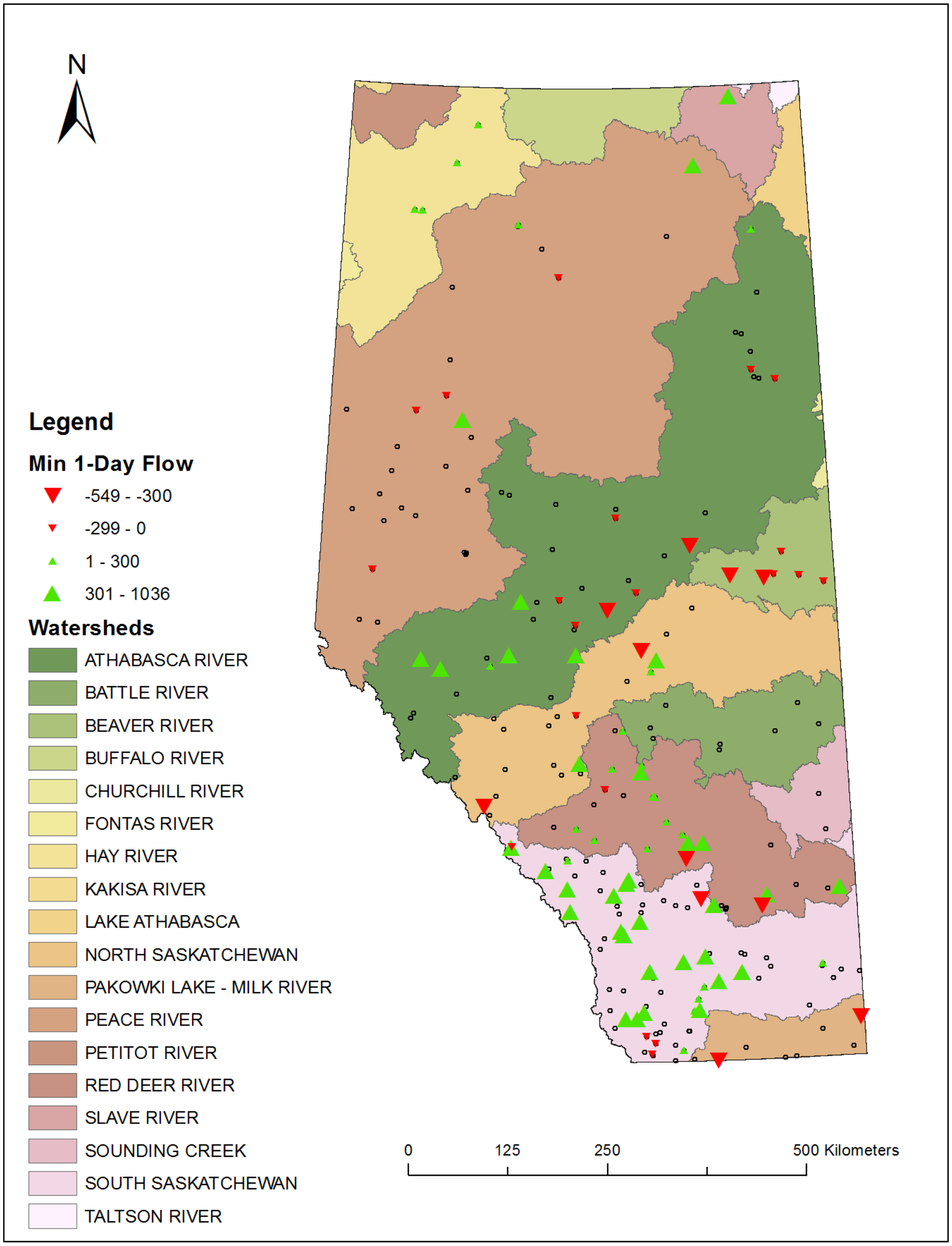

Figure 12: Trends for minimum 1-day streamflow. Shown are the number of significant (p<0.05) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

