Streamflow responses and trends between permafrost and glacierized regimes in northwestern Canada

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Abstract An assessment of the streamflow response of glacierized basins in southwestern Yukon was carried out to determine if there are apparent trends associated with climate warming. The study area includes portions of the sporadic and discontinuous permafrost zones. Annual mean, maximum and minimum flows, as well as the timing of the maximum and minimum annual discharge, were assessed using the Mann-Kendall test. A slight positive trend in annual mean discharge was generally observed throughout the study region, likely a result of combined precipitation increases and glacier melt contributions. Annual maximum flow trends are more variable with the majority of station records exhibiting a positive trend. Permafrost likely has a significant role in controlling annual peak discharge trends. Basins with little permafrost exhibited positive trends in response to additional meltwater contributions, while basins with significant permafrost exhibited negative trends, likely a result of the degrading permafrost enhancing subsurface flow processes. Positive trends in annual minimum flows were generally obtained, presumably due to greater groundwater contributions to baseflow.

Key words glacierized; discontinuous; sporadic permafrost; Mann-Kendall; trend analysis; streamflow response; Yukon Territory, Canada

INTRODUCTION

Permafrost has a dominant control over hydrological response in the northern regions by producing short pathways to the stream channel, with little interaction with subsurface processes (Hinzman *et al.*, 2005). A thicker active layer enhances infiltration and associated groundwater recharge, which in turn results in greater groundwater contributions to streamflow. Yukon hydrological response follows this principle, and is closely tied to the underlying permafrost (Janowicz, 2008). Similar to all cold regions, Yukon spring streamflow response is characterized by a rapid rise in discharge as a result of snowmelt contributions. Minimum annual discharge occurs in March or April, coinciding in timing to minimum annual groundwater inputs. The southwestern portions of Yukon Territory also have considerable glacier and ice cap coverage. Unlike nival regimes, which experience their peak flow in May or June due to snowmelt inputs, peak flows in glacierized basins are delayed until later in the summer due to supplemental inputs from glacier melt (Janowicz, 2004, 2008). Stahl & Moore (2006) found basins with as little as 2–3% glacierized area to supplement summer flows.

While there is as yet no definitive evidence to prove that climate variability in northern Canada is anthropogenic, air temperature and precipitation in Yukon Territory have fluctuated significantly over the last century. Air temperatures have generally increased throughout Yukon. Summer precipitation has generally increased, while winter precipitation has increased in northern regions and decreased in southern regions (Janowicz, 2010). There is also some evidence suggesting the trends may be associated with teleconnections between large-scale oceanic and atmospheric processes, such as the El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Barlow *et al.*, 2001).

Changing climate appears to be resulting in a likewise change in the permafrost and glacier distributions of northern regions, including the Yukon Territory. Increasing air temperatures are resulting in permafrost warming and associated thawing, which in turn results in a thicker active layer. Permafrost degradation is expected to be greatest within the discontinuous and sporadic permafrost zones since these permafrost classes are warmer, and therefore more susceptible to thawing (Hinzman *et al.*, 2005).

On a global scale, glaciers and ice caps have generally declined significantly since the end of the Little Ice Age (Zemp *et al.*, 2007). On a regional basis, glaciers throughout western North America have generally retreated since the Little Ice Age (Zemp *et al*., 2007; Moore *et al*., 2009). Considerable work has been carried out in recent years on glacier mass balance studies of northwestern North America. Schiefer *et al*. (2007) estimated the annual change in glacier volume for British Columbia for the 15 year period (1985–1999) to be 22.48 ± 5.53 km^3. The estimated loss varies regionally with the greatest decline observed in the Coast and St Elias Mountains, which have the greatest glacier and ice cap coverage. According to Barrand & Sharp (2010) Yukon glaciers have experienced a surface area loss of 22% in the last 52 years (0.42%/year), equating to 0.78 ± 0.34 m/year water equivalent, which accounts for 1.12 ± 0.49 mm/year of global sea level rise.

There have been a number of studies carried out in northern regions of North America on the impact of climate change on hydrological response (Kite, 1993; Burn, 1994; Loukas & Quick, 1996, 1999; Leith & Whitfield, 1998; Whitfield & Taylor, 1998; Spence, 2002). Dery & Wood (2005) investigated the discharge of 64 arctic or subarctic Canadian rivers from 1964 to 2003. They found a general 10% decline in mean annual discharge to the Arctic and North Atlantic Oceans over that period with potential teleconnection links.

