A century of hydrological variability and trends in the Fraser River Basin

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Abstract
This study examines the 1911–2010 variability and trends in annual streamflow at 139 sites across the Fraser River Basin (FRB) of British Columbia (BC), Canada. The Fraser River is the largest Canadian waterway flowing to the Pacific Ocean and is one of the world’s greatest salmon rivers. Our analyses reveal high runoff rates and low interannual variability in alpine and coastal rivers, and low runoff rates and high interannual variability in most streams in BC’s interior. The interannual variability in streamflow is also low in rivers such as the Adams, Chilko, Quesnel and Stuart where the principal salmon runs of the Fraser River occur. A trend analysis shows a spatially coherent signal with increasing interannual variability in streamflow across the FRB in recent decades, most notably in spring and summer. The upward trend in the coefficient of variation in annual runoff coincides with a period of near-normal annual runoff for the Fraser River at Hope. The interannual variability in streamflow is greater in regulated rather than natural systems; however, it is unclear whether it is predominantly flow regulation that leads to these observed differences. Environmental changes such as rising air temperatures, more frequent polarity changes in large-scale climate teleconnections such as El Niño-Southern Oscillation and Pacific Decadal Oscillation, and retreating glaciers may be contributing to the greater range in annual runoff fluctuations across the FRB. This has implications for ecological processes throughout the basin, for example affecting migrating and spawning salmon, a keystone species vital to First Nations communities as well as to commercial and recreational fisheries. To exemplify this linkage between variable flows and biological responses, the unusual FRB runoff anomalies observed in 2010 are discussed in the context of that year’s sockeye salmon run. As the climate continues to warm, greater variability in annual streamflow, and hence in hydrological extremes, may influence ecological processes and human usage throughout the FRB in the 21st century.

Keywords: Fraser River, British Columbia, climate variability, salmon, streamflow

Online supplementary data available from stacks.iop.org/ERL/7/024019/mmedia

1. Introduction

The Fraser River Basin (FRB) drains 240,000 km² or one quarter of British Columbia (BC), Canada, forming one of the greatest salmon rivers in the world (Fraser Basin Council 2009). The ecological, social and economic diversity of the FRB provides for extensive natural and human heritage. Cultural diversity encompasses many First Nations communities who continue to use the Fraser River and its tributaries for waterways and sustenance, especially related to local salmon runs (Benke and Cushing 2005, Fraser Basin Council 2006, 2009).
Despite the watershed’s vastness, immense diversity and its population of ≈2.7 million people (Fraser Basin Council 2009), few studies have examined climate change impacts on streamflow variability and trends across the FRB. Some studies on the FRB report increasing trends in observed annual flows and the occurrence of earlier peak flows in the latter half of the 20th century (Morrison et al 2002, Ferrari et al 2007). Observed mean summer water temperatures of the lower Fraser River have warmed by ∼1.5°C since the 1950s (Patterson et al 2007). With continued climate change, global climate model (GCM) simulations project that the Fraser River may exhibit more of a pluvial regime rather than a nival one owing to warmer winter air temperatures and phase changes in precipitation (Morrison et al 2002, Kerkhoven and Gan 2011) and incur a rise of 1.4°C in August water temperatures by 2100 (Ferrari et al 2007). Changes in the amount and timing of streamflows will also influence sediment and chemical (e.g., nutrients, carbon, and contaminants) fluxes in the FRB, which will have implications for water resources (e.g., water quality, channel and estuarine maintenance dredging) and aquatic habitats.

The success of migrating and spawning salmon populations relies heavily on water temperatures and flow levels. Fraser River sockeye experience high mortality rates during years of above normal river temperatures and discharge (Rand and Hinch 1998). Energy demands increase when water levels are high, especially in the lower Fraser River, leading to exhaustion and eventually death (Macdonald 2000). In addition, with some of the fall runs now occurring 3–6 weeks earlier (Cooke et al 2004), the migrating salmon are exposed to water temperatures that are ∼3°C higher than normal (Patterson et al 2007), influencing their swimming performance, metabolic rates and overall survival (Lee et al 2003). Thus as climate continues to change and as anthropogenic developments such as impoundments and diversions progress, there is an urgent need to better understand the variability in river conditions as this is crucial in determining the implications for ecological processes, such as the success of salmon runs, and human values associated with them (Knowler et al 2003, Evendon 2004).

