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Some aspects of the hydroclimatology of the Quesnel River Basin, British Columbia, Canada

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Abstract

In conjunction with available climate data, surface runoff is investigated at 12 gauges in the Quesnel watershed of British Columbia to develop its long-term (1926–2004) hydroclimatology. At Quesnel itself, annual mean values of air temperature, precipitation and runoff are 4·6 °C, 517 and 648 mm, respectively. Climate data reveal increases in precipitation, no significant trend in mean annual air temperature, but an increasing trend in mean minimum temperatures that is greatest in winter. There is some evidence of decreases in winter snow depth. On the water year scale (October–September), a strong positive correlation is found between discharge and precipitation ($r = 0.70$, $p < 0.01$) and a weak negative correlation is found between precipitation and temperature ($r = -0.36$, $p < 0.01$). Long-term trends using the Mann-Kendall test indicate increasing annual discharge amounts that vary from 8 to 14% (12% for the Quesnel River, $p = 0.03$), and also a tendency toward an earlier spring freshet. River runoff increases at a rate of 1·26 mm yr^{-1} m^{-1} of elevation from west to east along the strong elevation gradient in the basin. Discharge, temperature and precipitation are correlated with the large-scale climate indices of the Pacific Decadal Oscillation (PDO) and El-Niño Southern Oscillation (ENSO). Copyright © 2009 John Wiley & Sons, Ltd.

Key Words hydroclimatology; snow; Quesnel River; river discharge; British Columbia

Introduction

The Quesnel watershed is located in the interior plateau of east-central British Columbia (BC), Canada, covering an area of ~11 500 km^2 (Environment Canada, 2002). It is part of the Fraser River system, which is the largest river basin in BC spanning an area of ~232 000 km^2. Quesnel Lake is situated within the basin and the Quesnel River is the major outflow. There are three major inflows into the lake: Horsefly River, Mitchell River and Niagara Creek. Horsefly River drains the interior plateau region (~2750 km^2) where precipitation is about 500–1000 mm yr^{-1}. The Mitchell and the Niagara flow out of the Cariboo Mountains and ice fields/glaciers (<600 km^2), where precipitation attains 1500–2500 mm yr^{-1} (Potts, 2002). Downstream of Quesnel Lake are several other tributaries of the Quesnel River, the largest of which is the Cariboo River (catchment area of ~3260 km^2).

The Quesnel watershed is a mostly pristine environment of forest (63% by area), glacial mountain regions (~12%) and minimal agriculture (2%) (http://www.wsc.ec.gc.ca/). The average elevation is 1375 m, varying from ~500 m in the west to ~3000 m in the northeast. The northeast is mountainous, containing glaciers, alpine growth and old forest vegetation (Farley, 1979) and is partly home to the largest interior temperate rain forest in the world. The south and west cover the plateau of young forest growth (part of the western hemlock biogeoclimatic zone). It is also home to several towns, agricultural regions and limited commercial activity including mining and logging.

A distinctive ecological feature of the Quesnel River Basin is its role as a major source of sockeye salmon for the Fraser watershed. In 1993, for example, approximately 2·5 million sockeye salmon entered the Quesnel headwaters to spawn (Benke and Cushing, 2005). The region has also