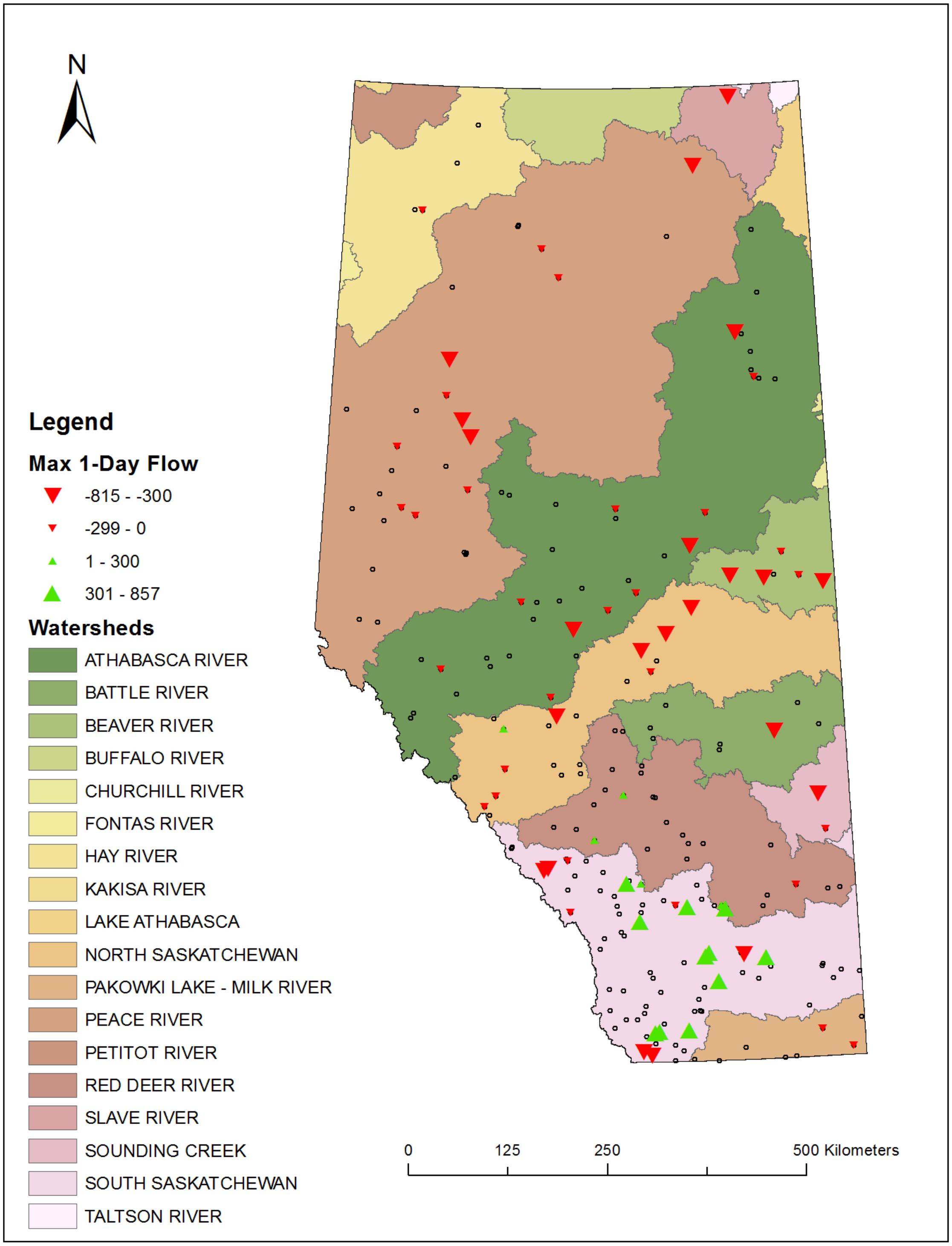

Figure 13: Trends for maximum 1-day streamflow. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

