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Century-long records reveal slight, ecoregion-localized changes in Athabasca River flows

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Abstract:

Reports of abruptly declining flows of Canada's Athabasca River have prompted concern because this large, free-flowing river could be representative for northern North America, provides water for the massive Athabasca oil-sands projects and flows to the extensive and biodiverse Peace–Athabasca, Slave and Mackenzie River deltas. To investigate historic hydrology along the river and its major tributaries, we expanded the time series with interpolations for short data gaps; calculations of annual discharges from early, summer-only records; and by splicing records across sequential hydrometric gauges. These produced composite, century-long records (1913–2011) and trend detection with linear Pearson correlation provided similar outcomes to nonparametric Kendall τ-b tests. These revealed that the mountain and foothills reaches displayed slight increases in winter discharges *versus* larger declines in summer discharges and consequently declining annual flows (~0.16% per year at Hinton; $p < 0.01$). Conversely, with contrasting boreal contributions, the Athabasca River at Athabasca displayed no overall trend in monthly or annual flows, but there was correspondence with the Pacific Decadal Oscillation that contributed to a temporary flow decline from 1970 to 2000. These findings from century-long records contrast with interpretations from numerous shorter-term studies and emphasize the need for sufficient time series for hydrologic trend analyses. For Northern Hemisphere rivers, the study interval should be at least 80 years to span two Pacific Decadal Oscillation cycles and dampen the influence from phase transitions. Most prior trend analyses considered only a few decades, and this weakens interpretations of the hydrologic consequences of climate change.

KEY WORDS climate change; historic hydrology; northern rivers; river flow trends

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INTRODUCTION

Although there is substantial interest in global warming, a more serious concern for many regions worldwide relates to impacts of climate change on water resources (Rouse *et al.,* 1997; Schindler and Donahue, 2006). There is particular interest in understanding changes in river flows because these provide primary water sources for domestic, municipal and industrial water supplies, and for irrigation and hydroelectric power generation. Changes in river flow magnitude or seasonality could challenge water supply sufficiency, and this would also impact natural ecosystems, including the aquatic or instream ecosystems that support fish, and the riparian or streamside ecosystems that provide biologically rich floodplain forests (Rouse *et al.,* 1997; Schindler and Donahue, 2006; Rood *et al.*, 2008).

To investigate the hydrological impacts of climate change, statistical analyses of historic river discharges are undertaken to detect significant patterns in annual or seasonal flows. This may lead to cautious future flow forecasting with empirical trend projection, based on the simplistic expectation that the near future will generally extend patterns from the recent past (Burn and Hag Elnur, 2002; Shepherd *et al.,* 2010). For analyses of historic flow patterns, 'extensive' analyses investigate multiple hydrometric sites and multiple rivers to detect broad-scale regional patterns (Zhang *et al.*, 2001; Rayne and Forest, 2010). However, to accommodate the various gauges, common but shorter historic time series are typically analysed. Conversely, 'intensive' analyses involve more detailed investigation of one river system (Burn *et al.*, 2004; Rasouli *et al.*, 2013). For this, there are strategies to infill and extend the historic records such as by splicing to coordinate data from sequential hydrometric gauges (Rood *et al.*, 2005; 2008). We have generally applied an intermediate approach, in which we have analysed multiple rivers and also undertaken data extensions (Rood *et al.,* 2005; 2008).

We and others have investigated flows from the central Rocky Mountains, which straddle the Canada–US border and the east-west Continental Divide, and detected significant correspondence between river flows and the Pacific Decadal Oscillation (PDO) (Hamlet and Lettenmaier, 1999; Rood *et al.*, 2005; St. Jacques *et al.*, 2010). For North

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America, this involves alternating warm and cool PDO phases, which are associated with low-flow *versus* high-flow intervals, respectively (Mantua and Hare, 2002; Neal *et al*., 2002). The PDO has a period of around four decades, and a phase transition occurred in the 1970s. This would confound analyses of recent hydrologic trends because river flow changes could reflect the PDO transition, rather than longer-term climate change (Seneca, 2004; Chen and Grasby, 2009; St. Jacques *et al.,* 2010).

We undertook the present case study to investigate the historic hydrology of the Athabasca River, one of the longest and largest free-flowing rivers of North America. Its headwaters are within relatively pristine Rocky Mountain zones of Jasper National Park and Willmore Wilderness (provincial) Park, minimizing alterations in watershed hydrology. After leaving the mountains and foothills, it drains vast areas of the Canadian boreal region, where climate change is likely to be considerable (Rouse *et al.,* 1997; Toth *et al.,* 2006). The river thus flows through three sequential hydroclimatic zones, with the Rocky Mountains, foothills and then the boreal ecoregions, and we considered it likely that these could experience somewhat different influences from climate change. The Athabasca subsequently flows downstream to support the globally significant Peace–Athabasca, Slave and Mackenzie deltas, which are ecologically rich and diverse, and have been impacted especially because of very large hydroelectric power projects along the Peace River, the adjacent river to the north (Prowse and Conly, 2002).

The Athabasca River provides a current international focus because it provides the water supply for the massive Athabasca oil-sands projects. These involve water-intensive mining and upgrading for bitumen and heavy oils, and because of the substantial water use and contaminant

Table I. Analyses of historic mean annual (Q_{annual}) or mean monthly (Q_{Month}) discharges of the Athabasca River, with locations sequenced downstream.

Station – Interval	↑ = increase; ↓ = decrease	Source
Jasper		
1914–1921; 1924–1930; 1971–2002	↓ Q_{annual}t	Rood *et al.* 2005
1914–1921; 1924–1930; 1971–2005	↓ Q_{Jul}t; Q_{Aug}^{**}; Q_{Sep}t	Rood *et al.* 2008
1960–2010	↓ Q_{annual}^{*}	Rasouli *et al.* 2013
1914–1930; 1970–2010	↓ Q_{annual}^{**} ↑ Q_{Feb}^{*}; Q_{Mar}^{*} ↓ Q_{Jul}^{**}; Q_{Aug}^{**}; Q_{Sep}^{*}	This study
Hinton		
1962–2009	Q_{annual} – no change	Rayne and Forest 2010
1915–1939; 1955–2009	↓$Q_{annual*}$	Peters *et al.* 2013
1915–1939; 1955–2011	↓ Q_{annual}^{**} ↑ Q_{Jan}^{**}; Q_{Feb}^{*} ↓ Q_{Jul}^{**}; Q_{Aug}^{**}; Q_{Sep}^{**}	This study
Athabasca		
1961–2000	↓ Q_{Mar}t; Q_{May}t	Burn *et al.* 2004
1913–1930; 1938–2001	Q_{annual} – no change	Seneca 2004
1965–2000	↓ Q_{May}t	Abdul Aziz and Burn 2006
1959–2009	↓ Q_{annual}t	Rayne and Forest 2010
1958–2009	Q_{annual} – no change	Peters *et al.* 2013
1960–2010	↓ Q_{annual}^{*}	Rasouli *et al.* 2013
1913–1930; 1938–2011	Q_{annual}; Q_{Month} – no change	This study
Below McMurray		
1957–1996	↓ Q_{annual}^{**}; Q_{Sept}^{*}	Zhang *et al.* 2001
1960–1997	Q_{Apr} and Q_{Oct} – no change	Burn and Hag Elnur 2002
1967–1996	↓ Q_{annual}^{*}	Yue *et al.* 2003
1972–1999	↓ Q_{Jan}t; Q_{Feb}t; Q_{Sep}^{*}	Woo and Thorne 2003
1965–2000	↓ Q_{May}t; Q_{Oct}t	Abdul Aziz and Burn 2006
1970–2001	↓ Q_{annual}^{*}	Schindler and Donahue 2006
1958–2009	↓ Q_{annual}^{*}	Rayne and Forest 2010
1958–2009	↓ Q_{annual}^{*}	Peters *et al.* 2013
1960–2010	↓ Q_{annual}^{*}	Rasouli *et al.* 2013
1937–1957 (16 yearly estimates); 1958–2011	Q_{annual} – probably no change	This study