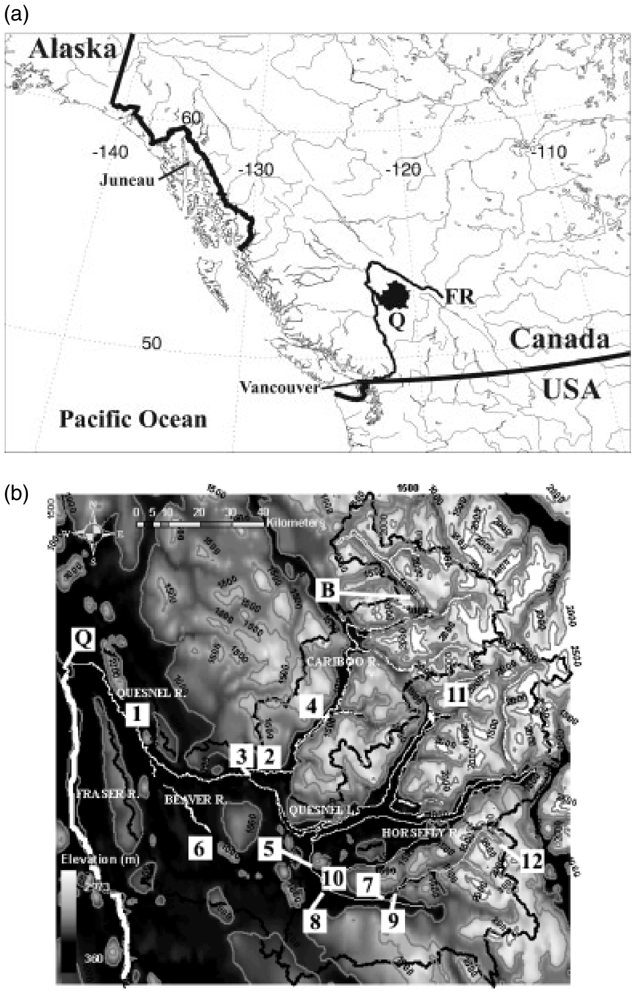

Figure 1. (a) Map of Western Canada showing the location of the Quesnel watershed (Q) and the Fraser River (FR). (b) Map of the Quesnel Watershed area showing gauge locations (refer to Table I) and the location of the two climate station, Quesnel (Q) and Barkerville (B). Contours of elevation at 500 m intervals are also shown

succumbed to a serious and detrimental mountain pine beetle infestation that is increasing in area owing in part to warmer winters (Carroll *et al*., 2003; Aukema *et al*., 2006; Stahl *et al*., 2006).

These ecological repercussions are associated with strong trends in air temperature throughout BC where some of the greatest climatic changes were observed in the twentieth century over the globe, apart from high latitude regions (Lettenmaier *et al*., 1994; Bonsal *et al*., 2001; Whitfield *et al*., 2002; Vincent and Mekis, 2006). Other consequences of this warming trend include earlier spring freshets, lower early summer flows and higher early winter flows over BC (Leith and Whitfield, 1999; Déry *et al*., 2009).

Continuing these observed trends, some studies (e.g. Fyfe and Flato, 1999; Bradley *et al*., 2004) project that rising CO_2 levels will lead to amplified warming at higher altitudes in this century, profoundly affecting the state of North American glaciers (Stahl and Moore, 2006a), water resources, and mountain ecosystems. Since the Quesnel River Basin is partially glaciated, these concerns are now being examined as part of an international study under the Western Canadian Cryospheric Network (WC^2N; http://wc2n.unbc.ca) (MacLeod and Déry, 2007). This research network investigates links between climatic change, glacier fluctuations, and water resources in the Western Cordillera of North America.

A number of studies have been conducted on recent trends in the discharge of North American rivers (e.g. Whitfield and Cannon, 2000; Zhang *et al*., 2001; Déry and Wood, 2004, 2005; Déry *et al*., 2005; Rood *et al*., 2005; McClelland *et al*., 2006). Most studies, which extend back only to the mid-1940s at best, indicate that there has been a decrease in river discharge over North America in recent decades (see Schindler and Donahue, 2006). It is known that the Pacific Decadal Oscillation (PDO), (Foreman *et al*., 2001; Stewart *et al*., 2005; Stahl and Moore, 2006a,b) and the El-Niño Southern Oscillation (ENSO; Woo and Thorne, 2003) both affect the hydroclimate of the Quesnel River Basin.