To our knowledge, this is the first comprehensive study that examines the interannual variability and trends in observed streamflow at 139 locations across the FRB using hydrometric data spanning a century (1911–2010). Specifically, we investigate the hypothesis that environmental change (whether natural or anthropogenic) may be leading to altered hydrological variability or extremes as has been observed in other regions of Canada (e.g., Déry et al 2009). Furthermore, we investigate whether there are links between either topography or anthropogenic developments with observed trends and fluctuations in annual streamflow across the basin. Although establishing the full range of impacts of changing flow regimes on ecological functions in the FRB is beyond the scope of this letter, we suggest linkages between variation in flow conditions and salmon returns. We use this example to highlight the relevance of streamflow variability on this keystone species within the FRB as the annual stock success in turn plays a vital role in both ecosystem health and human activities in the basin.

2. Study area

The Fraser River is the largest Canadian river by drainage area flowing into the Pacific Ocean. It extends from 49°N to 56°N and 118°W to 125°W and encompasses 13 major sub-watersheds (figure 1). The basin has a mean elevation of ∼1320 m with the main stem of the Fraser River and its vast network of tributaries situated between BC’s Coast Mountain and Rocky Mountain ranges. The Fraser River headwaters are in the Rocky Mountains near Jasper at the Alberta/BC border, from where it flows northwest through the Rocky Mountain Trench toward Prince George. There it turns sharply south where the Nechako River joins it and flows through the Fraser Plateau, collecting discharge from the Chilcotin River (figure 1). It passes through the Fraser Canyon west of the semi-arid interior plains before flowing westward at Hope and into the Strait of Georgia and Salish Sea near Vancouver, BC. The main stem of the Fraser River spans a distance of 1375 km and the watershed experiences a 3950 m drop in elevation from its highest point in the Rocky Mountains to its outlet at sea level (Benke and Cushing 2005). Although the proportion of land-use in the Fraser basin is only 2.2% urban and 0.6% agricultural (Benke and Cushing 2005), the area supports 53% of farmland in the province of BC (Fraser Basin Council 2009). These land-use values, along with the river’s designation as a Canadian Heritage River in 1998, and the relationship between First Nations communities and local salmon runs across eight First Nations language groups, all highlight the range of human demands and values associated with the Fraser River (Evendon 2004, Fraser Basin Council 2006, 2009).

Mean annual air temperatures across the basin range between 0.5°C in the northwest by the Skeena Mountains and 7.5°C in the south near the Okanagan region. Summer and winter mean air temperatures in the FRB range from 11°C to 16.5°C and −11°C to −1°C, respectively. Relatively dry conditions exist in the interior plateau, in the rain shadow of the Coast Mountains, where precipitation averages 400–800 mm yr⁻¹ (Benke and Cushing 2005). In contrast, coastal and mountainous sections may experience precipitation in excess of 3000 mm yr⁻¹. Snowfall forms an important component of the annual precipitation, especially in the basin’s northern and mountainous sections. For instance, the areally averaged 1 April snow water equivalent near Prince George (which is located on the northern-most section of the main stem) is 409 mm yr⁻¹ for 1966–89 (Danard and Murty 1994). As a result of its highly varying terrain and climate, the FRB has an extremely diverse vegetative cover consisting of alpine, subalpine, montane and coastal forests as well as mixed drier forests and grasslands in the interior plateau (Benke and Cushing 2005). Glaciers cover 1.4% of the FRB and augment the summer flows of alpine rivers and headwater streams through glacial melt (Stahl and Moore 2006).

Most of the FRB is minimally impounded, with the Nechako River being the only major system that is regulated (figure 1). Flow regulation began in the early 1950s when the Kenney Dam was constructed (Hartman 1996), resulting in some of the impounded water being diverted to the coastal...
Kemano River watershed and the remaining water stored in a reservoir spanning 922 km² and containing a volume of 32.7 km³ (Schiefer and Klinkenberg 2004). The area upstream of the Kenney Dam covers 15 600 km² or 7.2% of the FRB area as gauged at Hope, BC (see figure 1).