t: trend, $p < 0.1$.
*$p < 0.05$.
**$p < 0.01$.

concerns, there have been many recent investigations into the historical trends in annual and seasonal flows (Table I). These emphasized the lower reaches near Fort McMurray and concluded that recent Athabasca River flows have been declining. This prompted concern that continuing flow decline would impose challenges for the aquatic ecosystems and for human health (Schindler and Donahue, 2006). With the considerable scientific study and the implementation of an extensive environmental monitoring programme, this river has become a sentinel system to investigate cumulative hydrological and ecological impacts from climate change and human industrial activities in northern North America.

However, particularly, because of the limited hydrologic record for the Athabasca River near Fort McMurray and the oil-sands deposits, the prior studies have largely been restricted to recent decades or up to a half-century. Following the recognized complexity from the PDO for regional drainages (Rood *et al.,* 2005; St. Jacques *et al.,* 2010), in this study, we developed more extensive time series and investigated longer-term trends to assess the following hypotheses:

H_1: Our primary hypothesis was that summer and annual flows have been declining over the past century. This pattern would be relevant to future flow forecasts as a recent pattern of decline could continue into the 21st century.

H_2: Our secondary hypothesis was that different hydroclimatic ecoregions would display distinctive historic patterns. We anticipated that the directions of change would be consistent but that the magnitude could vary. Because winter warming would alter the seasonality and elevational transition of rain *versus* snow (Lapp *et al.,* 2005; Shepherd *et al.,* 2010), we anticipated that seasonal flows from the Rocky Mountain ecoregions might be the most affected, whereas the foothills and especially the boreal watershed zones might display more moderate responses.

METHODS

River discharges (Q) were obtained from Water Survey of Canada's HYDAT database (http://www.wsc.ec.gc.ca/applications/H2O/) for the hydrometric stations in Table II. We considered all gauges within the Athabasca River Basin and selected sites with the longest and most continuous data series, to represent the sequential hydroclimatic ecoregions (Figure 1). We sought to maximize the record intervals to increase the confidence of interpretation (Rood *et al.,* 2005; St. Jacques *et al.* 2010) and in some cases missing monthly and annual means resulted from short gaps in the daily Q records. For data gaps of 1 or 2 days, we interpolated missing values by averaging the discharges of the flanking days. Because the downstream Athabasca is a large, high-order river, the daily changes are

Table II. Study rivers and locations in the Athabasca River Basin, sequenced downstream

River and station	Latitude (N); Longitude (W)	Drainage area (km^2)	Mean Q (m^3/s)	Period of record	Years
Athabasca River					
1. Near Jasper, 07AA002	52°54′ 36″; 118°3′ 31″	3870	87	1914–1930; 1970–2011	59
2. At Entrance, 07AD001	53°22′ 37″; 117°41′ 42″	9530	187	1915–1939; 1955–1961	82
At Hinton, 07AD002	53°25′ 27″; 117°34′ 9″	9765	171	1961–2011	
3. Near Windfall, 07AE001	54°12′ 27″; 116°3′ 47″	19 600	253	1960–2011	52
4. At Athabasca, 07BE001	54°43′ 19″; 113°17′ 16″	74 602	420	1913–1930; 1938–2011	92
5. At McMurray, 07CC002	56°43′ 60″; 111°22′ 30″	100 000	–	1937–1959	18
6. Below McMurray, 07DA001	56°46′ 49″; 111°24′ 7″	132 585	620	1957–2011	57
Tributaries					
7. Sunwapta River, 07AA007	52°12′ 58″; 117°13′ 55″	29.3	~1	1948–1997; 2005–2011	56
8. McLeod River					68
Near Wolf Ck, 07AG001	53°39′ 15″; 116°16′ 50″	6310	40	1915–1930; 1958–1984	
Near Whitecourt, 07AG004	54°0′ 44″; 115°50′ 23″	9109	51	1968–2010	
9. Pembina R. nr Entwistle, 07BB002	53°36′ 15″; 115°0′ 17″	4330	20	1914–1922; 1955–2011	66
10. Lesser Slave River					73
At Slave Lake, 07BK001	55°18′ 17″; 114°45′ 22″	13 400	38	1915–1931; 1935–1940; 1960–1962; 1988–2011	
At Highway 2A, 07BK006	55°17′ 39″; 114°35′ 26″	14 400	51	1963–1988	
11. Clearwater R. at Draper, 07CD001	56°41′ 7″; 111°15′ 19″	30 800	119	1958–2010	52

The numbers correspond to positions on the Figure 1 map.

