Evidence for a climate-driven hydrologic regime shift in the Canadian Columbia Basin

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Abstract

Water resources from the Columbia River Basin are intensely used for domestic, agricultural, industrial, and hydroelectric generation needs. Water availability in the Pacific Northwest is influenced by several ocean-atmosphere modes of climate variability that occur in the Pacific Ocean. Climate change has the potential to alter these relationships and influence both the volume and timing of streamflow in the snowmelt-dominated tributaries to the Columbia River. Here, the historical influence of climate variability and recent climate warming on the volume and timing of streamflow for 40 tributary streams in the Columbia River Basin of Canada were evaluated. Regional relationships were found between streamflow and several Pacific Ocean Climate Indices, including the already established relationships with the Pacific Decadal Oscillation (PDO) and El Nino/Southern Oscillation (ENSO). However, in recent decades the statistical relationship between streamflow and climate indices has become weaker, which has implications for managers using these indices as decision-making tools. A comparison of the average annual streamflow for the cool PDO phase, which occurred from 1947-1976, to the more recent cool phase from 1999-2011 indicated a 11% decline across the Canadian portion of the basin. Removing the influence of these climate indices on historical streamflow revealed decreases in the residual streamflow beginning sometime in the 1980's. The potential role of increased temperatures on streamflow was investigated and statistically significant relationships between decreased streamflow and increased temperatures in the summer months were found, particularly to the number of days over 18°C. The results suggest that climate change may be altering the historical relationship between climate indices and streamflow in the Canadian portion of the Columbia Basin.

Résumé

Les ressources en eau du bassin du fleuve Columbia sont utilisées de manière intensive à des fins domestiques, agricoles, industrielles et à des fins de production hydroélectrique. La disponibilité de l'eau dans le Nord-Ouest du Pacifique subit l'influence de plusieurs interactions océan-atmosphère liées à la variabilité climatique qui se produisent dans l'océan Pacifique. Le changement climatique a le potentiel de modifier ces relations et d'influer à la fois sur le volume et le moment de l'écoulement fluvial dans les affluents dominés par la fonte des neiges du fleuve Columbia. Ici, nous examinons les répercussions historiques de la variabilité du climat et du réchauffement climatique récent sur le volume et sur le moment de l'écoulement fluvial pour 38 affluents du bassin du fleuve Columbia au Canada. Des relations régionales ont été constatées entre l'écoulement fluvial et plusieurs indices climatiques de l'océan Pacifique, notamment les relations déjà établies avec l'oscillation décennale du Pacifique (ODP) et El Niño-oscillation australe (ENSO). Cependant, au cours des dernières décennies, la relation statistique entre l'écoulement fluvial et les indices climatiques est devenu plus faible, ce qui a des répercussions pour les gestionnaires qui font appel à ces indices pour la prise de décisions. Une comparaison entre le débit spécifique annuel moyen pour la phase froide de l'ODP survenue de 1947 à 1976 et celui de la phase froide plus récente de 1999 à 2011 a révélé une baisse de 11 % dans l'ensemble de la portion canadienne du bassin. Le retrait de l'influence de ces indices climatiques sur l'écoulement fluvial historique a révélé des diminutions du débit résiduel ayant commencé entre 1980. Nous étudions le rôle éventuel de la hausse des températures et constatons des relations statistiquement significatives entre la réduction du débit et la hausse des températures au cours des mois d'été, en particulier en ce qui concerne le nombre de jours au-dessus de 18°C. Nous en arrivons à la conclusion que le changement climatique peut modifier la relation historique entre les indices climatiques et l'écoulement fluvial dans la portion canadienne du bassin du fleuve Columbia.

1. Introduction

Snowmelt affected regions around the world are expected to undergo seasonal changes in streamflow under global climate change scenarios (Barnett et al. 2005, Schnorbus et al. 2012). The Canadian portion of the Columbia Basin comprises only 15% of the total basin area; however, it provides 30-40% of the total annual runoff because it includes most of the high elevation and high precipitation areas (Hamlet and Lettenmaier 1999a, Cohen et al. 2000) (Figure 1). The Columbia River Basin supports over 400 dams producing a large portion of the energy needs of the Pacific Northwest, several unique ecosystems, numerous fish species, agriculture, and a growing population (Quigley et al. 2001, McClure et al. 2003, DellaSala et al. 2011). Operation of several of the larger dams in the basin is governed by the Columbia River Treaty, an agreement between Canada and the United States that came into effect in 1964 to manage the river for power and flood control. Thus, the future operation of this basin depends, in part, on future water yield in the Canadian portion of the basin. The timing and volume of streamflow, and its sensitivity to climate change, is of widespread importance for both ecologic and economic reasons.

Headwater streamflow in the Columbia Basin is influenced by snow and glacial melt. This regime allows winter precipitation to be temporarily stored and later available to contribute to spring and summer streamflow. This ability to store water through the season is highly sensitive to changes in regional air temperature. In the Canadian portion of the Columbia Basin, air temperatures in the last century have risen by 1.2 to 2°C (Rodenhuis et al. 2007), with similar or greater changes expected by the year 2050 (PCIC 2013). In general, warmer air temperatures mean less precipitation falls as snow, summer evapotranspiration increases, and, in the long-term, glacier contributions to streamflow decrease. These changes can translate into earlier annual peak streamflow and reduced summer streamflow (Cohen et al. 2000, Barnett et al. 2005, Bolch et al. 2010). A change toward an earlier freshet and center volume of streamflow (the date at which half the annual volume has been discharged) has been observed in streams across western North America; however, the results within the Canadian Columbia Basin were not regionally consistent and the trends not statistically significant (Regonda et al. 2005, Stewart et al. 2005).

In recent decades an apparent disconnect between increases in measured precipitation and annual yield has been observed in many Pacific Northwest streams (Luce et al. 2013).