3. Data and methods

Daily streamflow data at 148 FRB gauges (nine gauges on the main stem and 139 on its tributaries) for the period between 1911 and 2010 were extracted from Environment Canada’s Hydrometric Database (HYDAT) (Water Survey of Canada 2011; see figure 1 and supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). The criteria used in selecting the hydrometric stations include: (a) a location within the FRB, (b) an area upstream of the gauge ≥ 100 km², and (c) data availability for ≥10 yr. These criteria were chosen to exclude the many small (< 100 km²) basins and/or short (n < 10 yr) observational records available in the FRB. Data availability varies markedly across sites and improves in the latter half of the study period (see supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). The database includes hydrometric data for the Ootsa, Tahtsa, Tetachuck and Whitesail rivers in the Nechako River Basin for years prior to 1953 when the Kenney Dam was built. Although these four river systems were largely flooded as a result of the filling of the Nechako reservoir in the early 1950s, they provide valuable information on the natural hydrology in the upper reaches of the Nechako watershed. Since 1954, water diverted from the Nechako reservoir enhances the flow of the Kemano River that discharges directly to the Pacific Ocean, outside the FRB domain. Data from a hydrometric gauge at the Kemano Powerhouse (ID: 08FE002) were thus used to estimate the inter-basin transfer of water from 1954 to 2010. Apart from the site identification number, coordinates and upstream gauged area, information on flow regulation, mean basin elevation, and glacierized area were also extracted from HYDAT when available.

Time series of annual streamflow were then constructed based on the daily discharge time series. In addition, time series of the mean and coefficient of variation (CV) for 11 yr moving windows of annual streamflow were compiled. Gaps in the hydrometric time series were in-filled with the daily mean flow over the available period of record at each site. An average of 6.5% of the daily streamflow data at each site was in-filled in this manner (see supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). Déry et al (2011) found this gap filling strategy attenuated streamflow trend magnitudes, especially when missing data were consecutive and occurred at the beginning or end of the time series. This
study minimized such issues by using an inhomogeneous study period in some of the analyses thus maximizing data availability and spatial coverage. For nine sub-basins in the dataset, the hydrometric gauges were moved to a nearby location from their original site, leading to slight (<10%) changes in upstream gauged area. In these circumstances, the streamflow time series were combined for the ‘paired’ records by adjusting the hydrometric data for the missing contributing area at the gauge with the smallest basin extent (e.g., D´ery et al 2005, Wei and Zhang 2010). We thus assumed that the missing contributing area exhibited similar runoff rates to the gauged portion of the basin. Thus splicing of the hydrometric time series at the nine sites where gauges were moved resulted in a total of 139 time series of annual streamflow across the FRB. Homogeneity tests and analyses (such as in Tom´e and Miranda 2004) were conducted on the basins affected by gauge relocations but few, if any, were found to be significantly impacted by these.

Discharge data were first divided by their respective basin areas to obtain time series and statistics of areal river runoff $R$ (in mm yr$^{-1}$) at each site of interest. This included the mean and CV in annual streamflow that were calculated for all sites of interest for their respective periods of data availability over calendar years 1911–2010 (see supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). The CV was used in this study to quantify the interannual variability in streamflow as it facilitated comparisons between sites across the FRB where the variance in annual runoff varies by several orders of magnitude. Values of $R$ and CV were then correlated with the available geographic information (latitude, longitude, gauged area, mean basin elevation and glacier coverage) and with record length. Correlation values were considered statistically significant when $p < 0.05$.

The Mann–Kendall test (Mann 1945, Kendall 1975) was used to assess monotonic trends in the time series of CV for 11 yr moving windows of annual streamflow where data were available over four time periods (median years 1920–2005, 1940–2005, 1960–2005 and 1980–2005). The 11 yr moving windows were generated from the time series of annual streamflow and the number of sites included in the analyses increased for the latter half of the study period when data availability improved (see supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). For instance, the trend analysis for median years 1920–2005 includes only sites with available streamflow data spanning 1915 (first year of the first moving window) to 2010 (last year of the last moving window). An additional analysis was performed to explore trends in seasonal values of the CV in 11 yr moving windows of streamflow for 1980–2005. Here we considered winter to span December, January, February and March, spring to span April, May and June, summer to include July, August and September, and autumn to span October, November and December.