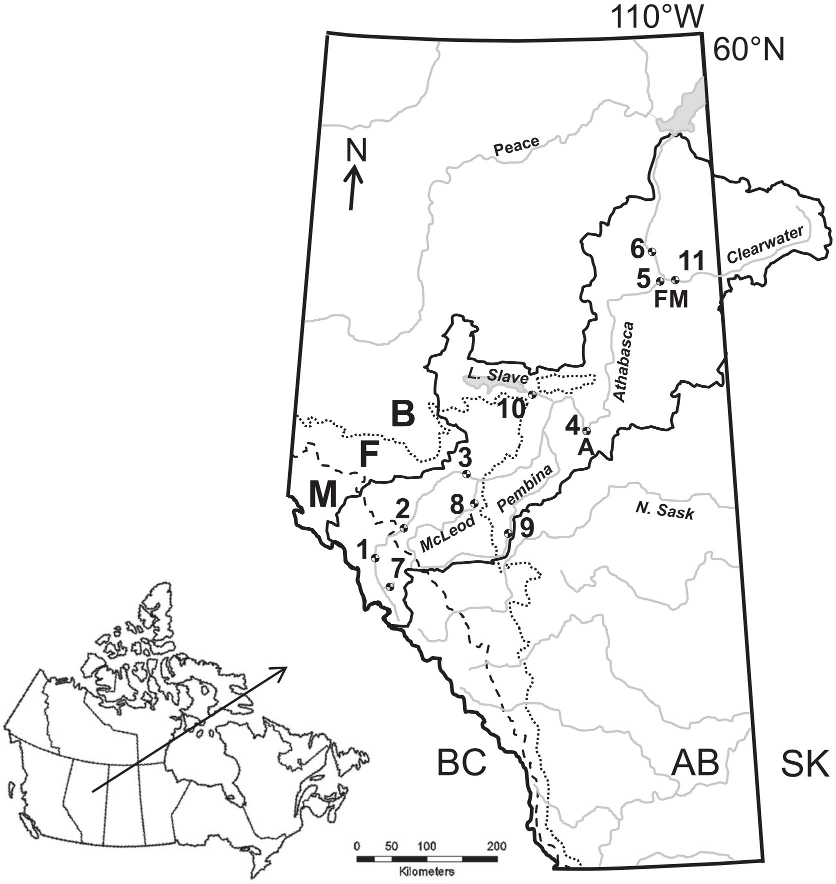

Figure 1. Map of the Athabasca River Basin showing the major hydroclimatic ecoregions: mountain (M), foothills (F) and boreal (B); the river and its major tributaries; and the locations of relevant hydrometric stations, as indicated in Table I. Cities are Athabasca (A) and Fort McMurray (FM). A Canadian map is provided, and the provinces are British Columbia (BC), Alberta (AB) and Saskatchewan (SK)

slight, allowing this interpolation. For example, at Athabasca, calculation of the 2010 daily Q by averaging the flanking values was 99.6% accurate (R^2).

Missing Q_{annual} more commonly reflected longer gaps and primarily the lack of winter data. For these, we estimated Q_{annual} through linear regression of the Q_{annual} for the years with complete datasets *versus* the averages of the available multiple-month Q. In the early record years, the manual recording was often limited to the warm season, and this interval had by far the greatest flows while winter flows were consistently very low. Consequently, the correlations between warm season and annual Q are very high. For example, at Athabasca, there was 96% correspondence between May through October mean Q and mean annual Q (Figure 2). The correspondence increased for March through September Q *versus* Q_{annual}, such as reaching 99.5% for the McLeod River (based on 19 years with year-round data between 1915 and 1968 and used to estimate annual Q for five other years with seasonal data).

We also coordinated Q data from sequential hydrometric gauges along particular rivers. We again applied

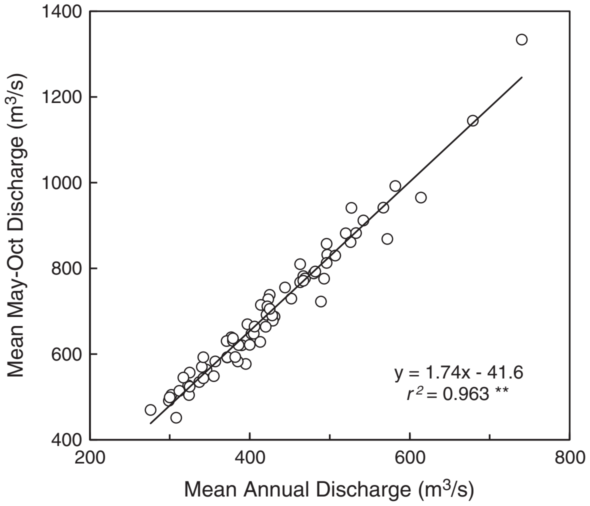

Figure 2. Mean annual discharge (Q_{annual}) *versus* mean of May through October discharge of the Athabasca River at Athabasca. The linear regression was used to estimate Q_{annual} for years with only seasonal Q data, and the close correspondence (96%; $p < 0.01$) was typical for other hydrometric sites

linear regression, coordinating Q_{annual} or Q_{Month} data for the two gauges for the period of overlap. Along the Athabasca, the Entrance gauge was established in 1915 and the nearby Hinton gauge followed in 1961. For the overlap in 1961, there was 99.9% association between the monthly mean discharges, and we directly combined these flow records. We also coordinated records for sequential gauges for the tributaries, including the McLeod and Lesser Slave rivers [e.g. McLeod Q_{month}: Near Whitecourt = Near Wolf Ck × 1.211; $r^2 = 0.984$; (monthly flows March–October 1969–1983)]. For linear regression, a line from the origin (0,0) was selected as the simplest fit if it provided a near-maximal coefficient of determination. However, the best-fit lines generally included a non-origin intercept and slope, and these empirical functions would account for flow differences because of changes in the drainage area with the change in hydrometric gauge location.

More complex data splicing was undertaken for the Athabasca River near Fort McMurray. A hydrometric site was established at Fort McMurray in 1937, and river stage data were collected through 1959. Data gaps arose, and in some of the 1950s, stages were measured on alternate days. We estimated intervening stages through interpolation, and for years with continuous monitoring, there was 99.9% association between daily stages and the mean of the flanking values. However, there was no stage-*versus*-discharge ratings calibration for this gauge. In 1957, another gauge was established 5 km downstream, and this 'below McMurray' gauge remains active. For the 3 years of overlap, there was close correspondence between the daily Q below McMurray (y) *versus* the daily stage at McMurray (x) that was best fit with a power function ($y = 259.8 \times e^{1.215x}$; $r^2 = 0.932$). We used this to estimate below McMurray Q from the historic stage data, but this introduced complexities as indicated in Results section.

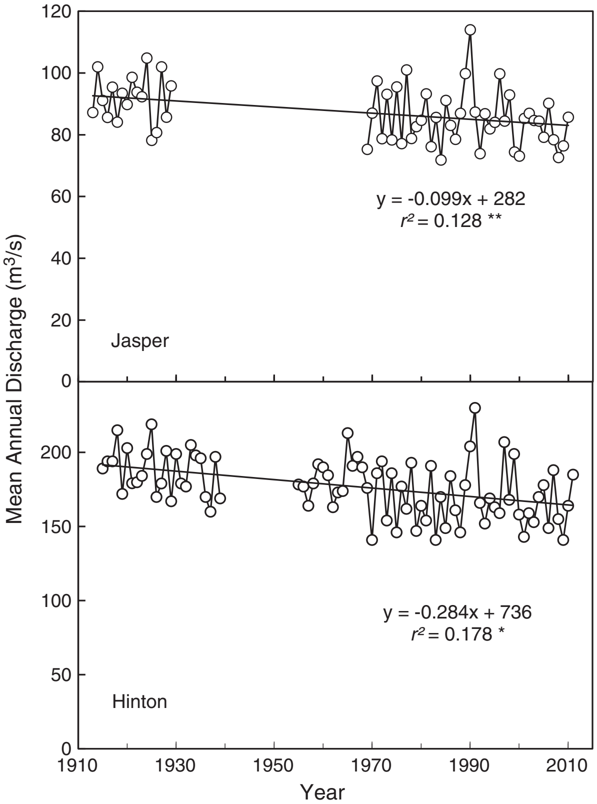

Figure 3. Mean annual discharges (Q_{annual}) of the Athabasca River at Jasper and Hinton. For this and following figures, linear plots display statistically significant associations; **: $p < 0.01$