Several atmospheric and ocean modes in the North Pacific have well-documented effects on air temperature and precipitation, and consequently streamflow in western North America (Hamlet and Lettenmaier 1999b, Fleming et al. 2007, Whitfield et al. 2010, Gobena et al. 2013) These are, the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The El Niño/Southern Oscillation is tracked as oscillations in equatorial sea-surface temperatures that shift phases every 2-7 years (NOAA 2013). ENSO affects the location of the jet stream and winter weather conditions in the Pacific Northwest (Seager et al. 2010). During warm (El Niño/positive) phases, the mid-latitude jet stream is typically at higher latitudes leaving most of the Pacific Northwest warmer and drier. During cool (La Niña/negative) phase, the jet stream flows directly toward the Pacific Northwest bringing cooler wetter winters.

The PDO index is based on oscillations in sea-surface temperatures in the North Pacific with specific phases lasting 20-30 years (Mantua et al. 1997, Mantua and Hare 2002). The cool/negative phase of the PDO is associated with wetter and cooler winters in the Pacific Northwest, and the warm/positive phase with warmer and drier winters (ibid). In the last century, PDO cool/negative phases occurred from 1947-1976, followed by a warm/positive phase from 1977-1998 (Hare and Mantua 2000, Peterson and Schwing 2003). From 1998, sea surface temperature and sea-level pressure anomalies have shifted to a new split pattern where the regions north of 40 degrees latitude are similar to a warm phase PDO, and regions below are similar to a cool phase PDO (Bond et al. 2003, Overland et al. 2008, Ding et al. 2015). This new pattern does not lie on the continuum of the diametric positive and negative PDO phases previously observed and instead represents an orthogonal mode of North Pacific sea surface temperature variability, called the Victorian Mode (VM) (ibid).

Both the PDO and ENSO indices are related to regional climate conditions through statistical and mechanistic associations. As a result, these indices are frequently used as management tools to predict

water availability seasons ahead of time (Garen 1992, Hamlet and Lettenmaier 1999b, Gobena et al. 2013). However, climatic changes have the potential to alter these relationships in time through shifting oceanic conditions, e.g. the shift to Victorian Mode, as well as through local effects, e.g. evapotranspiration. The effects of both climate mode variability and long-term climate warming on snowpack and streamflow characteristics have been examined in the Western USA (Griffin and Kellogg 2004, MacDonald, Berzins, N. 2009, Pandey et al. 2014). However, this work has not been carried out explicitly for streams in the Canadian portion of the Columbia Basin. This work examines historical changes and regional variability in the relationships between climate indicators and streamflow in the Columbia Basin of Canada. We further evaluate changes in the seasonal timing and annual runoff volume across the diverse landscape of the Basin.

2. Methods

2.1 Data

Daily mean streamflow data were obtained from the Water Survey of Canada for 42 stations across 40 unregulated rivers in the Columbia Basin of Canada (excluding the Okanagan basin). Years available varied by river, though eight records span more than 75 years (Table 1). Mean daily temperature and precipitation data were obtained for five Environment Canada climate stations; Golden, Revelstoke, Nakusp, Cranbrook, and Castlegar (Figure 1). Since the climate data were incomplete, each region is supplemented with data from ClimateBC (Wang et al. 2012). This was achieved through averaging climate station data with ClimateBC data, and filling in missing years with ClimateBC data. ClimateBC uses the Parameter Elevation Regression Independent Slopes Model (PRISM), which produces spatial climate data in complex terrain by incorporating digital elevation models and has the capacity to account for elevation effects such as rain shadows and air temperature inversions (Daly et al. 1997). ClimateBC simulates climate variables based on latitude, longitude, and elevation. The modeled output was verified by comparing it to the observed weather station records, correlation coefficients r^2 ranged from 0.75 to 0.95

for mean annual temperature, and from 0.64 to 0.85 for precipitation (not shown). Data for all climate indices were downloaded from the National Oceanic and Atmospheric Administration (NOAA) online Climate and Weather Data resource (DeBano 2000).

2.2 Analyses

2.2.1 Cluster Analyses

Due to the diversity in regional climate across the Canadian Columbia Basin, we separate individual streams into regional groups using Dynamic Time Warping (DTW) cluster analyses (Berndt and Clifford 1994). DTW finds the optimum alignment between two time-series by minimizing the distance between them through a non-linear transformation. The analysis used 26 streams with complete data records from 1974 to 2010. The study period was chosen to include the maximum number of complete time-series with long records. The z-scored data were partitioned using a shape clustering algorithm as implemented in the *dtwclust* package in R (Sarda-Espinosa et al. 2015). The within-group representativeness for all streams within a region was evaluated through Pearson correlation matrices. Grouping the streams allows regional differences to be explored, and, allows for efficient presentation of the results. Because it is recognized that streams within groups may not behave similarly due to differences in catchment characters, e.g. mean elevation, glacier coverage, aspect, etc., all subsequent statistical analyses were conducted on each stream individually, the results of which are available upon request.

2.2.2 Evaluating changes in yield through time

The specific yield and the shape of the annual hydrograph of the three main phases in North Pacific sea-surface temperature variability, i.e. the cool phase PDO (1947-1976), the warm-phase PDO (1976-1997) and the Victorian Mode (1998-2011) were compared. The PDO was selected due to the known association to streamflow in the Pacific Northwest (Hamlet and Lettenmaier 1999b, Fleming et al. 2007,

Whitfield et al. 2010, Gobena et al. 2013). Further, differences in monthly yield of each of the three periods were analyzed. Significant differences between time-periods were determined using ANOVA.

We evaluate trends in specific yield for the period from 1980 to 2011. The year 1980 was selected as a start year to evaluate the recent trajectory to avoid any trend bias that might arise from the relatively high streamflows that occurred through the 1947-1977 cool phase PDO, and, to compare to other regional studies that have evaluated climate impacts pre- and post-1980 (e.g. Pederson et al. 2013). Significance was determined using Mann-Kendall trend analysis on data prewhitened using methods outlined by Yue and Wang (2002).

Changes in streamflow timing were evaluated through changes in the date of the onset of snowmelt, center volume, and peak flow. The date of snowmelt onset and the annual maximum flow are determined using discharge averaged over 10 days to avoid erroneous determinations from precipitation spikes. Snowmelt onset is defined as the date the slope of the moving average discharge increases above 1.