There exists no comprehensive study on the hydroclimatology of the Quesnel River Basin. The basin contains vast forests, salmon stocks and industries such as mining that depend highly on water resources. The recent pine beetle infestation has been called by the Premier of BC as 'the worst natural disaster ever to hit our forests'

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Table I. Geographical characteristics of the 12 discharge-measuring locations in the watershed and the annual mean, maximum and minimum discharge values including the standard deviation. Watershed characteristics for each gauge are obtained from the Water Survey of Canada website, and when not available, are estimated from a 25-m resolution DEM. An * indicates an estimated value. For climate data at Quesnel, station number 13 was used before 1970 and station 14 thereafter

Num.	I.D.	River/ Tributary	Lat. (°N)	Lon. (°W)	Gauged Area (km^2)	Elev. (masl)	DISCHARGE (km^3 yr^{-1})				RUNOFF Mean (mm yr^{-1})
							Mean	Max.	Min.	St. Dev.	
1	08KH006	Quesnel	52·84	122·22	11,500	1,391	7·45	9·99	5·19	1·05	647·7
2	08KH001	Quesnel	52·62	121·57	5,930	1,419	4·04	5·61	2·73	0·69	681·5
3	08KH003	Cariboo	52·67	121·67	3,260	n/a	2·96	3·78	2·13	0·37	908·7
4	08KH013	Cariboo	52·73	121·44	2,870	1,177	2·88	3·57	2·27	0·34	1002·8
5	08KH007	Horsefly	52·33	121·41	2,310	1,160	0·95	1·23	0·67	0·13	409·6
6	08KH021	Beaver	52·48	121·85	847	712	0·06	0·10	0·04	0·02	75·2
7	08KH010	Horsefly	52·29	121·06	785	1,627	0·62	0·94	0·40	0·11	785·7
8	08KH019	Moffat	52·32	121·41	539	1,348	0·11	0·15	0·06	0·02	206·0
9	08KH020	McKinley	52·28	121·00	430	1,362	0·16	0·26	0·07	0·04	368·1
10	08KH008	Little Horsefly	52·37	121·31	422	989	0·14	0·18	0·12	0·02	340·1
11	08KH022	Mackay	52·37	120·72	144	1,168	0·15	0·19	0·10	0·02	1019·1
12	08KH030	Penfold	52·79	120·75	100*	1,687	0·22	0·26	0·15	0·04	2183·2
		Climate Stations									
13	1096600	Quesnel	52·97	122·47		488					
14	1096630	Quesnel Airport	53·02	122·50		545					
15	1090660	Barkerville	53·07	121·50		1,265					

(Office of the Premier of British Columbia, 2005). This is having profound effects on the region's ecology and on the forestry industry. Furthermore, huge numbers of salmon pass through this basin and migrate far into the Pacific Ocean. In addition, the area is upstream of the heavily populated lower Fraser River Basin. The goal of this study, therefore, is to present a focused look at conditions for the Quesnel watershed over an extended period (1926–2004) to better comprehend some aspects of its hydroclimate and contribute to studies such as the international WC^2N project. This work thus also provides an important framework for further international studies on hydroecological sensitivities in the area.

Datasets and Methods

Datasets

Daily discharge data were obtained from the Water Survey of Canada for 12 gauges throughout the Quesnel River Basin and for the Fraser River at Hope, from 1926 to 2004 (Figure 1 and Table I). Although none of the gauges were identified for inclusion in the Reference Hydrometric Basin Network (RHBN; Harvey *et al*., 1999), the watershed is in a fairly pristine environment with only minimal anthropogenic effects.

Climate data (1926–2003) were obtained from the Environment Canada website (http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html).

Monthly climate data used include various air temperature parameters, precipitation (including rainfall and snowfall) and snow depth (monthly last day depth on the ground). Daily information was extracted from the Environment Canada CD-ROM, also available online (available 1926–2002 inclusive). The only sites with reliable long-term data near the basin are Quesnel and Barkerville (Table I). Barkerville has the third longest record of meteorological data measurements in all of BC. Some data for Barkerville are missing, including most of 1948–1950, 1978–1979 and 1996, inclusively.

To verify their homogeneity, the Quesnel and Barkerville station data were compared with mean monthly temperature and precipitation amounts extracted from the Historical Canadian Climate Data (HCCD; http://www.cccma.bc.ec.gc.ca/hccd; Mekis and Hogg, 1999; Vincent *et al*., 2002). Daily data were not readily available from the HCCD archive and were therefore obtained from the Environment Canada CD-ROM. For temperature, the correlation coefficients between the two datasets are 1·0 at both Barkerville and Quesnel. For the precipitation data the correlation coefficients at both sites were similarly very high at 0·96 and 0·99 for Barkerville and Quesnel, respectively.