We next investigated interannual patterns of Q_{annual} or Q_{Month} values as well as for seasonal means (i.e. winter = mean Q of December, January and February, etc.). Particularly for the Q_{annual}, we considered the possible confounding influence from serial autocorrelation, because there is some carryover of water to the following year due to snow and ice melt, and groundwater contributions. However, there was no significant 1-year-lag autocorrelation (e.g. Jasper: $p = 0.937$, n.s. (not significant); Athabasca: $p = 0.241$, n.s.), and pre-treatment was thus less applicable. The need for statistical pre-treatment is probably reduced as the time series are lengthened, and pre-treatment can be disfavoured because it dampens some quantitative patterns (Yue *et al.,* 2003; Rayne and Forest, 2010; St. Jacques *et al.,* 2010).

To detect historic patterns, we undertook parametric Pearson product (linear) correlations (r) and nonparametric Kendall τ-b rank-order tests (Burn and Hag Elnur, 2002; Rood *et al.,* 2005; Rayne and Forest 2010). The two approaches are complementary, and we and others have found that as hydrologic data series lengthen the outcomes converge (Rood *et al.,* 2005, Rayne and Forest 2010). We plot and describe the best-fit linear regressions for significant patterns (*: $p < 0.05$), and for tables and interpretations, we also recognize statistical trends (t: $p < 0.1$) and highly significant patterns (**: $p < 0.01$).

To further explore the difference across the hydro-climatic ecoregions, we assessed the flows of particular Athabasca River segments, which were calculated as the differences in discharges between the sequential upstream and downstream gauges. This removes the redundancy due to the passage of downstream flow and thus reflects local inflow contributions. For this analysis, we also investigated Q_{Month} but emphasize Q_{annual} because these display the key results and avoid the complexities of transit time and flow lags due to conjunctive groundwater (Rood *et al.,* 2013).

Analyses considered calendar years rather than water years because autumn flows extend from the annual nival (snowmelt) recession and because we are ultimately interested in ecohydrology, and the aquatic and riparian activities extend into the autumn (Rood *et al.,* 2008). October through December flows of these cold-region rivers were very low, and there would thus be minimal difference for analyses based on chronological *versus* water years.

RESULTS

Hydrologic records and annual discharge patterns for the Athabasca River

Fourteen hydrometric gauges have been implemented along the Athabasca River. One-half are currently active (2013), and these are reasonably spaced along the river corridor. However, flow data are deficient for the final river segment, near the outflow into Lake Athabasca. Multiple gauges were implemented around 1970, but these had short periods of record and were largely abandoned. This segment is very difficult to gauge because the river flows into the complex Peace–Athabasca Delta, with a network of distributaries that provides extensive surface and groundwater exchange. Consequently, river levels were sometimes monitored but corresponding discharges were not estimated. The flow addition from this final segment is slight relative to the overall river discharge, and consequently, our analyses ended with the below McMurray gauge, which is downstream of Fort McMurray and the Clearwater River inflow, and well upstream from the complex delta (Figure 1; Table II). For comparison, Peters *et al.* (2013) present analyses for a downstream location (Embarras Airport) but that involved flow estimates based on the below McMurray data.

The Athabasca River headwaters are largely within Jasper National Park, and river gauging at the Town of Jasper commenced in 1914. The hydrologic records at Jasper and other locations are typical for western Canada as monitoring was abandoned in the 1930s (Table II). This coincided with the North American economic Great Depression and a major drought, and the costly manual hydrometric monitoring was suspended. This data gap is noteworthy for trend analyses because it occurred during a low-flow interval. Spanning the gap, the 1914–2010 records display a progressive decline in mean annual flows of the Athabasca River at Jasper (Figure 3), consistent with our prior analysis of the record to 2002 (Rood *et al.*, 2005).

Moving downstream, the combined record from Entrance and Hinton provides the second most extensive Q_{annual} record within the river basin, with 82 years from 1915 to 2011 (Table II) and continuous records through the winters. Similar to the upstream record at Jasper, the annual discharges declined progressively over the past century with an annual decline rate of about 0.16% (Figure 3). These data suggest an increase in the interannual variation, but the time series is limited for this conclusion.

Next downstream, a gauge was established at Windfall in 1960 and remains active. Its position is strategic because it is upstream from the inflow of the major foothills tributaries, the McLeod and Pembina Rivers, as well as the boreal tributary of the Lesser Slave River (Figure 1). Next, the Town of Athabasca is within the boreal ecoregion and about midway along the Athabasca River corridor (Figure 1). Hydrometric records commenced in 1913 (Table II), and these provide the earliest records for North American river flows to the Arctic Ocean and the most extensive records for the Mackenzie River system that provides by far the largest Western Hemisphere contribution to that ocean.

The infilled record for the Athabasca River at Athabasca is the most complete record in our study, with 92 years extending from 1913 to 2011 (Table II). In contrast to Jasper and Hinton, there has not been a significant pattern in annual river Q at Athabasca over the past century (Figure 4). The 2012 and 2013 data are being verified and both years apparently displayed above-average flows, and this would further oppose a possible pattern of recent flow decline.

Downstream, the Athabasca River flows near Fort McMurray are of particular interest relative to the oil-sands projects. The historic Q_{annual} pattern for this reach extended the upstream pattern at Athabasca (Figure 4), with 79.3% correspondence ($p < 0.01$) for the overlapping interval of direct measurement from 1958 to 2011. For the prior interval, with estimates from the 'At McMurray' stages, the pattern was also similar to that 'At Athabasca'. For 1950 and 1955–1957, there was 96% association ($p < 0.01$) between the Athabasca Q_{annual} and the McMurray estimates and that linear pattern closely matched the pattern for 1958 to 2011. For the earlier interval from 1938 to 1948, there was 91% correspondence ($p < 0.01$), but the estimates were offset downwards (Figure 4), suggesting a change in channel geometry and the subsequent stage-*versus*-discharge relationship.