We qualified trends as ‘detectable’ when their signal-to-noise ratios $\text{snr} > 1$, where snr equaled the absolute trend slope divided by the standard deviation over a given period of interest (D´ery et al 2011). Prior to the trend analyses, time series of CV for 11 yr moving windows of annual streamflow were pre-whitened to remove the effects of autocorrelation on the results (Yue et al 2002). This provided a measure of changing hydrological variability, or extremes, on a decadal time scale across the FRB (D´ery et al 2009). Note that detectable trends in time series of CV for 11 yr moving windows of annual streamflow were not uniquely attributable as they depended on the evolution of its statistical components, the corresponding means and standard deviations. This study focused on trends in the CV of streamflow as we were more interested in detecting changes in hydrological variability over time. Field significance (at a 10% level) of trend results was established using the bootstrapping methodology of Burn and Hag Elnur (2002).

Here we randomly resampled each of the time series of the CV in 11 yr moving windows 1000 times and recorded the distribution of significant trends. Finally, we explored the relationship between the mean and CV in 11 yr moving windows of annual runoff over median years 1917–2005 for the Fraser River at Hope (ID: 08MF005). This gauge encompasses 93% of the total FRB area and has one of the longest, continuous records of the basin’s streamflow.

4. Results

4.1. Streamflow variability and trends across the FRB

The mean areal annual runoff ($R$) varies substantially across the FRB, with low values ($R < 200$ mm yr$^{-1}$) in small streams in the central portion of the basin and in rivers to the lee of the Coast Mountains on the Chilcotin and Nechako plateaus (figure 2(a)). High values ($R > 1200$ mm yr$^{-1}$) occur in alpine streams that are glacier-fed and in the coastal watersheds near the mouth of the Fraser River where abundant rainfall augments runoff generated by snow and glacier melt at high elevations (see supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). Interannual variability in streamflow, expressed by the CV, peaks in small streams in the central portion of the basin and in rivers to the lee of the Coast Mountains and is attenuated in alpine and larger watersheds. Although high interannual variability is observed on the regulated Nechako River, some of its naturally flowing tributaries (the Stellako and Nautley rivers) show similar patterns in CV values. A comparison of figures 2(a) and (b) reveals a clear negative relationship between $R$ and CV values. In fact, the correlation coefficient between $\ln(R)$ and CV in annual streamflow for the 139 sites is $-0.77$ ($p < 0.001$). Values of $R$ correlate negatively with latitude and positively with glacier coverage, whereas values of the CV in annual streamflow correlate negatively with gauged area, mean basin elevation, and glacier coverage (table 1). An additional analysis reveals the absence of a statistically significant relationship between the CV in annual streamflow and length of the observational records. Thus we find no evidence that record length suppresses the statistics of interannual variability in streamflow in the FRB.

Detectable trends for the CV in annual streamflow show remarkable spatial consistency over different time periods (figure 3). The paucity of hydrometric data for the first half
Figure 2. (a) The mean annual runoff $R \times 10^3 \text{mm yr}^{-1}$ and (b) the CV in annual runoff at all sites across the FRB. The star denotes Kenney Dam.

Table 1. Correlation coefficients between various topographical parameters and the annual runoff ($R$) as well as the coefficient of variation in annual streamflow (CV) across the FRB. Bold values indicate statistically significant correlations and $n$ provides the number of sites used in the analyses.

| Topographical parameter | $R$  | CV  |
|-------------------------|------|-----|
| Latitude, $^\circ$N ($n = 139$) | $-0.25$ | $-0.07$ |
| Longitude, $^\circ$W ($n = 139$) | $-0.03$ | 0.05 |
| Gauged area, km$^2$ ($n = 139$) | $-0.10$ | $-0.17$ |
| Mean elevation, m ($n = 83$) | 0.17 | $-0.39$ |
| Glacier area, % ($n = 53$) | 0.49 | $-0.30$ |