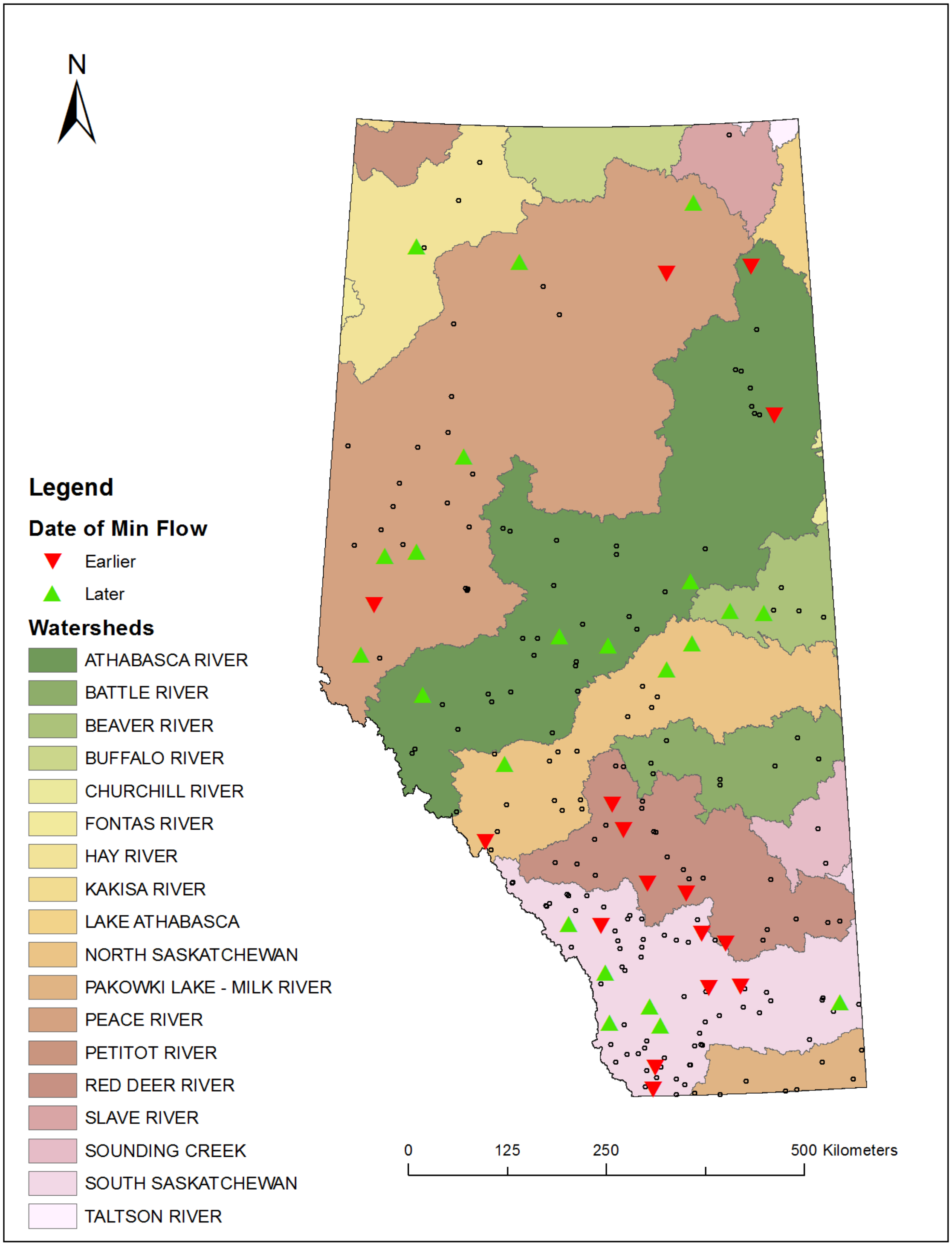

Figure 14: Trends for the date in which the minimum daily flow occurs Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