2.2.3 Evaluating the changing statistical relationship between streamflow and Climate Indices

The statistical relationship between stream discharge and the mean October to April PDO, ENSO, and VM were evaluated though Spearman Rank correlation analysis. The analyses were conducted for the full period of record, for the period pre- and post-1980 for reasons described above, and, for the period pre- and post-1998 to evaluate shifts in streamflow related to the Victorian Model. We use the Chow Test (Chow 1960) to determine significant differences between time periods in the relationships between streamflow and climate indices.

In a separate analysis, and because the PDO exerts a statistically significant influence on streamflow volumes in the Columbia Basin, the effects of this climate driver were removed from the raw annual streamflow time-series using regression analysis. Due to the recent changes in the North Pacific sea-surface temperatures and the potential influence of the VM, we also detrend the raw streamflow time-series using the VM, and, PDO and VM together. The detrended time-series were examined for changes in

slope pre- and post- 1980 using the Chow Test. The statistical significance of the post-1980 trends of data prewhitened using Yue and Wang (2002) was determined using the Mann-Kendall trend statistic.

2.2.4 Investigating potential cause for streamflow declines

To evaluate the potential role of evapotranspiration on June and July streamflow through a regression model. These months were chosen because the largest declines by magnitude were observed in these months (not shown) and the streamflow in these months is less affected by glacier melt. A conceptual model is used to describe monthly June/July streamflow using climate variables that account for the inter-annual variability in moisture availability:

Equation 1: $Q_{Jun/Jul} = a + bP1_{Jun/Jul} + cP2_{Dec\text{-}Mar} + dP3_{Fall} + eQ_{Apr\text{-}May}$

Where P1 is the total monthly precipitation in June or July (immediate availability), P2 is the winter precipitation (storage), P3 is fall precipitation of the previous year used as an estimate of antecedent soil moisture, and Q is the early season streamflow (April + May streamflow) used to reflect changes in the timing of streamflow and the loss of snowmelt available for June and July streamflow. This statistical model allowed us to control for the effect of the interannual variability in moisture availability to June and July streamflows so the residual effects due to temperature alone could be evaluated. The residual component from the above equation was then compared to mean monthly temperature and cumulative degree-days over 18°C using Spearman Rank correlation coefficients. Although typically used to track the need for building cooling requirements, this metric was chosen because it is widely and frequently available within climate datasets. Further, degree-days over 18ºC provides a metric to evaluate the increased number of warm days, the effect of which can be lost when examining only average annual temperatures. It was hypothesized that in higher elevation basins with larger areas of permanent snowpack, the statistical relationship between monthly residual streamflow and monthly temperature would be greater in June and/or July than in low elevation basins, while the relationship to degree-days over 18°C would be negative in all basins in both months due to increases in evapotranspiration.

3 Results

3.1 Cluster Analyses

Five groups were determined based on statistical similarities in streamflow using DTW cluster analysis. These are the North Columbia, Northeast Columbia, Southeast Columbia, West Columbia, and South Columbia (Table 1, Figure 1). The Northeast Columbia was further divided into the Northeast and Northwest Regions due to stronger predictive power by using climate data from either side of the Selkirk Mountains. Revelstoke climate data was used for streams in the Northwest region and climate data from the Golden station was used for streams in the Northeast region. The Castlegar station was used for the South Columbia regions, the Nakusp station for West Columbia, and the Cranbrook station for the Southeast Columbia region. Because the resulting groups for the 26 streams analyzed were spatially contiguous, the remaining unanalyzed streams with shorter periods of record were grouped based on proximity to streams that were included in the analyses.

The statistical separation of the streamflow data into six regions allows for a regional perspective on the historical changes in streamflow within similar climate regions. In general, within group streams were well correlated. Exceptions include two highly glaciated streams in the North Columbia region, Beaver and Canoe creeks. These two creeks exhibited different temporal trends, and different relationships to all climate indices and air temperature metrics. The Canoe Creek basin is more heavily glaciated (19%) than most other watersheds with data. Further, the watershed is located at the northern extent of the basin, approximately 130 km north of the other streams monitored in the North Columbia region. The large area of unmonitored streams in the northern reaches of the basin represents a sizeable data and knowledge gap.

3.2 Changes in historical yield

Comparing the mean hydrographs through the last three PDO cycles revealed several interesting changes (Figure 2). The PDO phase from 1947 to 1976 is distinctly different from the two following phases, the PDO warm phase from 1977-1997 and the VM phase from 1998-2011, which are similar. The

similarity in streamflows during the warm phase PDO and the VM may arise because the VM is similar to a warm phase PDO above 40 degrees latitude. Example hydrographs for each region using the streams with the longest record are shown in Figure 2. Comparing the changes form the cool phase PDO (1946-1976) to the most recent VM ‘warm’ phase (1998-2011) we find that mean annual streamflow has declined in most streams, streamflow dropped by 3% in the North, 12% in the Northeast, 9% in the Northwest, 17% in the West, 11% in the Southeast, and 7% in the South. The mean decrease across the study region was 11% and 16 of the 28 streams analyzed showed significant differences in streamflow between the two time periods at $p<0.05$ (Table 3).

The data also indicated that flow during VM period generally occurred earlier in the year than during the cool phase PDO, and, annual peak and late summer flow volume were lower during the VM period (Figure 2). Changes to an earlier onset of melt, reaching of center volume, and occurrence of peak flow between the two periods analyzed ranged from 0 to 14, 0 to 8, and 0 to 12 days, respectively. The average change in all three metrics of streamflow timing were between 3 and 4 days (Table 3).

Changes in monthly streamflow were similar across all streams. From the cool PDO to the VM period March and April streamflow increased by approximately 20% followed by declines from May to October by up to 25% (Figure 3). The average slope of all streamflow time-series from 1980 to 2011 was -2.0 x 10^6 m^3 yr^{-1}, 14 of the 36 streams showed trends that were significant at $p<0.05$ (Table 3).

After removing the effects of climate variability (PDO, VM) on streamflow, 36 of 37 streams indicated declines in streamflow volume post-1980, 29 of which were statistically significant at $p<0.05$. Streams with non-significant trends were primarily found in the North and Southeast region. All streams indicated significant changes in coefficients pre- and post-1980 using the Chow Test. Detrended time-series for representative streams in each region are shown against the raw time-series in Figure 4, the mean and 2σ standard error for the detrended slope based on regression against VM and PDO independently and together are also shown.