Values and definitions of the Southern Oscillation Index (SOI) and the PDO index are obtained from the Climate Diagnostics Center (CDC) of the National Oceanic and Atmospheric Administration (NOAA) website (http://www.cdc.noaa.gov/ClimateIndices).

Methods

Missing discharge data were in-filled using methods developed and outlined in Déry *et al*. (2005) and they were then used to calculate annual statistics. The monthly climate data were used to compute annual and seasonal values for air temperature and also for annual precipitation amount, including the snow and rain components. Temperature data were adjusted to compensate for the change in station altitude at Quesnel. Daily temperature information was used to compute average and extreme (absolute) maximum, mean and minimum values for each season and each year at Quesnel. This was not done at

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Barkerville owing to the abundance ($\sim$15%) of missing data on the daily scale. Long-term trends were then determined using the Kendall-Theil slope combinations and these trends were quantified in relation to their mean value over the period of record. Trends in discharge were calculated over various time periods and only for the gauges where no less than 49% of the data were missing for the respective period. The significance level (probabilities, p) of the results was assessed using the Mann-Kendall test (Déry *et al.*, 2005) and a value $p < 0{\cdot}05$ is considered significant. All trends and correlation values presented in the text are significant at this level; otherwise a p value is presented. The standard 'water year' (1 October to 30 September of the following calendar year, inclusive) was used wherever climate variables were compared directly with runoff amounts since the spring freshet contains water stored in the snow pack from the preceding cold season.

Results and Discussion

Air temperature

On the annual scale, the mean air temperature at Quesnel is 4·6 °C (1926–2003 inclusive) and this varies between 1·5 and 7·1 °C with a standard deviation of 1·1 °C. No significant trend is detectable unlike some other temperature-related parameters (Table II). Fraser and Smith (2002) found increases of 1·1 °C per decade over the region, but this was for the 1895–1995 period. From the daily information at Quesnel, an increase in mean minimum temperature (1·4 °C $(78\ \text{yr})^{-1}$) is evident. The trend in the absolute maximum and minimum temperatures is decreasing (−0·9 °C $(78\ \text{yr})^{-1}$) and increasing (5·2 °C $(78\ \text{yr})^{-1}$), respectively. Zhang *et al.* (2000) found increases in daily maximum (not significant) and minimum temperatures (significant) for some grid cells near the area over the last century. Increases in cloud cover, which may occur in conjunction with increased precipitation, would provide a plausible explanation for these trends, as minimum (overnight) temperatures are higher and maximum (daytime) temperatures are lower. Farther north in western Canada, Stewart and Burford (2002) found increases in temperature during winter months associated with increases in cloud fraction.

On the seasonal scale at Quesnel, temperatures in winter have increased over the long-term as is evident in the annual average mean as well as in the minimum (Table II). In fact, the strongest seasonal increase in any temperature parameter is found in winter mean minimum values (3·5 °C $(78\ \text{yr})^{-1}$). Spring and summer months, however, show weaker inter-annual trends with no significant change in mean temperature, a very slight increase in minimum temperature and a decrease in maximum temperature. Autumn temperatures show a significant decrease in mean maximum values only.

Comparisons between monthly temperature information at Quesnel and Barkerville show there is a high and statistically significant correlation between mean annual temperature ($r = 0{\cdot}87$) despite a change of elevation of $\sim$700 m.

Precipitation and snow depth

The average total annual precipitation at Quesnel is 517 mm, ranging between 283 and 724 mm with a standard deviation of 89 mm yr^{-1}. This has been increasing over the long-term by 18%. This is less than the increase of 4% per decade found by Fraser and Smith (2002) and comparable to the trend of $\sim$20% from Zhang *et al.* (2000) over the last century and over a broader area including the basin. At Barkerville, precipitation is much greater owing to orographic effects with a mean annual amount of 1072 mm with no significant long-term trend. Compared to Quesnel, there is only a weak correlation for annual mean precipitation ($r = 0{\cdot}38$). Seasonally, the highest correlation is found in summer with $r = 0{\cdot}67$.