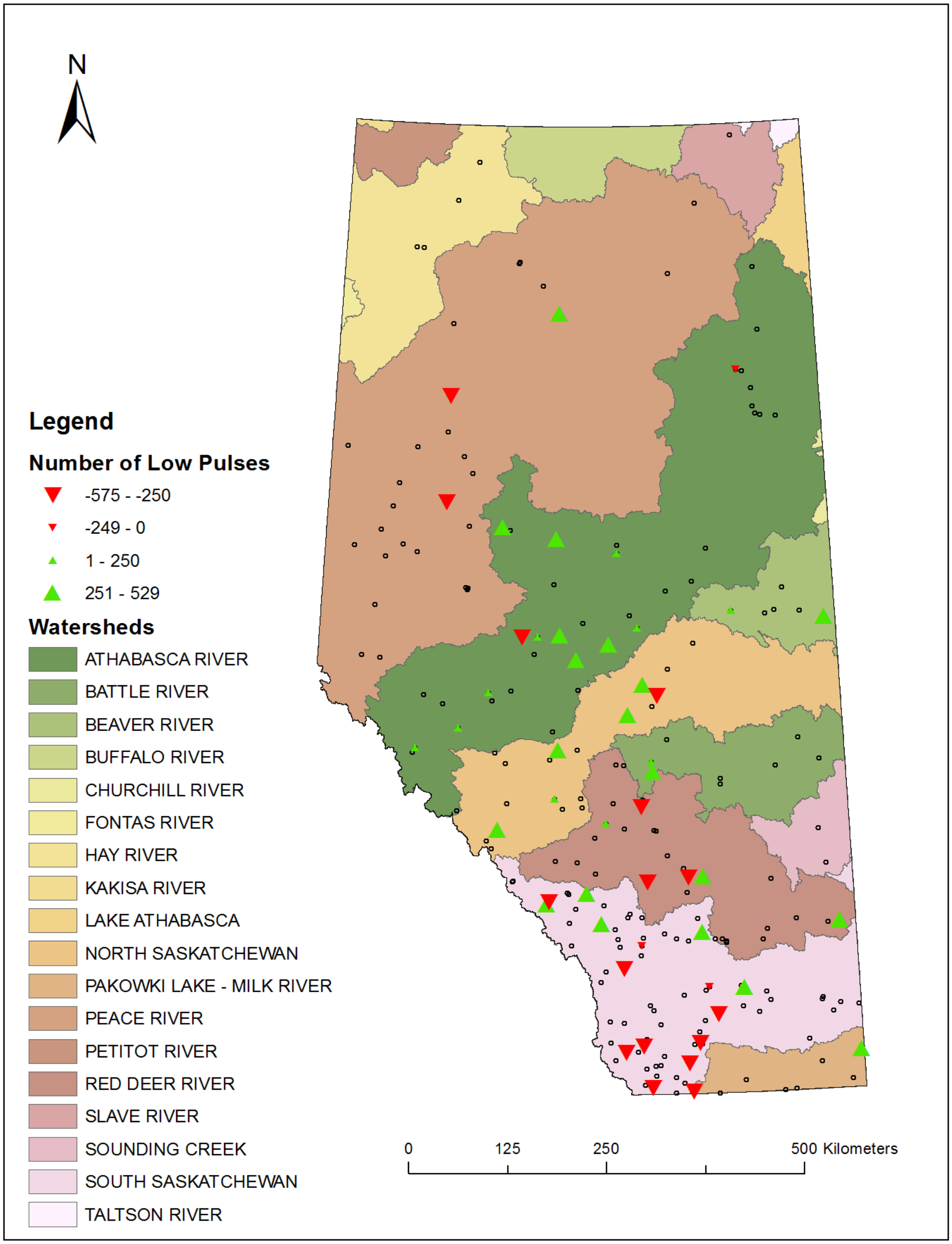

Figure 15: Trends in the number of low pulses per year. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