3.3 Regional correlations to Pacific Climate Indices

Similar to other studies we found statistically significant relationships between streamflow and the PDO and ENSO (Hamlet and Lettenmaier 1999b, Fleming et al. 2007, Whitfield et al. 2010, Gobena et al. 2013). Results are summarized by region in Table 2. Spearman rank correlation coefficients between the PDO and streamflow records ranged from -0.53 to 0.12, with Canoe Creek as an outlier at 0.12; the ENSO and streamflow ranged from -0.44 to 0.19, again with Canoe Creek as an outlier. Only two streamflow records showed statistical significance to the VM (Kicking Horse River and Split Creek).

Prior to the 1998 shift in oceanic conditions in the North Pacific, all climate indices had stronger and more significant Spearman Rank correlations to annual streamflow than post-1998 time-series. Post-1998 coefficients were not only weaker; they were often reversed in sign from negative to positive. In addition, fewer individual streams indicated significant correlations to each of the climate indices post-1998 (Table 2). The Chow Test indicated that 23 of 35 streams exhibited significant changes ($p<0.1$) in correlations to the PDO pre- and post-1980, and 7 additional streams indicated significant shifts post-1998. For ENSO, no streams indicated significant changes in 1980, and 4 streams indicated significant changes in coefficients post-1998. The relationships between monthly streamflow and climate indices has also changed pre- and post- 1998. Prior to 1998, the PDO, and ENSO indicated significant Spearman Rank correlations to streamflow in the summer months, particularly June, July, and August. Post-1998, correlations to summer streamflow for all indices weakened and were non-significant. However, correlations between all indices and April and September flow increased.

3.4 Examining the effects of temperature on streamflow

After removing the inter-annual variability of moisture availability to summer streamflow (Equation 1), the residual flows were positively and significantly correlated to mean monthly June temperature in the more northerly regions (North, Northeast), and only to mean monthly July temperatures in the North Columbia (Table 4). In both months percent glacier cover, probably as an indicator of basin

elevation, was a strong predictor in the relationship between temperature and residual streamflow, in that coefficients were parabolically correlated to percent glacier cover (r^2 = 0.75, June; 0.64, July). Fleming and Dahlke (2014) also found strong parabolic relationships between glacier cover and climate parameters including air-temperature and teleconnections from paired glacier and non-glacier stream analyses in Canada and Norway. In all regions in both months the residual streamflow was negatively correlated to the number of degree-days over 18°C, explaining up to 55% of the variability in June with *r* values ranging from -0.14 to -0.74 in June, and -0.04 to-0.67 in July (Table 4).

4. Discussion

Distinct hydrometric changes occurred through the major shifts in Pacific climate modes with the warm phase PDO and the VM being more similar than the cool phase PDO (Figure 2). The statistical separation of stream yields into six regions allowed for the comparison of changes in streamflow metrics between regions of diverse climatic and landscape attributes. Specifically, changes to an earlier onset of melt were most evident in the South and West regions, whereas declines in peak flow and annual yield were most evident in the Southeast region (Figure 2). Considering these changes at a monthly resolution, all regions indicated similar changes with increases in March and April flows, and declines in streamflow from May to October. The largest fractional changes (by percent) occurred in August, but the largest by magnitude were in June and July. The magnitude of the summer and late summer declines (15-25%) is particularly troubling because low flows in the summer coincide with high human demand for irrigation and domestic use, and, moving forward potentially a higher need for electricity that can translate to further reductions in streamflow. These human interests at this time of year compete with organismal needs because lower flows reduce available habitat and increase the temperature of water (Viviroli et al. 2007).

Alongside changes in monthly streamflow and declines in annual yield, the analyses presented here indicate widespread change in the statistical relationships between Pacific climate indices and streamflow metrics during the 1947-2011 time-period. These changes are relevant because climate indices are often

used to predict annual or seasonal streamflow based on historical relationships for regional planning across the basin (Garen 1992, Hamlet and Lettenmaier 1999b, Gobena et al. 2013). Post-1998 relationships were occasionally reversed in sign from a negative to a positive relationship as were post-1980 relationships (not shown), and particularly in the more northern rivers. Reversals in the sign of the statistical relationship between climate indices and streamflow were also noted in the monthly analyses. This was most evident for the May and June streamflows (not shown). The Chow test determined that most streams showed significant changes in their relationship to the PDO post-1980, and some showed significant changes post-1998. These results suggest that care should be taken when considering what time periods are used when calibrating statistically-based forecast models.

In other regions of the Pacific Northwest and the Rocky Mountains, the effects of Pacific climate indices have also changed. Pederson et al (2013) report that, prior to 1980, a north-south dipole existed between the southern and northern US Rocky Mountain spring snow water equivalent that related to Pacific climate indices; however, since 1980 there have been persistent and synchronous declines in snowpack driven primarily by increases in spring air temperatures (Mote et al. 2005, Mote 2006, Barnett et al. 2008). These changes have resulted in an earlier runoff and peak streamflow through much of the US Rocky Mountains.

Similarly, spring and summer air temperatures across the Columbia Basin of Canada have increased (Rodenhuis et al. 2007). It is possible that the changes observed in the statistical relationships between Pacific climate indices and streamflows have occurred because climate mode variability is overprinted by regional climate change effects. Removing the effect of the PDO, and the PDO and VM together, on streamflow records indicated significant declines beginning sometime in the 1980's for 29 of a possible 37 streams. This result supports the hypothesis that regional climate may be overprinting these synoptic-scale effects.

Further, the analyses on residual streamflows highlight the regional differences in response to temperature metrics. In the more northern regions warmer temperatures led to increases in streamflow,

perhaps due to enhanced snow melt, while in the southerly reaches warmer temperatures led to decreases in streamflow. The strong negative relationship between streamflow and air temperature metrics, in particular the number of degree-days over 18^{o}C, suggests increased evapotranspiration could be a factor in the more southerly regions. Increases in air temperature can extend the growing season and increase evapotranspirative loss. Though evapotranspiration was not explicitly measured, a particularly hot year in the Kootenay region (2003) resulted in historic low flows at Moyie, Slocan, and Kootenay Rivers, which were attributed to both low snowpack and to hot and dry conditions that persisted through the summer months (BC 2003, Murdock et al. 2007). In-depth studies in other regions have shown similar effects. For example, in the Experimental Lakes Area (ELA) a 1.6^{o}C increase in air temperature over the 1970-1990 time period combined with an increase in the length of the summer period resulted in an increase in evapotranspiration by ~50% (Shindler et al. 1996). This resulted in a decrease in the amount of precipitation available for runoff. In the early 1970's in the ELA 40-50% of the precipitation appeared as runoff, by the late 1980's, only 15-50% of the precipitation was available for runoff (Shindler et al. 1996). Simulations of mountain runoff in warming scenarios have also shown decreased streamflow due to evapotranspiration losses (Foster et al. 2016).