4.2. Impact of anthropogenic developments on streamflow variability and trends across the FRB

Over 1954–2010, an average of 3.2 km$^3$ yr$^{-1}$ was diverted from the Nechako watershed to the Kemano River to generate and supply hydroelectricity for an aluminum smelter in Kitimat, BC. This diversion leads to a 4.2% reduction (equivalent to a decline of 14.7 mm yr$^{-1}$ in the annual runoff) on the Fraser River at Hope over that period. After the construction of Kenney Dam, the CV in annual streamflow for the Fraser River at Hope over two periods of equal duration rises slightly from 0.124 (1912–53) to 0.129 (1954–95). In the absence of naturalized discharge data for the Nechako River, however, it is unknown how flow regulation and water retention in this watershed affects interannual streamflow variability at downstream locations, such as on the main stem of the Fraser River.
Apart from the Nechako River, several smaller tributaries of the Fraser River, especially in the North Thompson, South Thompson, Thompson–Nicola and Bridge–Seton sub-watersheds, are regulated. The CV in annual streamflow for these systems averages 0.36, considerably higher than in naturally flowing rivers of the FRB (table 2). Limiting the comparison to watersheds < 10,000 km² and to the closest nearby gauge with natural flows yields mean CV values in annual streamflow of 0.40 and 0.26 for regulated and natural systems, respectively. Nonetheless, it is important to note that
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Figure 4. Monotonic trends in the 11 yr moving windows in the CV of seasonal streamflow across the FRB during (a) winter, (b) spring, (c) summer and (d) autumn over 1980–2005 (referenced by median year). The star denotes Kenney Dam. Trend slope and signal-to-noise ratio are noted as $m$ and $snr$, respectively.

many of the regulated streams lie in regions with a relatively dry climate where natural runoff varies substantially from year to year (see table 2 and supplementary data available at stacks.iop.org/ERL/7/024019/mmedia). Thus flow regulation within the FRB does not necessarily lead to suppressed interannual variability in streamflow.

5. Concluding discussion

This study provides new information on streamflow variability and trends across the FRB that expands on the work of Foreman et al (2001) and others. Consistent with our results, Foreman et al (2001) reported a tendency toward
These trends toward a warmer, wetter climatic regime but with less snowfall have imposed modifications on the surface hydrology of the FRB including greater interannual variability in river runoff as reported in the present study. Furthermore, more temperate wintertime conditions have led to the proliferation of the mountain pine beetle (*Dendroctonus ponderosae*) with mature pine tree mortality rates reaching 80% (e.g., Picketts *et al* 2012). Deforestation from this pest outbreak along with industrial wood harvesting reduces the interception of snow by the tree canopy, favors greater snowpack accumulation at the surface, and enhances runoff productivity through less water demand from vegetation (Boon 2012). Thus deforestation yields higher runoff during wet years than would be expected for pristine environments. Glacier melt during warm, dry years moderates runoff fluctuations from headwater catchments, offsetting low precipitation amounts (Fountain and Tangborn 1985, Fleming and Clarke 2005). Glaciers in BC are currently retreating and downwasting at an accelerating rate (Schiefer *et al* 2007), suggesting that many of the alpine watersheds may experience declining summer flows and hence greater interannual variability in streamflow (Stahl and Moore 2006). Large-scale teleconnection patterns such as El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) strongly modulate the climate of the FRB (e.g., Thorne and Woo 2011). Polarity changes in ENSO and the PDO are projected to occur more frequently and with greater intensity in the 21st century (e.g., Müller and Roeckner 2008, Lapp *et al* 2012), yielding an increasing threat of hydrological extremes across the FRB, especially in glacierized watersheds. Rapid shifts between El Niño and La Niña conditions in the tropical Pacific Ocean over recent years are consistent with these model projections and with the amplifying hydrological variability across the FRB reported in this study. This will likely impose greater challenges for water resource managers as well as for humans, fauna and flora of the FRB. In addition to implications for water resources, one of the greatest on-going concerns of FRB streamflow is its role on migrating salmon and the likely effects of changing conditions on salmon stock sustainability.