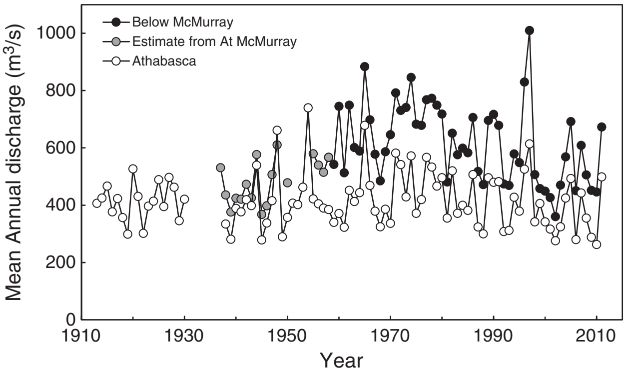

Figure 4. Mean annual discharges (Q_{annual}) of the Athabasca River at Athabasca and below Fort McMurray. For Fort McMurray, black symbols represent Q_{annual} values from below McMurray, and grey symbols indicate estimates based on 'At McMurray' stages

As previous researchers have reported (Table I), there was a significant decline in Q_{annual} at below McMurray for the measured interval from 1958 to 2011 ($Q_{annual} = (-3.03 \times \text{year}) + 6629$; $r = 0.35$, $p < 0.05$). If the derived 1950 and 1955–1957 estimates are included (Figure 4), there is no significant pattern, and this absence of a pattern is further supported if the 1937 to 1948 estimates are included ($r = 0.14$; n.s.). Although the lack of discharge calibration for the early record confounds this statistical analysis, the observed pattern is consistent with the pattern displayed upstream at Athabasca and indicates that over the past eight decades, there has not been a decline in Q_{annual} for the overall Athabasca River (Figure 4).

To complement the Athabasca River records, we also assessed the five major tributaries along the river corridor (Table II; Figure 1). Of these, the McLeod, Pembina and Lesser Slave river records commenced in 1914 or 1915 and thus provide time series extending about a century. For these, there was no significant Q_{annual} pattern (Figure 5), consistent with the lack of trend for the Athabasca River at Athabasca.

Analyses across hydroclimatic ecoregions

The Q_{annual} were correlated along the longitudinal Athabasca River corridor, but the correspondence declined with increasing river distance (Table III). Adjacent gauges had associations from 69% to 79%, and this fell to about 20% for mountain or foothills locations *versus* the boreal sites (Table III). These longitudinal comparisons are clarified with analyses of the river segment flows, with subtractions to remove the inflow from the upstream reach. This reduced the correspondences, and adjacent gauges displayed associations from 19% to 49% (Table IV). These segment correspondences declined along the corridor, and there were no significant association between the mountain (Jasper) or foothills (Hinton – Jasper or Windfall – Hinton) contributions and those of the boreal region downstream (McMurray – Athabasca). This confirms differentiation in historic patterns across the hydroclimatic ecoregions.

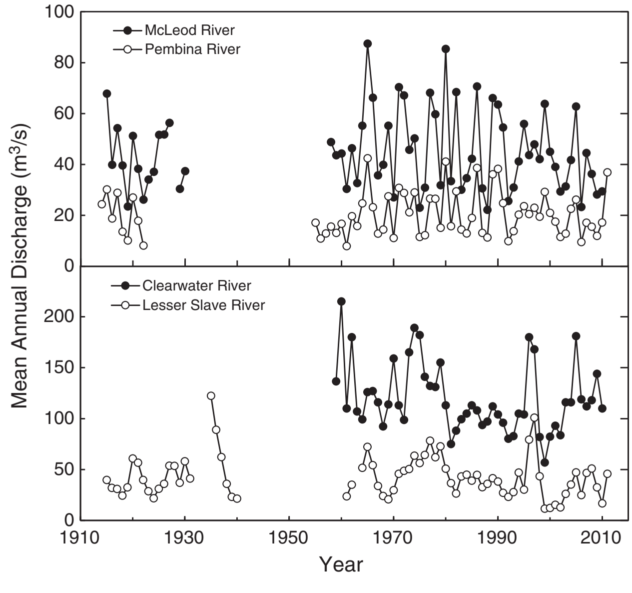

Figure 5. Mean annual discharges (Q_{annual}) of the major tributaries of the Athabasca River, with the McLeod and Pembina Rivers of the foothills ecoregions (top) and the downstream Lesser Slave and Clearwater Rivers of the boreal region (bottom)

Table III. Associations (R^2; %) for mean annual discharges of the Athabasca River at sequential hydrometric gauges

	Hinton (F)	Windfall (F)	Athabasca (B)	McMurray (B)
Jasper (M)	78.3	59.3	22.2	20.8
Hinton (F)		70.3	23.6	19.6
Windfall (F)			69.1	44.3
Athabasca (B)				78.6

The bracketed letters indicate the hydroclimatic ecoregions: M = mountain; F = foothills; B = boreal. *N*'s ranged from 41 to 75 and averaged 54 years, and all associations were highly significant ($p < 0.01$).

This conclusion is further supported by the tributaries' records. These display strong correspondences within ecoregions but distinct patterns across the ecoregions, despite relative proximity (Figure 1; Table IV). There were modest associations (11% or 14%) between the annual discharges of the foothills tributaries and the flow of the Athabasca in the mountain region (Jasper) and higher correspondence between the Athabasca River segments and tributaries within the foothills ecoregion (26% to 87%). In comparing the foothills and boreal reaches, for five comparisons, there were no significant correlations, and the other three comparisons provided associations of 8%, 8% and 25%, with the higher value (Athabasca River Win-Hin and Lesser Slave River) representing the lowest foothills zone, adjacent to the upper boreal zone. Within the boreal ecoregion, there was only a single comparison across reaches with independent flows, and this provided a 37% association. These analyses confirm that the sequential hydroclimatic ecoregions displayed different hydrologic patterns over the past century.

Historic patterns in monthly and seasonal discharge

Analyses of the historic monthly discharges revealed the temporal contributions that were responsible for the Q_{annual} changes. For these analyses, as with our prior Q_{annual} investigations (Rood *et al.,* 2008), the parametric Pearson correlation and nonparametric Kendall τ-b correlations provided highly consistent results (Table V). The exception was for Q_{Feb} at Jasper, which displayed a peculiar data distribution that suggests early gauging problems during that cold month when ice cover would complicate measurements.