Further, changes in air temperature alongside changes in land-use may produce effects not accounted for when considering changes in temperature alone. For example, the loss of vegetation in the catchment from logging, fire, or insect kills generally results in an increase in catchment specific yield (e.g. Matheussen et al. 2000, Pugh and Small 2012). However, large areas of logged terrain can expose snow to more solar radiation in the winter, leading to earlier melt (Winkler et al. 2005, 2010, Molotch et al. 2009). These land-use effects may lead to an effectively longer growing season and increased evapotranspiration resulting in measurable declines in summer streamflow.

Regional downscaled climate models project increases in high elevation precipitation and snow-water equivalent for the region, which is projected to lead to increases in annual streamflow from the historical (1961 to 1990) baseline by the 2050s (Schnorbus et al. 2011, 2014). However, as of yet, there is

no evidence for an increase in streamflow in the region. It is possible that precipitation has increased at higher altitudes increasing annual snow storage alongside. However, recent analyses of lower tropospheric winds over northwestern USA have indicated declines in wind speeds (Luce et al. 2013). These results suggest that orographic precipitation may have declined in these regions, affecting streamflows and increasing the discrepancy between low-elevation precipitation records and expected watershed yields (Luce et al. 2013). It is difficult to determine whether or not decreasing or increasing precipitation at elevation may explain the trends observed in the Columbia Basin of Canada because high-elevation snow and precipitation records are limited. Snow data is only routinely monitored at or below tree-line, and a large portion of the basin exists above this elevation. Some models suggest that snowpack may be increasing at higher elevations (Schnorbus et al. 2011), though, existing snow stations indicate water equivalent has been decreasing through the 1980-2011 period and the snowline has increased in altitude (Ward 2011). In summary, changes to snowpack above treeline remains largely unknown and it is unclear how much snow storage may be increasing or decreasing at high altitudes above the snowline.

A final alternative explanation for declining trends in streamflow and the change in the statistical relationships to Pacific climate indices is that the fundamental relationship between these indices and moisture delivery to the basin have changed. Since the 1970’s the mid-latitude jet stream has been moving northward, impacting the average storm track in the Pacific Northwest (Hartmann 1983, Kossin et al. 2014). This drift may be responsible for large-scale changes in regional precipitation patterns that have altered streamflow conditions and the statistical relationships between streamflow and Pacific climate indices. Examining the impact of basin-wide land-use change and storm-track trajectories was beyond the scope of this study. However, given the importance of this resource to both the regional ecology and economy, the cause of both decreased flows and altered statistical relationships warrants further study.

5. Conclusion

Available streamflow and climate data across the Canadian portion of the Columbia Basin indicate that annual streamflow has decreased since 1980. In addition, the statistical relationships between Pacific climate indices (PDO/ENSO) and streamflow showed significant changes pre- and post- 1980. Statistically significant relationships between an increase in the number of warm days and decreases in streamflow were also found. These observations are suggestive of a regime shift in the drivers of streamflow in the Canadian Columbia Basin. The nature of these changes is likely related to recent climate change; however, the particular mechanisms, including changes to storm trajectories, evapotranspiration, or snowpack conditions, remain unclear.

Acknowledgements

The work was supported by the Columbia Basin Trust and through a postdoctoral fellowship to Brahney from the National Science and Engineering Research Council. We would like to thank Justin Robinson and the Selkirk Geospatial Research Center for technical support.

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Table 1 Stream meta-data for the Canadian Columbia Basin grouped by regions determined through Dynamic Time Warping cluster analysis. Note 'Period of Record' and 'Years of Data' will not always coincide as gauges were sometimes not functional for years at a time.