The interannual variability in streamflow remains low in rivers such as the Adams (CV = 0.14), Chilko (CV = 0.13), Quesnel (CV = 0.14–0.17) and Stuart (CV = 0.22), where the principal salmon runs of the Fraser River occur (Eliason *et al* 2011). This low streamflow variability increases the likelihood of salmon surviving the migration back to their spawning grounds. Rand *et al* (2006) link the success of the early Stuart sockeye salmon population to river water levels, with years of higher than normal discharge (such as 1997) forcing salmon to exert greater amounts of energy during their up-river migration. In the lower Nechako River (downstream of the confluence with the Stuart River), flows are relatively

### Table 2. The mean and standard deviation (SD) of annual runoff (R) and the coefficient of variation in annual streamflow (CV) for natural and regulated rivers. Note that n provides the number of sites used in the analyses.

| Rivers       | Mean R (mm yr⁻¹) | SD R (mm yr⁻¹) | Mean CV | SD CV |
|--------------|------------------|----------------|---------|-------|
| Natural (n = 96) | 809            | 672             | 0.20    | 0.09  |
| Regulated (n = 43) | 426            | 750             | 0.36    | 0.18  |
shallow, especially since the construction of the Kenney Dam, affecting water temperatures and hence fish metabolism (Hartman 1996, Rand et al. 2006). Thus in the FRB, low flows result in warmer water temperatures whereas high flows accompany strong currents, with both situations increasing energy demands for migrating salmon. Our trend analyses reveal a tendency toward greater interannual variability in streamflow and thus recent increases in the frequency and/or intensity of low/high flow conditions. Increased streamflow variability from environmental change may therefore hinder the survival rate of the Fraser River sockeye during their spawning migration. For instance, spring freshets will occur earlier and be of shorter duration as snowpacks decline (Cunderlink and Burn 2004). In late summer and autumn, discharge may be lower but remain higher during winter as more precipitation falls as rain, rather than snow (Healey 2011). Spawning conditions during late summer and autumn could therefore be compromised through warmer water temperatures and lower flows in the FRB coastal streams while in winter stronger freshets and storms would scour the spawning gravels before the fry are ready to emerge (Melack et al. 1997).

The Fraser River experienced an unexpected record sockeye salmon run of >30 million up-river migrating fish in 2010, surpassing all other runs in the past century (Cone 2012). However, the excess abundance of 2010 was not homogeneous throughout the Fraser sub-basins. The majority of sockeye returned to the Adams and Chilko Rivers while other upstream returns were near or below expected values (Cone 2012). These events coincided with relatively low flows across northeastern sections of the FRB, most notably in the Upper Fraser and Quesnel watersheds, that were concomitant with an El Niño event that year (figure 6). In fact, the hydrometric gauges on the Fraser River at Marguerite (ID: 08MC018) and Quesnel River near Quesnel (ID: 08KH006), both upstream of the Chilko and Adams rivers, registered historical low values of annual runoff with departures reaching $-1.7$ and $-2.0$ standard deviations from the 1981–2010 mean values, respectively. Concurrently, in the upper reaches of the Nechako and Chilcotin watersheds where fish returns were abundant, positive anomalies in annual runoff were observed, illustrating the regional variability in streamflow generating processes and responses to large-scale climate oscillations (e.g., Fleming et al. 2006, Thorne and Woo 2011). The relationship between these regional runoff anomalies and basin variations in the salmon returns should be explored further to determine if an historical pattern exists between these factors. Investigation of future effects is also of interest, for example to see whether the abundance of the 2010 sockeye salmon run will be expressed in the 2014 run when their offspring return and if flow variation influences their lifecycle. While the 2010 FRB flow regimes may have played a role in influencing the spatial patterns of returning spawners that year, fecundity, reproductive success and their offspring’s success will be affected by hydrometric variability from spring 2011 through to spring 2012 when they are in the freshwater rearing stages.

Future work should explore relationships between streamflow conditions (e.g., water temperatures and levels, sediment and nutrient fluxes) and the factors that control these (e.g., precipitation and snowmelt) and the subsequent implications for water resources, aquatic ecosystems, salmon returns and human activities in the FRB.