For the mountain and foothills zones, there were opposing patterns across the seasons. There were increasing January,

Table IV. Correspondences (r^2) for mean annual discharges (Q_{annual}) of Athabasca River segments ($\underline{\text{Jas}}$per, $\underline{\text{Hin}}$ton, $\underline{\text{Win}}$dfall, $\underline{\text{Ath}}$abasca, $\underline{\text{McM}}$urray; 'Hin-Jas' = Hinton Q – Jasper Q, etc.) and tributaries

	Athabasca River segments				Tributaries			
	Hin-Jas (F)	Win-Hin (F)	Ath-Win (T)	McM-Ath (B)	McLeod (F)	Pembina (F)	Lesser Slave (B)	Clearwater (B)
Jasper (M)	0.492**	0.138*	0.174**	0.021	0.114*	0.136**	0.023	0.002
Hin-Jas (F)		0.229**	0.225**	0.001	0.257**	0.286**	0.002	0.012
Win-Hin (F)			0.454**	0.036	0.632**	0.466**	0.249**	0.023
Ath-Win (T)				0.193**	$\underline{0.427}$**	$\underline{0.455}$**	$\underline{0.624}$**	0.167**
McM-Ath (B)					0.000	0.004	0.468**	$\underline{0.702}$**
McLeod (F)						0.868**	0.078*	0.000
Pembina (F)							0.076*	0.000
L. Slave (B)								0.372**

Hydroclimatic ecoregions: M = mountain; F = foothills; T = transitional; B = boreal. *N*'s averaged 51 years and ranged from 41 to 64. Underlined values indicate partially redundant correspondence between a river segment and a tributary that inflows within that segment.
*$p < 0.05$.
**$p < 0.01$.

Table V. Analyses of historic mean monthly, seasonal (winter = December–February, etc.), and annual discharges *versus* year for Athabasca River locations with records extending back a century: Jasper (mountain), Hinton (mountain and foothills) and Athabasca (mountain, foothills and boreal)

	Jasper		Hinton		Athabasca
	Pearson r	Kendall's τ	Pearson r	Kendall's τ	Pearson r
Month					
January	0.169	0.069	0.327**	0.277**	0.053
February	0.350**	0.134	0.322**	0.265**	0.061
March	0.316*	0.226*	0.105	0.131^{t}	0.118
April	−0.060	−0.016	−0.207^{t}	−0.011	0.05
May	0.005	0.015	−0.074	−0.033	−0.026
June	−0.052	−0.050	−0.141	−0.107	−0.051
July	−0.340**	−0.201*	−0.346**	−0.224**	0.058
August	−0.403**	−0.336**	−0.454**	−0.345**	−0.052
September	−0.294*	−0.177*	−0.386**	−0.269**	−0.089
October	−0.010	−0.071	−0.058	−0.077	−0.035
November	−0.045	−0.050	0.033	0.030	−0.204
December	0.009	0.077	0.104	0.119	−0.028
Season					
Winter	0.099	0.101	0.330**	0.264**	−0.027
Spring	−0.060	−0.030	−0.148	−0.062	−0.026
Summer	−0.370**	−0.262**	−0.424**	−0.296**	−0.032
Autumn	−0.241^{t}	−0.147^{t}	−0.287**	−0.236**	−0.156
Annual	−0.358**	−0.243**	−0.424**	−0.311**	−0.039

Parametric Pearson r correlations are provided, and nonparametric Kendall's τ-b correlations are also included for locations with significant patterns, and no significant changes were detected at Athabasca. '−' indicates declining flow.
t: trend, $p < 0.1$.
*$p < 0.05$.
**$p < 0.01$.

February and March flows especially for Hinton (Table V), and this was also displayed for the Pembina River, the foothills tributary with the longest hydrometric record (January: $r = 0.328$**; February: $r = 0.384$**; March: $r = 0.307$*). This was opposed by significant declines in mid to late summer flows (July, August and September) for the Athabasca River at Jasper and at Hinton (Table V) but not for the Pembina River (e.g. July: $r = 0.106$, n.s.). Summer monthly flows were vastly higher than winter flows and consequently the net effect was the observed Q_{annual} decline (Figure 6; Table V). Following some boreal contributions, there was no significant monthly

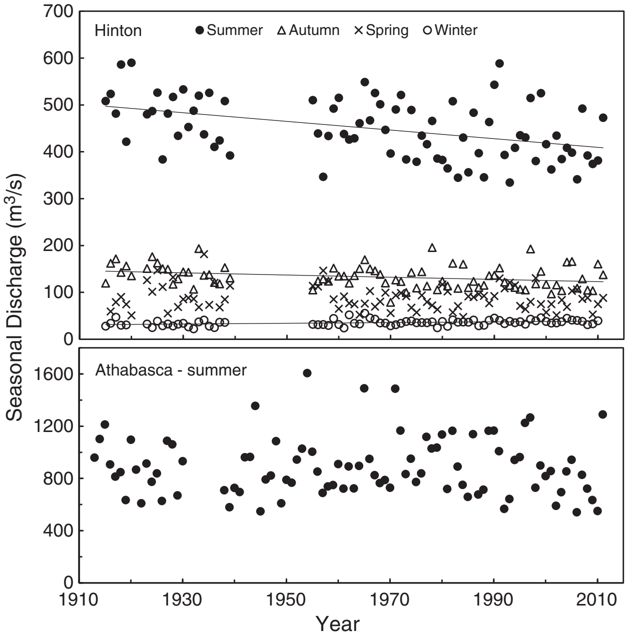

Figure 6. Seasonal (3-month mean) discharges of the Athabasca River at Hinton (top) and summer season (June, July and August) discharges at Athabasca (bottom). At Hinton, the regressions were summer $y = -0.924x + 2267$, autumn $y = -0.235x + 596$ and winter $y = 0.074x - 109$; all three $p < 0.01$

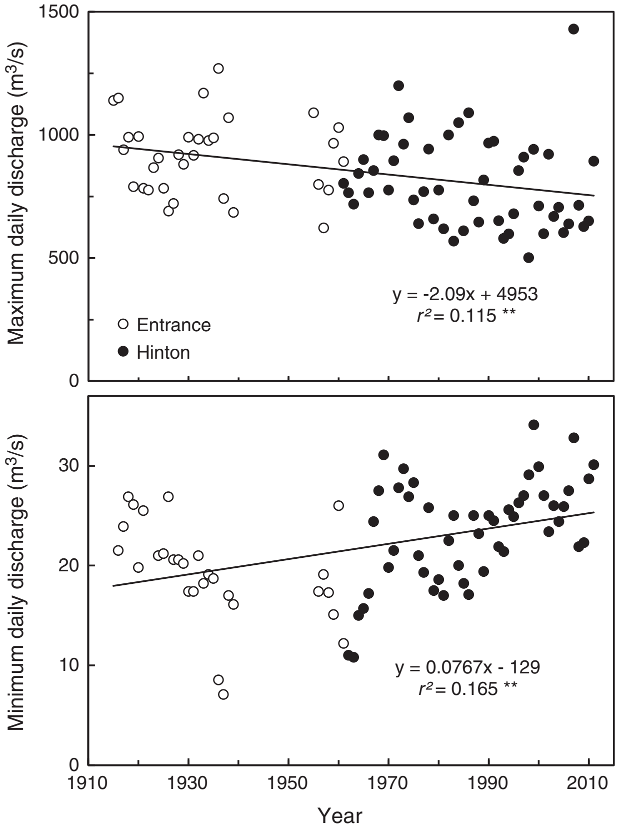

Figure 7. Yearly maximum (top) and minimum (bottom) mean daily discharges of the Athabasca River at Hinton

pattern for the Athabasca River at Athabasca (Table V), or for the boreal tributary, the Lesser Slave River (e.g. July: $r = -0.184$, n.s.).