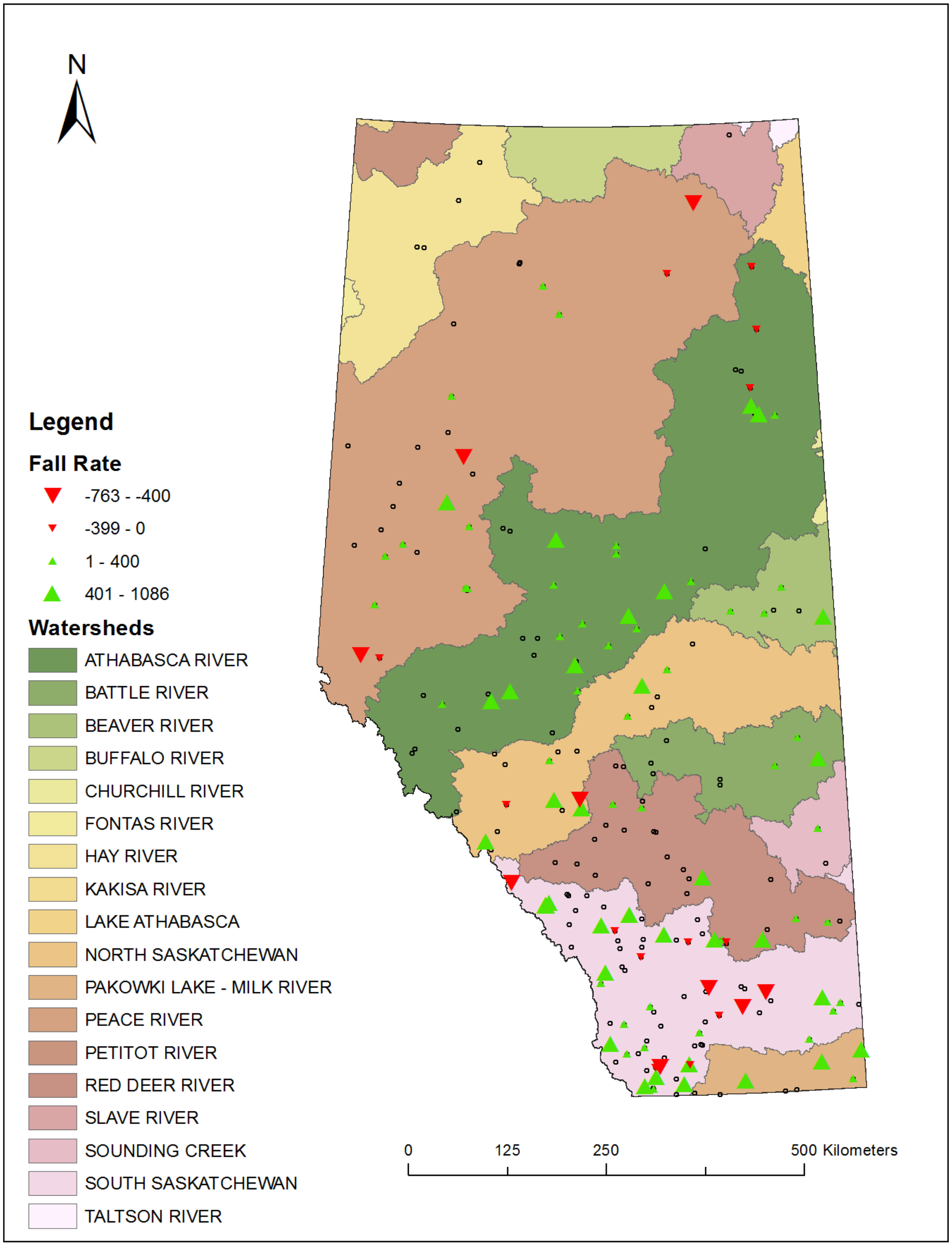

Figure 16: Trends in the annual average fall rate. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