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References

BC Ministry of Water, Land and Air Protection 2002 Indicators of Climate Change for British Columbia 2002 (www.env.gov.bc.ca/cas/pdfs/indcc.pdf, accessed March 2012)

Benke A C and Cushing C E (ed) 2005 The Fraser River Rivers of North America (New York: Elsevier, Academic) pp 607–732

Boon S 2012 Snow accumulation following forest disturbance Ecohydrol. at press
Burn D H and Hag Elnurm M A 2002 Detection of hydrologic trends and variability *J. Hydrol.* **255** 107–22

Cone T 2012 personal communication

Cooke S J, Hinch S G, Farrell A P, Lapointe M F, Jones S R M, Macdonald J S, Patterson D A, Healey M C and van der Knaap G 2004 Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia *Fisheries* **29** 22–33

Cunderlink J M and Burn D H 2004 Linkages between regional trends in monthly maximum flows and selected climatic variables *J. Hydrol. Eng.* **9** 246–56

Danard M and Murty T S 1994 On recent climate trends in selected salmon-hatching areas of British Columbia *J. Clim.* **7** 1803–8

D´ery S J, Hern´andez-Henr´ıquez M A, Burford J E and Danard M and Murty T S 1994 On recent climate trends in selected salmon-hatching areas of British Columbia *J. Hydrol.* **1807** 22–33

D´ery S J, Mlynowski T J, Hern´andez-Henr´ıquez M A and Staneeo F 2011 Interannual variability and interdecadal trends in Hudson Bay streamflow *J. Mar. Syst.* **84** 341–51

D´ery S J, Stieglitz M, McKenna E C and Wood E F 2005 Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964–2000 *J. Clim.* **18** 2540–57

Eliason E J, Clark T D, Hague M J, Hanson L M, Gallagher Z S, Jeffries K M, Gale M K, Patterson D A, Hinch S G and Farrell A P 2011 Differences in thermal tolerance among sockeye salmon populations *Science* **332** 109–12

Evendon M D 2004 *Fish vs. Power: An Environmental History of the Fraser River* (Cambridge: Cambridge University Press)

Ferrari M R, Miller J R and Russell G L 2007 Modeling changes in summer temperature of the Fraser River during the next century *J. Hydrol.* **342** 336–46

Fleming S W and Clarke G K C 2005 Attenuation of high-frequency interannual streamflow variability by watershed glacial cover *J. Hydraul. Eng.* **131** 615–8

Fleming S W, Moore R D and Clarke G K C 2006 Glacier-mediated streamflow teleconnections to the Arctic Oscillation *Int. J. Climatol.* **26** 619–36

Foreman M G G, Lee D K, Morrison J, Macdonald S, Barnes D and Williams I V 2001 Simulations and retrospective analyses of Fraser Watershed flows and temperatures *Atmos. Ocean* **39** 89–105

Fountain A G and Tangborn W V 1985 The effect of glaciers on streamflow variations *Water Resour. Res.* **21** 579–86

Fraser Basin Council 2006 *Bridge Between Nations: A History of First Nations in the Fraser River Basin* (Vancouver: Fraser Basin Council) (www.fraserbasin.bc.ca/publications/documents/Books_Bridge_Between_Nations.pdf, accessed October 2011)

Fraser Basin Council 2009 *State of the Fraser Basin Report, Sustainability Snapshot 4, The Many Faces of Sustainability* (Vancouver: Fraser Basin Council) (www.fraserbasin.bc.ca/publications/indicators.html, accessed May 2011)

Hartman G F 1996 Impacts of growth in resource use and human population on the Nechako River: a major tributary of the Fraser River, British Columbia *GeoJournal* **40** 147–64

Healey M 2011 The cumulative impacts of climate change on Fraser River sockeye salmon (*Oncorhynchus nerka*) and implications for management *Can. J. Fish. Aquat. Sci.* **68** 718–37

Kendall M G 1975 *Rank Correlation Methods* (New York: Oxford University Press) p 202

Kerkhoven E and Gan T 2011 Differences and sensitivities in potential hydrologic impact of climate change to regional-scale Athabasca and Fraser River basins of the leeward and windward sides of the Canadian Rocky Mountains respectively *Clim. Change** **106** 583–607