Averaging across sequential months attenuates some variation and further reveals the seasonal patterns, with the strongest effects displayed for the Athabasca River at Hinton (Figure 6). At this location that reflected mountain and foothills contributions, there was progressive increase in the winter discharge over the past century, no significant pattern for the transitional season of spring, relatively steep flow decline in summer, and slight decline in autumn. Somewhat similar responses were indicated at Jasper, but the record is more limited, and statistical outcomes are weaker (Table V). In contrast to these headwater patterns, with the subsequent boreal contributions, there were no significant seasonal patterns at Athabasca (Table V). Thus, the monthly and seasonal patterns support the Q_{annual} results, with significant changes for the mountain and foothills region, but subsequent patterns were opposed and dampened by drainage from the boreal regions. Consequently, there were no century-long patterns for the seasonal flows at Athabasca.

As a further consideration, we also investigated possible historic changes in maximum and minimum daily flows of the Athabasca River. Such changes could reflect 'climate intensification', the principle whereby global warming and climate change would result in more extreme weather events and thus more severe floods and droughts (Milly *et al.*, 2002). Opposing this prediction, at Hinton, there was gradual decline in the Q_{max} and apparently, gradual increase in Q_{min} over the past century (Figure 7). However, the minimum flows generally occurred in the winter months when measurement was challenged by river ice, and this diminishes the confidence in this pattern. Downstream at Athabasca, there were no significant patterns in either maximum or minimum discharges ($r = 0.025$, n.s.; $r = 0.035$, n.s.), and this further indicates different hydrologic responses in the boreal *versus* higher ecoregions.

Coordination with the Pacific Decadal Oscillation

The discharge plots reveal some coordinated variation over the past century and particularly higher flows around 1970 and then a decline to around 2000, although this is complicated by the interannual variation. This pattern is suggested by some of the monthly and seasonal plots and more prominently in the plots of annual discharges, especially for the downstream locations along the Athabasca River (Figure 4). We and others have recognized the coordination between historic flows of western North American rivers and the PDO, and this is strongly reflected in overall flows of the Athabasca River (Figure 8). There was thus a regionally cool phase of the PDO from around 1950 to 1970 that was associated with higher flows. Subsequently, a phase transition followed from around

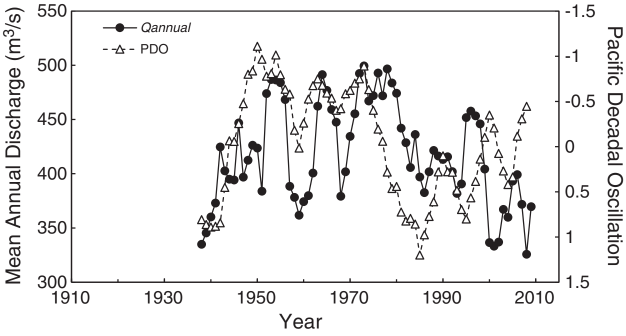

Figure 8. Moving 5-point averages for mean annual discharges of the Athabasca River at Athabasca and for the inverted (declining *y*-axis scale) Pacific Decadal Oscillation index

1970 to 1985, and this was associated with flow decline throughout the Athabasca River Basin.

Interestingly, there appears to be lower correspondence between the PDO and Athabasca River flows in the recent record, and particularly after about 1997 when the PDO can neither be assigned to a warm nor cool phase. For the 60 years prior to 1997, there was significant correlation between the 5-year running mean for the PDO and annual discharge (Pearson $r = -0.389$, $p = 0.002$; Kendall's $\tau = -0.281$, $p = 0.002$). For the 11 years after 1997, there was no significant correlation (Pearson $r = 0.387$, $p = 0.240$; Kendall's $\tau = 0.345$, $p = 0.139$). The shorter record after 1997 contributes to the lack of significant effect, but it is notable that the apparent correlations were of similar strength, but inverted in the pre-1997 *versus* post-1997 intervals. As streamflow records are extended, this possible change in relationship between the PDO and river discharge should be further investigated.

As a final analysis, the Athabasca River Basin also provides some insight into the hydrologic consequence of glacial recession. The Athabasca Glacier provides an outflowing glacial tongue from the Columbia Icefield, which provides the largest ice and snow field in the Rocky Mountains. Despite the name, the Athabasca Glacier provides the source for the Sunwapta River, which later joins the larger Athabasca River, which originates from adjacent glacial valleys from the Columbia Icefield. Summer, melt-season flow records for the Sunwapta River commenced in 1948, and over the past half-century, there was progressive increase in June flows ($Q_{Jun} = (0.016 \times \text{Year}) - 29.3$; $r^2 = 0.130$; $p < 0.01$) and apparently in melt-season flows ($Q_{Jun\text{–}Sep} = (0.0072 \times \text{Year})$ 10.9; $r^2 = 0.065$). Increased glacial melt would be consistent with regional warming and with the observed recession of the Athabasca Glacier. The increase in summer season glacial melt opposes the observed decline in summer and annual flows of the upper Athabasca River, and this is consistent with the very minor area and limited meltwater contributions from glaciers relative to the overall Athabasca River watershed.

DISCUSSION

Rejecting the null hypothesis of no change, there were statistically significant patterns in historic flows for the mountain and foothills reaches of the Athabasca River and tributaries. Consistent with our prior analyses (Rood *et al.*, 2005) and our primary hypothesis (H_1), there were declines in summer and annual flows at Jasper, and these patterns extended to Hinton, within the foothills ecoregion. The current study extends the analyses to a century, increasing the confidence in these patterns (Table I).

In contrast to our expectation that these patterns would extend downstream, by the Town of Athabasca, there was no significant pattern in annual, monthly or seasonal flows over the past century. Flow records are shorter for the Athabasca River downstream around Fort McMurray, but those Q_{annual} were closely correlated (79%) with flows at Athabasca. The historic plots do display decline at Fort McMurray from around 1970 to 2000, as has been the focus of a sequence of prior reports (Table I). However, this was probably a temporary pattern, and the longer record indicates that the flows around 1970 were unusually high, and the subsequent decline returned to flows that were typical for the longer record.