To assess changes in precipitation occurrence and intensity, daily data were examined over the first and second half of the period and the distributions were compared. From 1926 to 1964 there were 4555 days

Table II. The long-term (1926–2003) change in various temperature parameters and precipitation characteristics over the annual and seasonal time scales at Quesnel including the statistical significance (p values) of these changes

TREND (°C)	PERIOD									
	Annual	p	Winter	p	Spring	p	Summer	p	Autumn	p
Mean minimum	1·4	<0·01	3·5	0·01	1·3	<0·01	0·3	0·02	0·2	0·18
Mean	0·3	0·27	2·2	0·03	−0·1	0·41	0·0	0·11	−0·5	0·17
Mean maximum	−0·9	0·06	1·3	0·21	−1·3	0·02	−1·5	0·01	−1·5	0·01
Mean absolute minimum	1·7	0·02								
Absolute minimum	5·2	0·03								
Mean Absolute Maximum	−1·6	<0·01								
Absolute Maximum	−0·9	<0·01								
TREND (%)										
Precipitation	18	<0·01	1	0·49	28	0·01	25	0·01	14	0·02
Rain	24	<0·01	0	0·10	30	0·03	25	0·01	32	0·01
Rain/Precip	6	0·12								

Note: Mean absolute value refers to the trend in the average of extreme values each month, and absolute value refers to the trend in extreme values from each year. September 2002 is missing. Winter months are December, January and February.

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with precipitation ($\geq$0·1 mm) and from 1964 to 2002 there were 5674. For precipitation amounts greater than 10 mm, the number of days for each period, respectively, was 454 and 459, and for amounts greater than 30 mm, the number of days was 19 and 12. The trend in increasing precipitation can be associated with more days of low precipitation amounts rather than intense events.

Changes in the precipitation phase indicate a greater annual increase in rainfall amount (24%) compared to all precipitation (liquid + frozen) (18%). The fraction of the annual amount of rain to total precipitation yields a mean value of 0·71.

Monthly snow depth information was examined when available for Quesnel from 1946 to 2003, inclusive (Figure 2). The mean depth of snow on the ground measured on the last days of January and February was 30 and 29 cm, respectively. Over the long-term, large decreases of 88 and 51% were found. At the end of March, there were fewer instances of any snow remaining on the ground in recent years. From 1946 to 1983, there were 18 years for which some snow was found, whereas from 1984 to 2003, there was only a single year.

Discharge and Runoff

Mean characteristics and trends. The mean annual runoff for the Quesnel River at Quesnel is 648 mm, and this varies yearly from 451 to 869 mm with a standard deviation of 91 mm yr^{-1}. Table I shows the discharge-related statistics for the 12 gauges, and Table III shows the trends for the gauges. Different time periods were examined to provide greater insight into the variability of runoff (Figure 3). Trends are positive for nearly all the gauges and periods. The strongest increase occurs in the 1944–1974 period (with an average increase of 24%), and the weakest but still increasing trend is in the most recent 30 years (with an average increase of 5·7%). Over the entire period, an increasing trend of between 8 and 14% is evident.

To examine inter-annual changes in discharge throughout the water year further, daily averages are computed over three time periods. Figure 4 shows the annual cycle of daily discharge averaged over all years, the first half and second half of available years at Quesnel as well as the difference between the two periods. Consistent with other studies (Stewart *et al*., 2005; Déry *et al*., 2009), we see a trend toward an earlier spring freshet but there is also an increase in discharge, particularly during the summer months. This is consistent with increases in seasonal precipitation that are highest for spring and summer at 25 and 28%, respectively (Table II) and it may also be related to increases in glacial melt in alpine portions of the basin. Interestingly, there is a slight decrease in streamflow during autumn, which is consistent with an earlier spring freshet and an advance in the annual recession to autumn baseflows.