Knowler D J, MacGregor B W, Bradford M J and Peterman R M 2003VALuing freshwater salmon habitat on the west coast of Canada *J. Environ. Manag.* **69** 261–73

Lapp S L, St Jacques J-M, Barrow E M and Sauchyn D J 2012 GCM projections for the Pacific Decadal Oscillation under greenhouse forcing for the early 21st century *Int. J. Climatol.* at press

Lee C G, Farrell A P, Lotto A, MacNutt M J, Hinch S G and Healey M C 2003 The effect of temperature on swimming performance and oxygen consumption in adult sockeye (*Oncorhynchus nerka*) and coho (*O. kisutch*) salmon stocks *J. Exp. Biol.* **206** 3239–51

Macdonald J S 2000 Mortality during the migration of Fraser River sockeye salmon (*Oncorhynchus nerka*): a study of the effect of ocean and river environmental conditions in 1997 *Canadian Technical Reports on Fisheries and Aquatic Sciences* vol 2315, p 117

Mann H B 1945 Non-parametric test against trend *Econometrica* **13** 245–59

Melack J M, Dozier J, Goldman C R, Greenland D, Milner A M and Naiman R J 1997 Effects of climate change on inland waters of the Pacific coastal mountains and western great basin of North America *Hydrolog. Process.* **11** 971–92

Morrisson J, Quick M and Foreman M G G 2002 Climate change in the Fraser River watershed: flow and temperature projections *J. Hydrol.* **263** 35–44

Müller W A and Roeckner E 2008 ENSO teleconnections in projections of future climate in ECHAM5/MPI-OM *Clim. Dyn.* **31** 533–49

Patterson D A, Macdonald J S, Skibo K M, Barnes D, Guthrie I and Hills J 2007 Reconstructing the summer thermal history for the lower Fraser River, 1941 to 2006, and implications for adult sockeye salmon (*Oncorhynchus nerka*) spawning migration *Canadian Technical Reports of Fisheries and Aquatic Sciences* vol 2724, p 43

Picketts I M, Werner A T, Murdock T Q, Curry J, D´ery S J and Dyer D 2012 Planning for climate change adaptation: lessons learned from a community-based workshop *Environ. Sci. Policy* **17** 82–93

Rand P S and Hinch S G 1998 Swim speeds and energy use of upriver-migrating sockeye salmon (*Oncorhynchus nerka*): simulating metabolic power and assessing risk of energy depletion *Can. J. Fish. Aquat. Sci.* **55** 1832–41

Rand P S, Hinch S G, Morrison J, Foreman M G G, MacNutt M J, Macdonald J S, Healey M C, Farrell A P and Higgs D A 2006 Effects of river discharge, temperature, and future climates on energetics and mortality of adult migrating Fraser River sockeye salmon *Trans. Am. Fish. Soc.* **135** 655–67

Schiewer E and Klinkenberg B 2004 The distribution and morphometry of lakes and reservoirs in British Columbia: a provincial inventory *Can. Geogr.* **48** 345–55

Schiewer E, Menounos B and Wheate R 2007 Recent volume loss of British Columbian glaciers, Canada *Geophys. Res. Lett.* **34** L16503

Stahl K and Moore R D 2006 Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada *Water Resour. Res.* **42** W06201

Thorne R and Wool M K 2011 Streamflow response to climatic variability in a complex mountainous environment: Fraser River Basin, British Columbia, Canada *Hydrolog. Process.* **25** 3076–85

Tome A R and Miranda P M A 2004 Piecewise linear fitting and trend changing points of climate parameters *Geophys. Res. Lett.* **31** L02207

Water Survey of Canada 2011 *HYDAT Database* (www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm, accessed January 2011)

Wei X and Zhang M 2010 Quantifying streamflow change caused by forest disturbance at a large spatial scale: a single watershed study *Water Resour. Res.* **46** W12525

Yue S, Pilon P, Phinney B and Cavadias G 2002 The influence of autocorrelation on the ability to detect trend in hydrological series *Hydrolog. Process.* **16** 1807–29