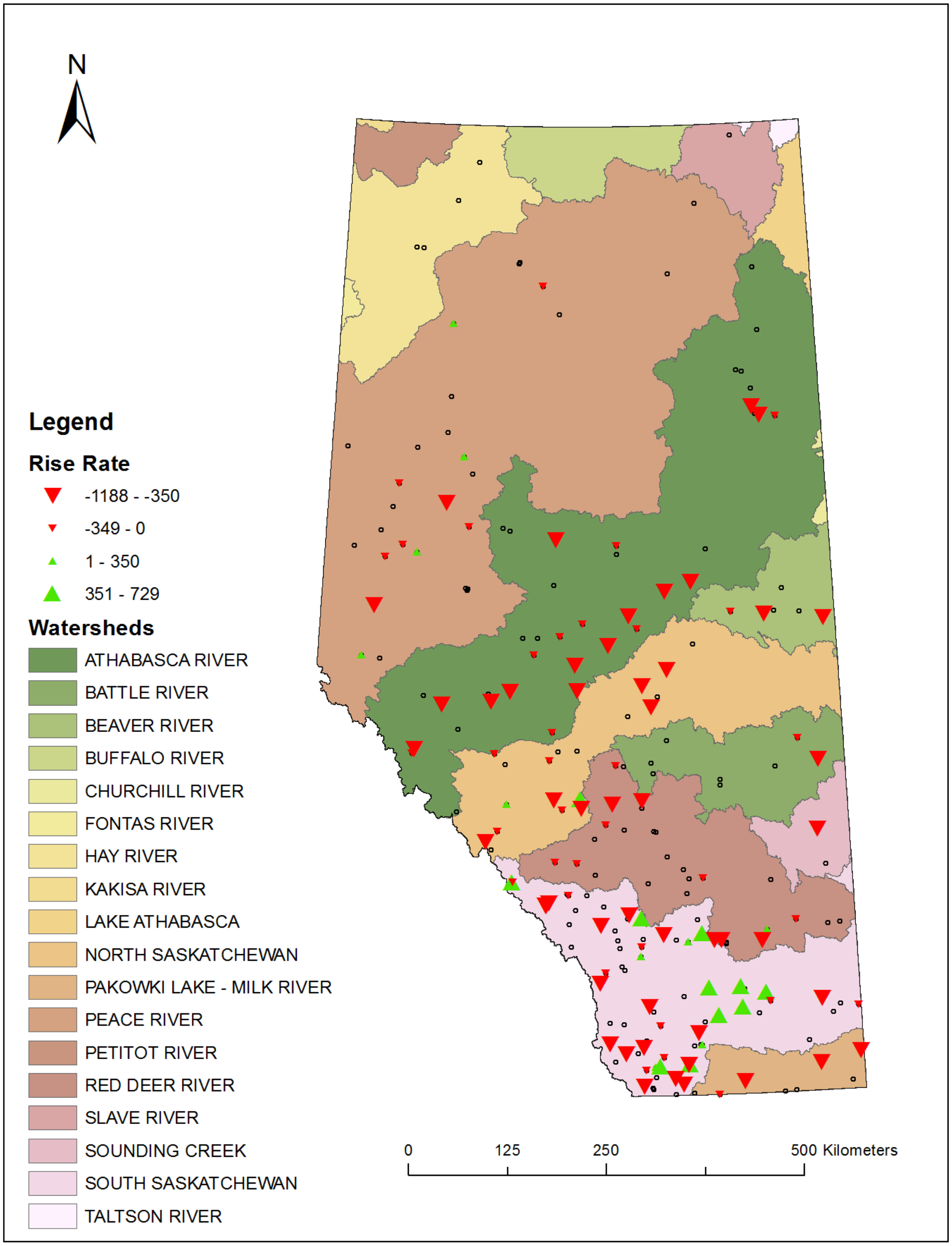

Figure 17: Trends in the annual average rise rate. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