Region	River Name	Period of Record	Env. Can. Identifier	Years of Data	Regulation Type	Altitude at Gauge (m)	Latitude Decimal	Longitude Decimal	Drainage Area km^2	Nearest Climate Station to drainage area	% Glacier Cover
	Blaeberry R. abv Willowbank Crk.	1966-2011	08NB012	42	Natural	987	51.4814	-116.9683	587	Golden	7.46
	Canoe R. blw Kimmel Crk.	1971-2011	08NC004	37	Natural	1250	52.7314	-119.3844	305	Golden	19.08
North	Beaver R. near the mouth	1985-2011	08NB019	27	Natural	844	51.5097	-117.4617	1150	Revelstoke	7.86
	Split Crk. at the mouth	1974-2011	08NB016	38	Natural	1053	51.5269	-116.8986	81	Golden	0.29
	Gold R. abv Palmer Crk.	1973-2011	08NB014	39	Natural	1220	51.6769	-117.7167	429	Golden	13.39
	Kicking Horse R at Golden	1974-2011	08NA006	50	Natural	806	51.3000	-116.9778	1850	Golden	4.28
	Spillimacheen R. near Spillimacheen	1917-2011	08NA011	66	Spillway	920	50.9042	-116.4058	1460	Golden	4.4
NorthEast	Columbia R. at Nicholson	1917-2011	08NA002	108	Natural	786	51.2436	-116.9131	6660	Golden	2.52
	Columbia R. at Fairmont	1946-1996	08NA045	53	Natural	831	50.3236	-115.8625	891	Golden	0.08
	Kootenay at Kootenay Crossing	1946-2011	08NF001	71	Natural	1298	50.8869	-116.0461	416	Golden	0
	Beaton Crk near Beaton	1953-2010	08NE008	58	Natural	589	50.7358	-117.7289	97	Revelstoke	0
	Kirbyville Crk. near the mouth	1973-2005	08ND019	33	Natural	775	51.6394	-118.6706	112	Revelstoke	2.96
	Goldstream R. below Old Camp Crk.	1964-2011	08ND012	53	Natural	660	51.6683	-118.5969	934	Revelstoke	6.08
NorthWest	Illecillewaet R. at Greeley	1964-2012	08ND013	49	blae	512	51.0125	-118.0850	1150	Revelstoke	6.15
	Kuskanax Crk. near Nakusp	1964-2010	08NE006	50	Natural	823	50.2775	-117.7481	330	Revelstoke	0
	Incomappleux R. near Beaton	1953-1995	08NE001	47	Natural	732	50.7736	-117.6767	1020	Revelstoke	10.56
	Duncan R. blw B.B. Crk.	1964-2011	08NH119	50	Natural	690	50.6381	-117.0472	1310	Revelstoke	7.77
	Arrow Crk. near Erickson	1947-2011	08NH084	56	Natural	842	49.1589	-116.4511	78	Castlegar	0
	Bull R. near Wardner	1919-2011	08NG002	93	Regulated	863	49.4931	-115.3639	1520	Cranbrook	0.08
	Elk R. near Natal	1953-2011	08NK016	62	Natural	1210	49.8661	-114.8683	1840	Cranbrook	0.73
	Mather Crk. blw Houle Crk.	1973-2010	08NG076	40	Natural	1205	49.7250	-115.9250	135	Cranbrook	0
	Moyie R. at Eastport	1930-2011	08NH006	85	Natural	847	48.9994	-116.1786	1480	Cranbrook	0
SouthEast	Moyie R. abv Negro Crk.	1965-2011.	08NH120	48	Natural	1178	49.4222	-115.9411	239	Cranbrook	0
	Duck Crk. near Wynndel	1946-2011	08NH016	47	Natural	871	49.2028	-116.5322	57	Castlegar	0
	Flathead R. at Flathead	1952-2011	08NP001	75	Natural	1526	49.0006	-114.4764	1110	Cranbrook	0
	Fording R. at the mouth	1970-2011	08NK018	B	Natural	1279	49.8938	-114.8663	621	Cranbrook	0
	St-Mary R. at Wycleff	1947-1994	08NG012	54	Natural	953	49.6003	-115.8628	2360	Cranbrook	0.03
	St-Mary R. blw Morris Crk.	1973-2011	08NG077	39	Natural	1177	49.7417	-116.4500	208	Cranbrook	0
	Barnes Crk. near Needles	1951-2011	08NE077	62	Natural	639	49.9075	-118.1253	204	Nakusp	0
	Inonoaklin Crk. abv Valley Crk.	1972-2010	08NE110	36	Natural	531	49.8978	-118.1900	298	Nakusp	0
	Slocan R. near Crescent Valley	1914-2011	08NJ013	89	Natural	492	49.4606	-117.5644	3330	Castlegar	0.07
West	Kaslo R. blw Kemp Crk.	1965-2011	08NH005	55	Natural	768	49.9075	-116.9519	442	Castlegar	0.56
	Duhamel Creek abv. Diversions	1922-2015	08NJ026	28	Natural	744	49.5903	-117.2422	52.9	Castlegar	0
	Lardeau R. at Marblehead	1946-2011	08NH007	65	Natural	566	50.2631	-116.9672	1640	Nakusp	1.01
	Sullivan Crk. near Canyon	1965-2011	08NH115	50	Natural	1073	49.1039	-116.4264	6	Castlegar	0
	Big Sheep Crk. near Rossland	1950-2011	08NE039	65	Natural	788	49.0167	-117.9444	347	Castlegar	0
	Granby R. near Grand Forks	1967-2011	08NN002	54	Natural	595	49.0442	-118.4386	2060	Castlegar	0
	Kettle R. near Ferry	1929-2011	08NN013	84	Natural	849	48.9481	-118.7653	5700	Castlegar	0
South	Boundary Crk. near Porthill	1931-2011	08NH032	83	Natural	642	48.9972	-116.5681	242	Castlegar	0
	Salmo R. near Salmo	1950-2011	08NE074	63	Natural	685	49.0469	-117.2936	1240	Castlegar	0
	Anderson Crk. near Nelson	1967-2011	08NJ130	52	Natural	770	49.5014	-117.2597	9.1	Castlegar	0
	Columbia at Brichbank	1937-2015	08NE049	80	Regulated	446	49.1577	-117.7252	87400	Castlegar	0
	Deer Crk. at Deer Park	1959-2011	08NE087	54	Natural	1126	49.4250	-118.1900	82	Castlegar	0

Table 2 Comparison of the mean Spearman Rank correlation coefficients between streamflow and climate indices used in this study. Correlations are shown for the full record, and, pre- and post-1998 as well as the number of streams showing significant correlations at *p*<0.05. The climate indices used are based on the mean from October to April.

	Full Record	# Sig.	Pre-1998	# Sig.	Post-1998	# Sig.
PDO	-0.34	31	-0.41	28	-0.13	0
ENSO	-0.24	14	-0.30	15	-0.23	0
VM	-0.09	2	-0.16	2	0.00	0

Table 3 Changes in streamflow and the timing of streamflow between Pacific climate modes shown as regional averages. The climate modes compared are the PDO cool phase from 1947-1976 and the current Victoria Mode phase 1998-2011. The number of significant declines between PDO phases is determined by ANOVA and given as the number of significant/number of streams in the region with sufficient data to test between time-periods. Significance in the slope streamflow from 1980-2011 is determined by Mann-Kendall analyses with autocorrelation correction (Yue and Wang 2003). Significance is determined at *p*<0.05.

	Yield Δ between PDO phases (Cool to VM)	# Sig.	Mean sen's Slope 1980-2011 ($1x10^6$ m^3 yr^{-1})	# Sig.	Date of Peak flow (days)	Date of Center Volume (days)	Date of Onset of Melt (days)
North	-3.4	0/0	-0.08	0/3	-8	-4	-1
NorthEast	-11.5	3/3	-2.34	2/4	-5	-2	-2
NorthWest	-9.2	2/5	-1.83	4/6	-6	-4	-6
West	-10.9	6/7	-3.24	1/9	-1	0	-2
SouthEast	-17.3	2/4	-2.59	3/5	-3	-4	-5
South	-7.5	3/9	-2.08	4/8	-2	-4	-6
Average	-10.6		-2.0		-3	-3	-4

Table 4 Regional average correlation coefficients for the residual of the statistical model for June and July streamflow and mean monthly temperatures and degree days over 18°C from ClimateBC. Included are the number of significant correlations based on Spearman Rank correlation analysis at *p*<0.05 within each region.