There has been only limited work to date on the impact of climate change specific to Yukon hydrology. Janowicz & Ford (1994) carried out an assessment of the impacts of climate warming on the water supply to the upper Yukon River with their results indicating that annual inflows to the glacierized upper Yukon River would increase by 39% due to increasing temperature and precipitation. Whitfield & Cannon (2000) and Whitfield (2001) assessed recent climatic and hydrological variations for stations in British Columbia and Yukon, finding hydrological response to be characterized with higher annual and peak flows and lower summer and fall flows. Similarly, Janowicz (2001) noted a dramatic change in annual peak flows with increases in glacierized regions of southwestern Yukon, and a progressive decrease moving northward into more dominant permafrost regions. Zhang *et al*. (2001) and Yue *et al*. (2003) found that winter low flows in northern British Columbia and Yukon have increased significantly, while annual mean and peak flows increased in glacierized basins of southern Yukon and northern British Columbia. Walvoord & Striegl (2007) found a general increase in winter discharge within the Yukon River basin. Fleming & Clarke (2003) carried out an assessment of the streamflow response of five glacierized and four non-glacierized basins in northern British Columbia and southwest Yukon in response to climate warming. They found a trend of increasing and decreasing annual flow in glacial and nival regime streams, respectively. Janowicz (2008) carried out an assessment of annual mean, maximum and minimum flows using 43 hydrometric station records distributed between continuous, discontinuous and sporadic permafrost zones in Yukon Territory and adjacent areas of northern British Columbia and western Northwest Territories. Annual mean flows were observed to have slight positive trends within continuous and discontinuous permafrost zones, with variable results within sporadic permafrost regions. Annual peak flows have largely decreased within the continuous permafrost regions, and less so within the discontinuous regions, and results within the sporadic permafrost zones are variable. Winter low flows have experienced significant changes within the continuous and discontinuous permafrost regions over the last three decades, and with variable results within the sporadic permafrost regions.

This paper summarizes the results of a study carried out to assess apparent trends of streamflow characteristics of glacierized basins with Yukon Territory drainage.

SETTING

Yukon Territory, in northwestern Canada, consists of three permafrost regions: continuous, discontinuous and sporadic, while the immediate study area is underlain by sporadic and discontinuous permafrost only (Fig. 1) (Natural Resources Canada, 1995). Not including the Arctic islands, the greatest glacier and ice cap coverage in Canada occurs in the western Cordillera

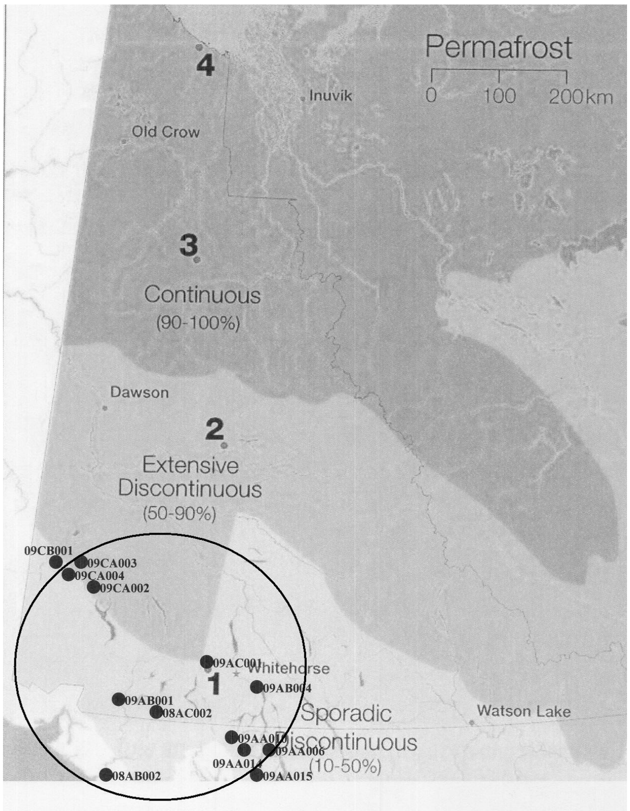

Fig. 1 Location plan, permafrost zones, hydrometric stations (adapted from Smith *et al*., 2004).

with areas of 22 000 and 4300 km^2 for the Coast and St Elias Mountains, respectively (Moore *et al*., 2009). The Yukon Territory portions of the Yukon and Alsek River basins have approximately 7400 and 3500 km^2 of glacier and ice cap coverage, respectively, representing 15 and 20% of total basin drainage area.