Elevation and spatial variations. The Quesnel River Basin lies in complex terrain that leads to important spatial variability in its hydroclimatological characteristics. For instance, runoff increases significantly with elevation ($r = 0{\cdot}61$) owing to orographic effects on precipitation. Using a linear regression, river runoff increases at a rate of 1·26 mm yr^{-1} m^{-1} of elevation from west to east. This relationship can also be seen in the correlation of runoff with both latitude and longitude with $r = 0{\cdot}56$ ($p = 0{\cdot}06$) and $-0{\cdot}48$ ($p = 0{\cdot}11$), respectively, although they are not significant at the 5% level.

Comparison with the Fraser River. To place this study in a broader context, annual discharge from the Quesnel River is compared with data from the Fraser River at Hope, BC. A major inflow of the Fraser, the Nechako River, was partially diverted in 1952, but these changes in flow led to only a small reduction in the overall flow of the Fraser River (~1%) (Foreman *et al*., 2001). The correlation coefficient ($r = 0{\cdot}83$) shows a strong connection.

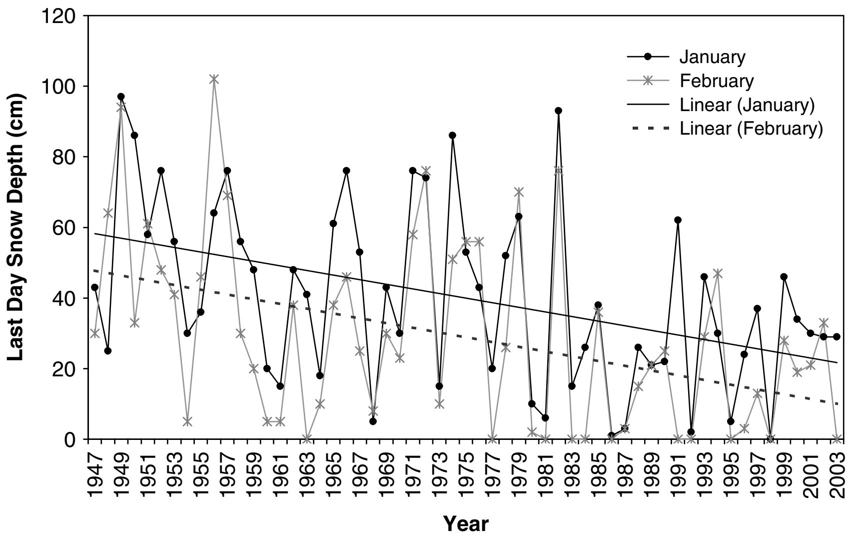

Figure 2. The depth of snow on the ground at Quesnel on the last day of January (black) and February (grey) over the period 1946–2003 including the linear best–fit trend line for each month

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Table III. The long-term trend in discharge for gauges in the Quesnel watershed over different time periods as well as the entire record length. Gauges and trend values are shown only for period lengths for which no less than 49% of the data are missing

Gauge number	River/Tributary	DATA PERIOD CHANGE (%)/SIGNIFICANCE (p)							
		1975–2004 (%)	p	1944–1974 (%)	p	1944–2004 (%)	p	1926–2004 (%)	p
1	Quesnel	11·9	0·15	20·2	0·02	12·1	0·06	11·9	0·03
2	Quesnel	1·5	0·44	33·3	<0·01	7·7	0·16	13·9	0·03
3	Cariboo	6·2	0·29	21·0	<0·01	8·5	0·11	8·8	0·08
5	Horsefly	6·4	0·19			8·9	0·07	11·9	0·02
7	Horsefly	−0·5	0·49			6·5	0·13		
8	Moffat	13·1	0·23	22·1	0·02	7·1	0·22	9·0	0·14
9	McKinley	1·1	0·44			10·0	0·04	8·0	0·07
Average		5·7		24·2		8·7		10·6	
Min.		−0·5		20·2		6·5		8·0	
Max.		13·1		33·3		12·1		13·9	