	June				July			
	Mean Monthly Temperature	# Sig.	Degree Days over 18°C	# Sig.	Mean Monthly Temperature	# Sig.	Degree Days over 18°C
North n=5	0.51	5	-0.30	1	0.19	2	-0.36
NorthEast n=4	0.36	3	-0.26	1	-0.11	1	-0.49
NorthWest n=6	0.21	2	-0.26	2	-0.32	4	-0.63
West n=6	-0.03	1	-0.45	4	-0.11	2	-0.42
SouthEast n=9	0.02	0	-0.44	8	-0.25	2	-0.48
South n=9	-0.14	0	-0.61	9	-0.26	3	-0.45

Figure Captions

Figure 1. The Columbia Basin study area in southeastern British Columbia. The CBTR is divided into six hydrologic regions, five based on Dynamic Time Warping cluster analysis, the northeast and northwest regions were divided along the Selkirk Mountain divide.

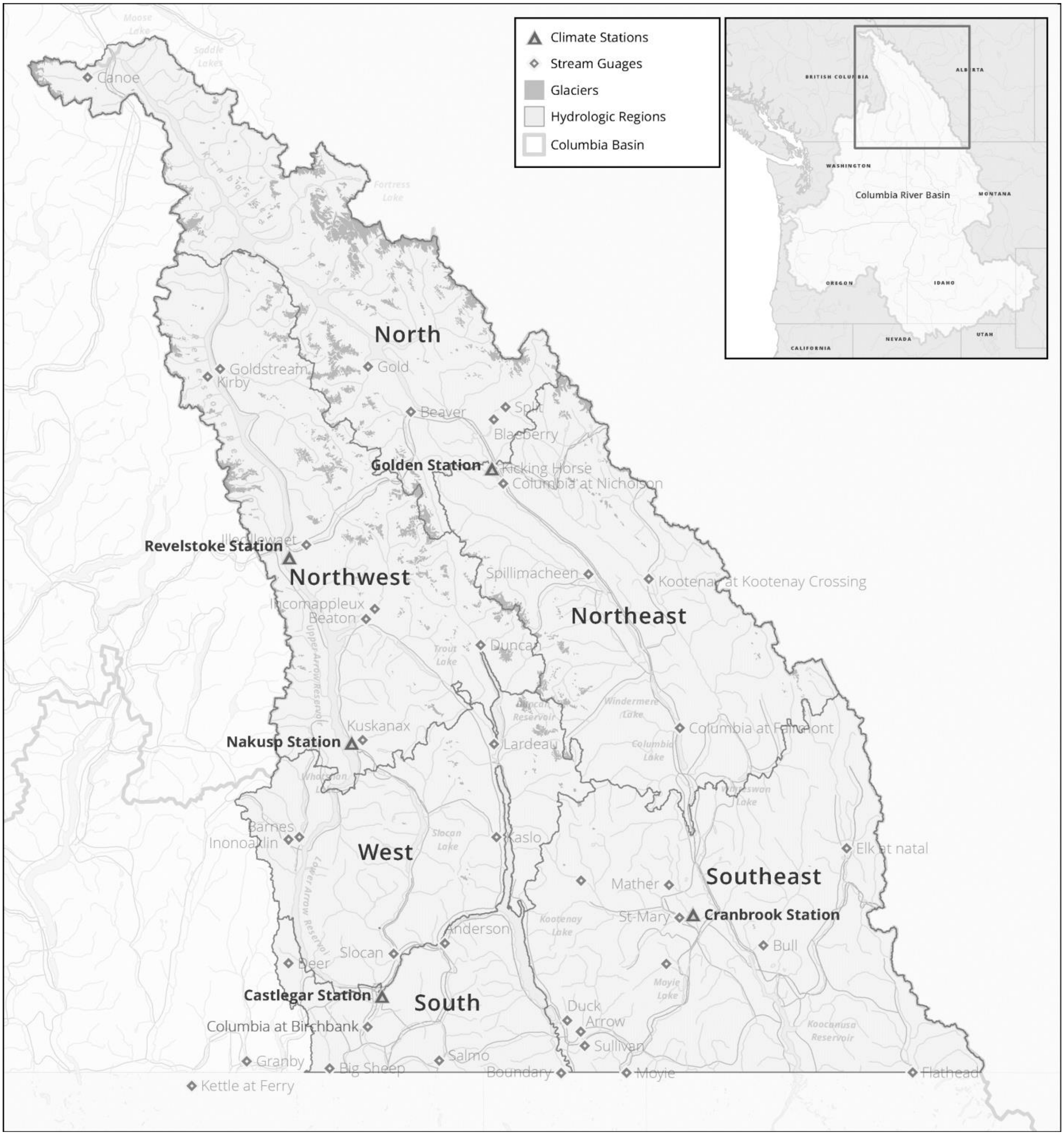

Figure 2. Annual hydrographs for streams with the longest record in each of the 6 Canadian Columbia Basin sub-regions. Values represent daily means through the three main north Pacific regime shifts, the cool phase from 1947 to1976, the subsequent warm phase from 1977 to 1997, and the Victorian Mode from 998 to 2011.