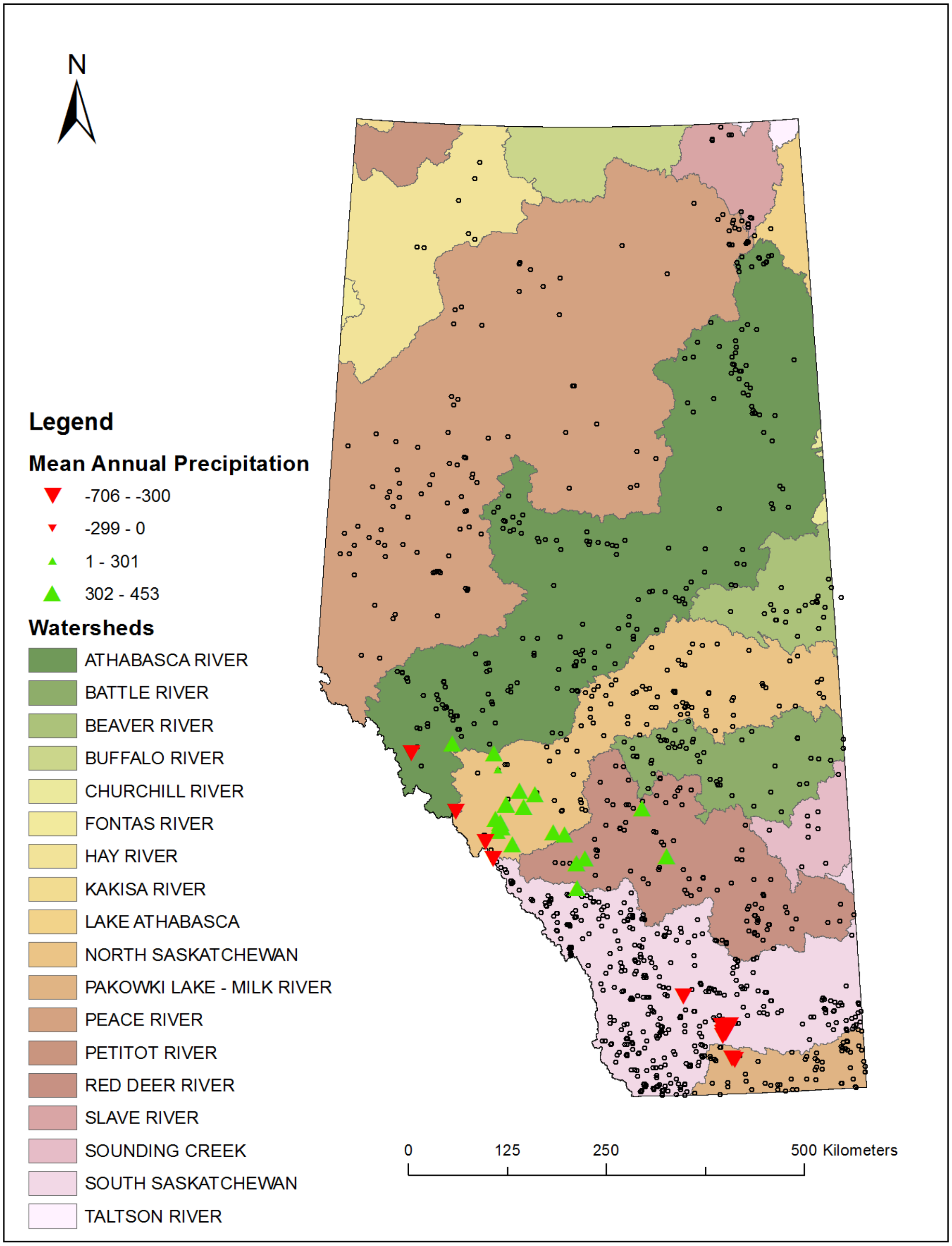

Figure 18: Trends in the mean annual precipitation. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.