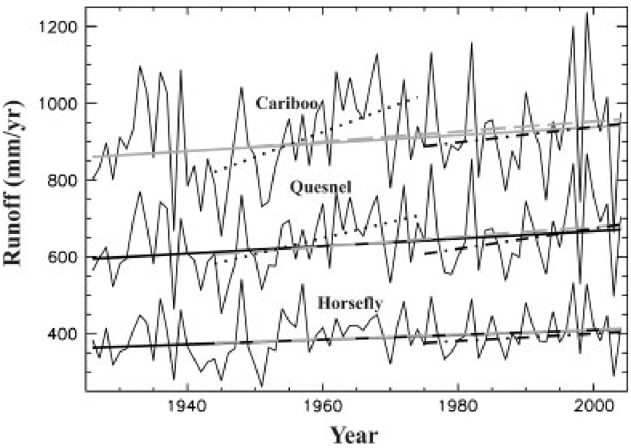

Figure 3. Annual runoff (mm yr^{-1}) for the Quesnel River and two of the major tributaries in the Quesnel watershed (1926–2004). Best-fit trend lines are also shown that are significant (black) and not significant (grey) for the periods 1975–2004, 1944–1974, 1944–2004, and the whole period of 1926–2004

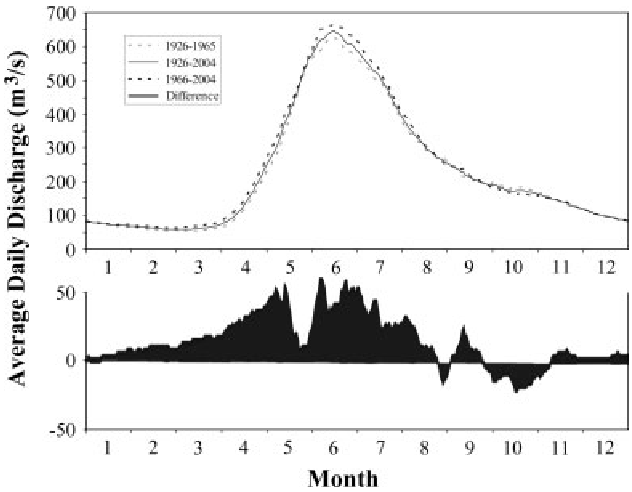

Figure 4. The annual cycle of daily discharge for three periods: 1926–1965 (dashed grey), 1966–2004 (dashed black), the whole record, 1926–2004 (black) and the difference between the two 'half' periods (filled in black) for the Quesnel River (gauge 1 in Table I)

Teleconnections

Changes in discharge are examined under different phases of both the PDO index and SOI (1926–2004). Mean values for the indices were calculated from November to the following March. Each index was then compared to the mean seasonal precipitation, temperature and discharge for the winter and each season in the following year (Table IV). For the PDO index, higher discharge amounts are associated with a negative-cold phase in the following summer ($r = -0{\cdot}31$). When compared with climate variables, colder temperatures are associated with a negative-cold phase up to the following summer ($r = 0{\cdot}48$) and for precipitation, higher amounts are generally associated with the negative-cold phase (the opposite anomalies may be associated with the positive-warm phase).

For the SOI, higher discharge amounts in the following summer are associated with the positive-cold phases ($r = 0{\cdot}44$). This is somewhat in agreement with Woo and Thorne (2003) but they examined peak flows and the SOI from the preceding October-March period. Again, compared to climate variables, we see a positive correlation with the winter precipitation and a negative correlation with temperature in the winter, the following spring and summer.

Summary

Some long-term trends in climate and hydrological variables are discernible in the Quesnel watershed. For comparison on the water year scale, Figure 5 shows the mean temperature, precipitation and runoff over the study period. Statistically significant trends are found in runoff and precipitation at Quesnel over the period 1926–2003, inclusive, with increases of 12 and 18%, respectively. The strongest increase in discharge occurs in the 1944–1974 period examined here. Higher summer discharge is associated with a negative PDO and/or a positive Southern Oscillation phase in the preceding winter.