Consequently, for the Athabasca River watershed, there were significant flow changes for the headwater zone, but this pattern diminished downstream. There were also monthly and seasonal changes, and these were also restricted to the upper zones. There was interannual variation over the century-long record, with some stochastic year-to-year variation superimposed on multiple-year intervals of high *versus* low flows that corresponded in part with the PDO. With the century-long interval that spans two PDO cycles and dampens some variation, there was no overall linear pattern for the lower reaches that integrate drainage from the mountain, foothills and boreal zones. This major conclusion contrasts with the repeated interpretation from analyses of shorter intervals primarily for the river near Fort McMurray (Table I).

The results support our more novel secondary hypothesis (H_2) that there would be differences across the sequential hydroclimatic ecoregions. However, the nature of the differences was unexpected. We anticipated that the sequential ecoregions would display common direction of change but variation in response magnitude. In contrast, we found ecoregion-localized patterns, with summer and annual flow declines being restricted to the mountain and foothills regions. In contrast, the boreal ecoregions displayed patterns that were not only different in magnitude but also were even different in direction and thus opposed the patterns from the mountain and foothills headwater region. This indicates that adjacent hydroclimatic ecoregions displayed different hydrologic consequences from recent climate change, and this will complicate projections of prospective future water supplies. This also confirms the challenge of hydroclimatic modelling over broad and diverse geographical regions, which provides a foundation for global circulation models. Regional climate models provide downscaling that is typically based on topoclimatic patterns due to aspects such as altitude and aspect (Shepherd *et al.*, 2010), but the prospect of opposing hydrological responses in adjacent ecoregions will complicate these analyses.

The longitudinal analysis is also important because there are localized patterns of water use. Hydroelectric power generation is favoured for the steeper headwater reaches, flows for dilution of pulp-and-paper mill effluent are important for the middle reaches and environmental flows to compensate for impacts from the oil-sands activities occur at the downstream end of this river system. Similar longitudinal differences in water use are likely to apply for many other rivers around the Northern Hemisphere and worldwide.

This study is directly relevant to water supplies for the Athabasca oil-sands projects (Schindler and Donahue, 2006; Peters *et al.,* 2013) and for hydroecological consequences for the Peace–Athabasca, Slave and Mackenzie deltas (Prowse and Conly, 2002; Toth *et al.,* 2006). It also provides broader relevance to the investigation of historic patterns to analyse the hydrological consequences of climate change and particularly emphasizes that sufficient data durations are essential for interpretation. The prior literature investigating hydrologic consequences of climate change has been dominated by studies with only a few decades of hydrologic record. It is likely that subsequent interpretations are incomplete and, similar to prior conclusions for the Athabasca River, may be misleading.

Climate change forecasts anticipate that there will probably be amplified hydrological changes at higher latitudes (Rouse *et al.,* 1997). For these regions, the early manually measured hydrologic records were often incomplete through the cold winters. Because these rivers commonly display nival, or snowmelt dominated hydrographs, the winter flow contributions are slight, and data extrapolations to estimate Q_{annual} from warm-season records will often provide highly accurate estimates. Consequently, this strategy of extending the time series should be broadly applicable, and this would considerably extend the data series for many other northern rivers. This would enable synthetic data series that extend over a century and thus absorb the transitions from climate oscillations. It should thus be relatively easy to considerably extend the data series from which we analyse the historic patterns to enable cautious projections of future water supplies from northern rivers (Toth *et al.,* 2006; Shepherd *et al.,* 2010; St. Jacques *et al.,* 2010).

This raises the important question of what data interval would be sufficient to detect prospective consequences of climate change. A common but somewhat arbitrary interval of 30 years is regarded as the transition from 'weather' to 'climate', and many of the earlier hydrologic analyses considered intervals of only 30 or 40 years (Table I). This was common as studies investigated broader geographical trends and thus assessed many rivers in a region such as in western Canada (Burn and Hag Elnur, 2002; Woo and Thorne, 2003; Burn *et al.*, 2004; Abdul Aziz and Burn, 2006). For these analyses, an emphasis had been for comparisons across multiple rivers, and consequently, a common interval was selected. However, this would result in the shortest interval of the multiple rivers, thus limiting the study duration.

In contrast to that approach, it is now recognized that river flows display some coordination with climate oscillations, and especially the PDO, (Rood *et al.*, 2005; St. Jacques *et al.*, 2010; Whitfield *et al.*, 2010; Peters *et al.* 2013), as we observed for the Athabasca River flows. Consequently, to detect hydrologic patterns associated with climate change, river flow records must be sufficiently long to absorb the reversing influences from PDO phase transitions. Because the PDO period is around four decades, we would recommend that sufficient hydrometric time series should be at least two PDO cycles or around 80 years. Because the PDO period is uncertain and probably somewhat variable, we would further encourage that century-long time series should be sought, as we undertook in this study.

Challenging this objective, relatively few continuous hydrometric records exist for the past century. In western North America and other regions worldwide, there was substantial investment in hydrological monitoring that commenced around the 1910s, but these early records required manual measurement. It was consequently typical for gaps in the hydrometric record, during economic-downturns, or during major events such as the World Wars. Additionally, gauges were typically associated with bridge crossings, and as bridges were relocated, the gauges were moved or abandoned.

To compensate for the subsequent gaps in the river discharge records and to coordinate data from sequential gauges, in this study, we present a strategy for infilling and splicing across hydrometric gauges, extending our previous approaches (Rood *et al.,* 2005; 2008). However, it must be recognized that any data manipulation could introduce not only error or imprecision but potentially bias, non-random error. Thus, following any splicing, the composite record should be assessed for offsets, but this is difficult because the hydrologic records are naturally highly variable. Subsequently, as we describe for the Athabasca River system, it is strategic to assess multiple locations and also regional tributaries, and the consideration of correspondences within and across rivers can assist in the detection of problems due to data extension. This analysis of multiple reaches and tributaries also assists with the detection of trends both over time and over the rivers' longitudinal extent.

Finally, this study investigated the long, large and free-flowing Athabasca River and provides the longest hydrologic time series for any river draining the Rocky Mountains towards the Arctic Ocean. We found that flows had been declining in the headwater reaches, but boreal contributions provided opposing patterns, resulting in no overall pattern. It will be important to further consider prospective changes in river flows of other boreal and subpolar rivers in the Northern Hemisphere to determine whether this represents a wide spread pattern. There have been some prior analyses of other Arctic drainages including the Peace, Slave, Liard and Mackenzie rivers (Rouse *et al.,* 1997; Burn *et al.*, 2004; Rayne and Forest, 2010; Rasouli *et al.*, 2013), which provide by far the largest Northern Hemisphere contributions to the Arctic Ocean. However, the prior analyses assessed intervals of only three or four decades and would be prone to the confounding influence from the PDO phase transition. We thus specifically recommend that future studies should work to extend the hydrologic time series and investigate longer-term patterns for these and other Arctic drainages in the Northern Hemisphere.

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