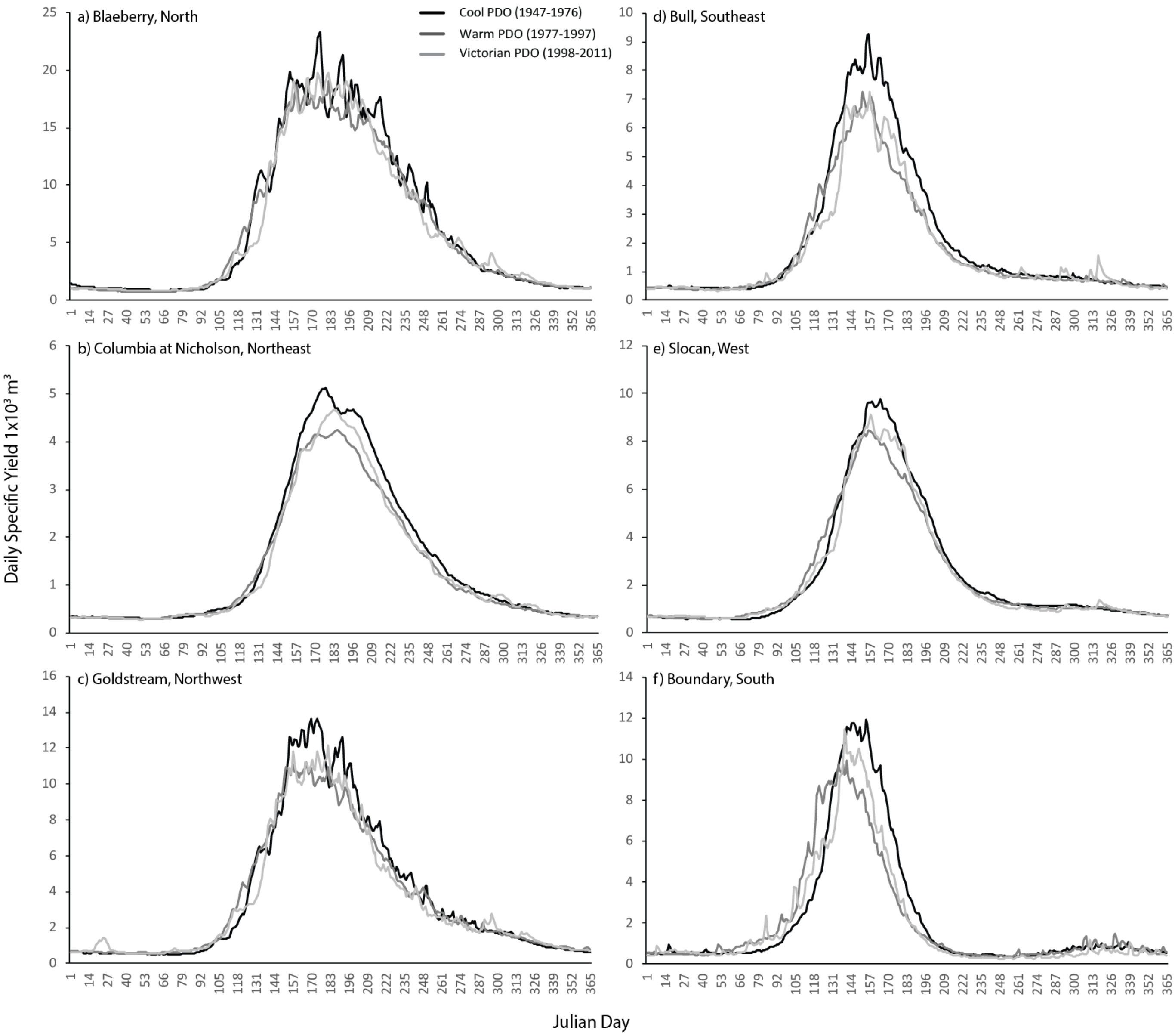

Figure 3. Changes in mean streamflow between the cool phase PDO (1947-1976) and the Victoria Mode (1998-2011) for each month by percent. The solid black line represents the mean for 36 streams and the shaded area is the 2σ standard error.

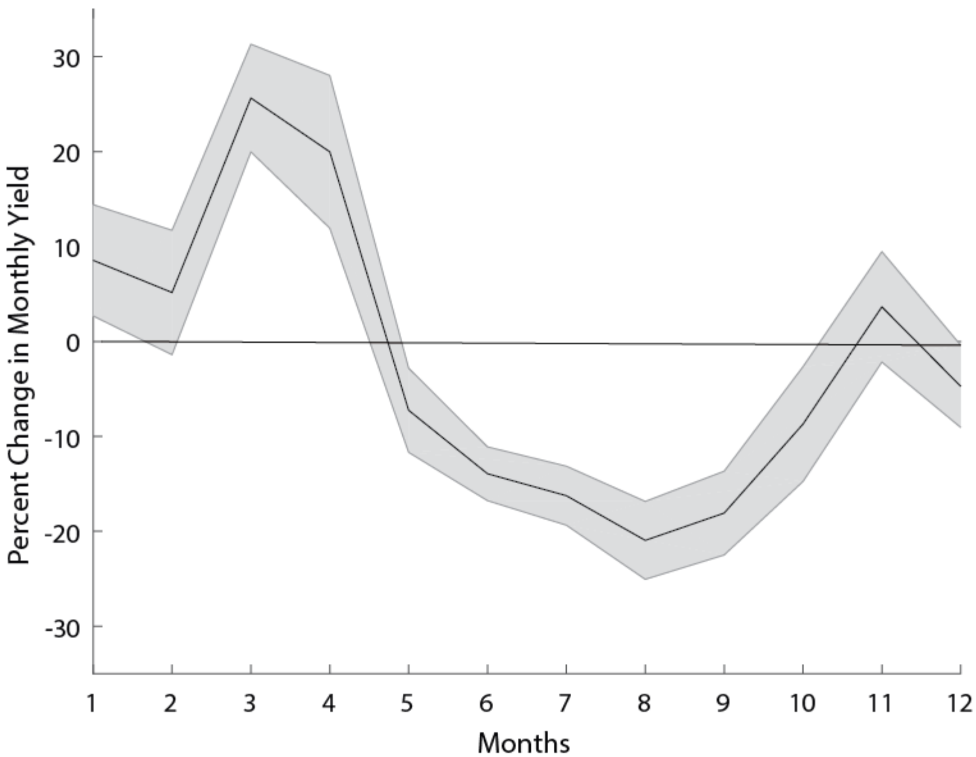

Figure 4. Detrended and raw annual streamflow in all 6 sub-regions for streams with the longest recorded Raw annual specific yield is shown in gray and the detrended time-series in black. The slope from 1980-2011 and the 2σ standard error for the slope is indicated, error is based on a sensitivity test by also removing VM alone and together with the PDO.