For temperature, there is no significant trend in mean annual values but trends exist in other temperature

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Table IV. Correlation coefficients (r) between teleconnection index values (PDO and ENSO) and mean seasonal discharge, temperature and precipitation with significance values (p)

			spr + 1	sum + 1	fal + 1	win + 1
DISCHARGE						
PDO	r		−0·07	−0·31	0·00	−0·12
	p		0·55	0·01	0·99	0·32
SOI	r		0·01	0·44	0·04	0·06
	p		0·94	<0·01	0·71	0·58
PRECIPITATION						
PDO	r	−0·49	0·08	−0·26	0·21	−0·26
	p	<0·01	0·50	0·02	0·07	0·02
SOI	r	0·32	−0·05	0·14	−0·14	0·04
	p	<0·01	0·66	0·22	0·23	0·72
TEMPERATURE						
PDO	r	0·46	0·45	0·48	0·00	0·11
	p	<0·01	<0·01	<0·01	0·98	0·33
SOI	r	−0·38	−0·43	−0·24	−0·02	−0·06
	p	<0·01	<0·01	0·03	0·86	0·61

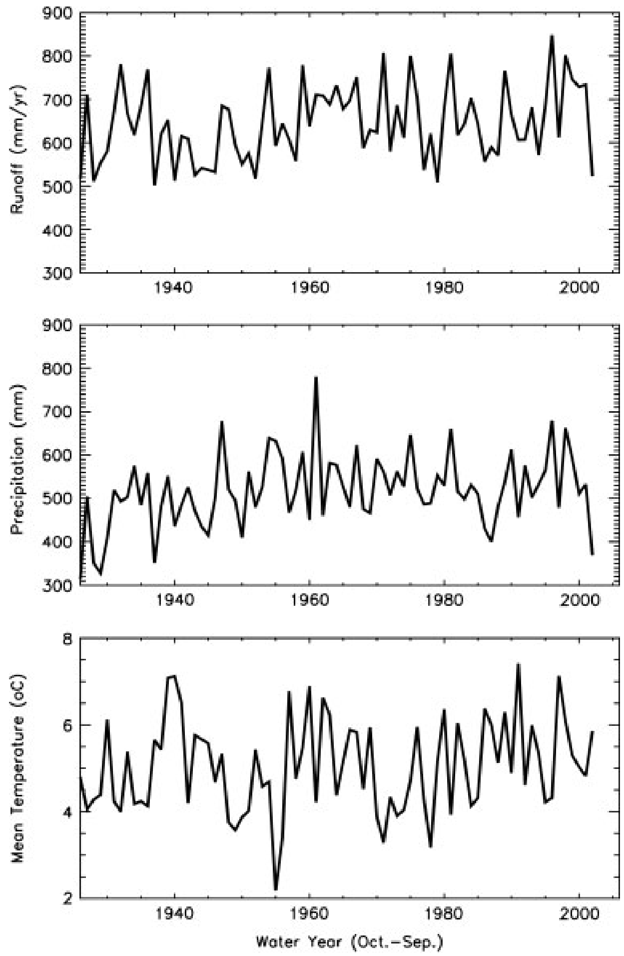

Figure 5. Long-term trend in water year runoff (mm yr^{-1}) for the Quesnel River at Quesnel (gauge 1 in Table I), as well as precipitation (mm yr^{-1}) and temperature (°C) both from the town of Quesnel

parameters, such as minimum (overnight) values that are significant and greatest during winter. Precipitation has increased (except during winter) at Quesnel and, furthermore, the increased amounts are associated with increased frequency and reduced intensity in precipitation, although a more detailed study is required to establish these trends. There is a shift toward more rain rather than snow that has contributed to snow depth decreases at Quesnel. Some correlations with large-scale climate indices (PDO and SOI) are found that are stronger for temperature than for precipitation.

Trends in mean air temperature values at seasonal time scales seem to be coherent throughout the basin (despite differences in elevation). This is not the case for precipitation, although more locations need to be examined. Differences in precipitation can be expected as the terrain of the watershed is highly variable, especially in the north and east.

The increasing discharge of the Quesnel River is different from the decreasing trend found in other Fraser River sub-basins (Foreman *et al.*, 2001) although the inter-annual variability of the two is strongly correlated. Increases in discharge and the time of peak flows as well as increases in water temperatures affect fish throughout their migration route upstream. Changes in snow depth during late winter and early spring may also be ecologically disruptive but more work and data are required to determine the impacts in the Quesnel watershed.

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