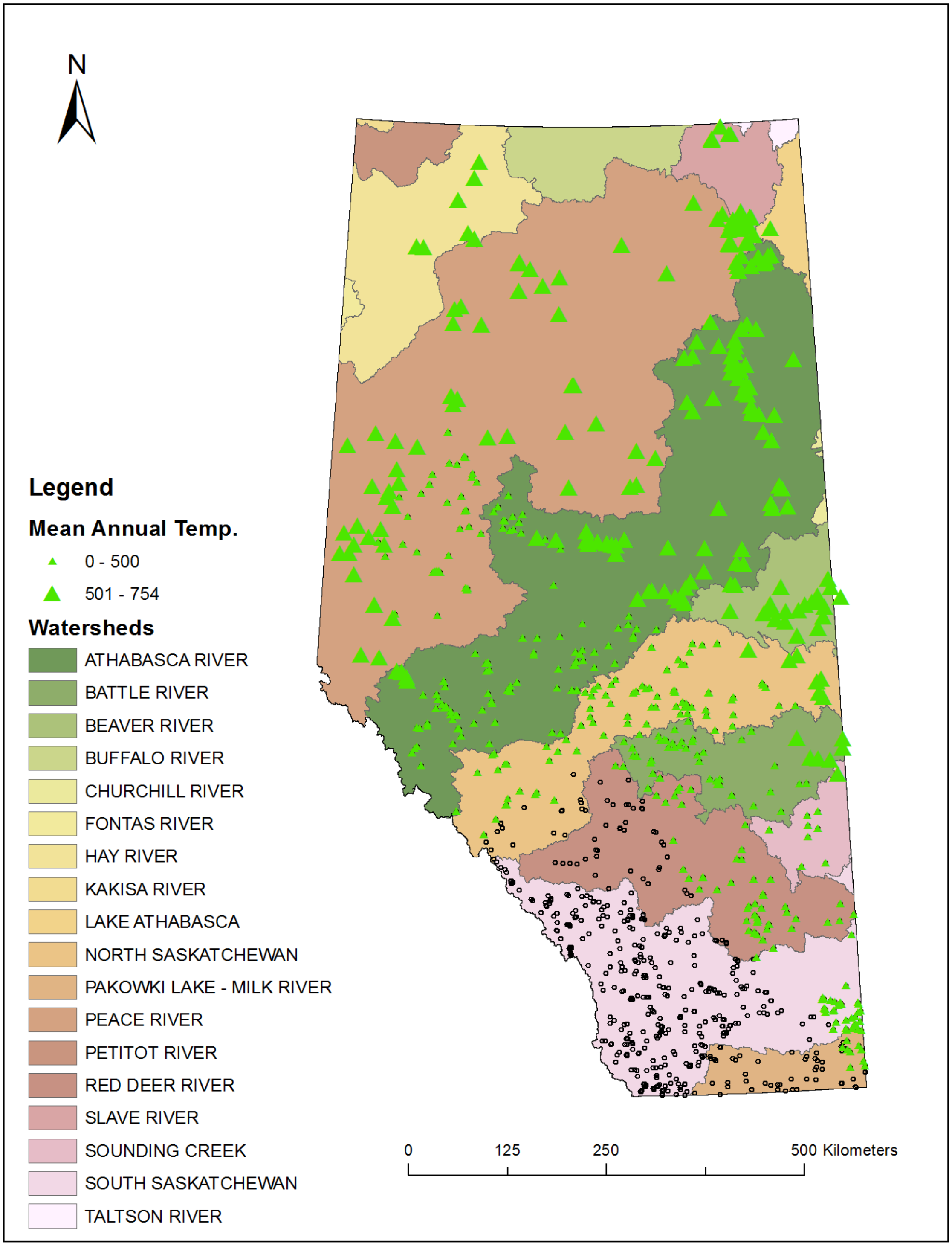

Figure 19: Trends in the mean annual temperature. Shown are the number of significant ($p<0.05$) events at each station using Mann Kendall approach. Larger arrows represent more significant events.