METHODOLOGY

Data from active hydrometric stations downstream of glacierized basins in the upper Yukon and Alsek River basin in southwest Yukon, northwest British Columbia and southeast Alaska were used in the analyses. Table 1 provides a summary of station and drainage area, glacier area and mean annual temperature.

Table 1 Study drainage basin parameters.

Station name	Drainage area (km^2)	Glacier area (%)	Mean annual temp. (^{o}C)
Atlin River nr Atlin	6 810	12.7	–0.6
Marsh Lake nr Whitehorse	19 400	8.3	–1.5
Takhini River nr Whitehorse	6 930	5.1	–3.0
Duke River nr Mouth	631	9.5	–4.9
Kluane River at Mouth Kluane Lk	4 950	6.0	–5.7
White River at Alaska Hwy	6 240	38.6	–8.7
Tatshenshini River at Dalton Post	1 750	7.0	–2.5
Alsek River at Bates R	16 200	21.0	–3.5
Alsek River nr Yakatat	28 000	31.9	–2.4

Trend analyses were carried out on the time series of annual mean, maximum and minimum discharge, as represented by the 7-day average minimum annual low flow, and timing of minimum and maximum daily discharge, as represented by the Julian day. The Mann-Kendall trend test was used to assess trends in the three hydrograph parameters (Mann, 1945; Kendall, 1975). The standard normal variate value (Z) is associated with a specific level of significance. The significance level provides an indication of the strength of the trend. A significance level of 0.001 (99.9%) indicates a very strong trend, 0.01 (99%) indicates a strong trend, 0.05 (95%) indicates a moderate trend, and 0.1 (90%) indicates a weak trend. A level of significance of greater than 0.1 indicates there is no statistically significant trend.

RESULTS AND DISCUSSION

Table 2 provides a summary of the trend analyses. The assessment of annual mean discharge generally indicates a slight positive trend throughout the study region. Based on temperature and precipitation trends, increases in the southern portions of the study area, within the sporadic permafrost zone, may be a result of combined precipitation increases and glacier melt contributions. The nominal increases in the remainder of the study basin may be a result of glacier melt contributions.

Table 2 Mann-Kendall trend statistics.

Station name	Station number	Area (km^2)	Record period	n (years)	Mann-Kendall Z statistic: QAnnual	QMax	QMin	JDyMx	JDyMin
Atlin	09AA006	6 810	1951–08	57	3.05***	2.66**	2.46***	–0.41	–2.10**
Marsh	09AB004	20 300	1951–09	48		2.28**		0.61	
Takhini	09AC001	6 930	1949–08	58	0.32	–1.88*	1.69*	–1.14	–1.05
Duke	09CA004	631	1981–08	25	0.56	0.42	2.08**	–0.07	0.14
Kluane	09CA002	4 950	1953–08	55	0.19	1.08	4.51****	0.06	0.56
White	09CB001	6 240	1975–08	32	0.43	–1.77*	3.08***	–1.80*	0.6
Tatshenshini	08AC002	1 750	1989–08	19	0.18	1.05	1.19	–1.58	0.23
Alsek –Bate	09AB001	16 200	1975–08	32	1.72*	–0.1	0.3	–2.06*	0
Alsek - Yak	08AB002	28 000	1993–08	16	0.16	0.54	–0.05	–0.95	–0.09

Level of significance: *0.10; **0.05; ***0.01; ****0.001

Annual maximum flow trends are more variable in comparison to the annual mean, with the majority of station records exhibiting a positive trend, two of which are significant, one with no change, and two with significant negative trends. Permafrost likely has a considerable role in controlling annual peak discharge trends, since air temperature has increased relatively uniformly over the study area. The two stations with strong positive trends are in the sporadic permafrost zone, supporting the theory of increased glacier melt contributions; while the two stations with strong negative trends are in the discontinuous permafrost zone. The difference may be due to overlapping signals of permafrost degradation and glacier melt where greater meltwater runoff may be entering the groundwater system rather than running off near the surface, resulting in smaller peak flow events.

Positive trends in annual minimum flows were obtained for all stations within the study region, with the exception of two stations within the southwestern portion which remain unchanged. Increases in air temperature suggest the increase to be largely related to permafrost degradation with greater groundwater contributions to baseflow, though in some cases increased annual and peak flows may also contribute to winter flows. Basins with little permafrost appear to experience minimal increases in winter baseflow. The timing of annual maximum flows was generally observed to advance, while the timing of annual minimum flows is not consistent.

CONCLUSIONS

An assessment of streamflow response of the glacierized drainage basins within the sporadic and discontinuous permafrost zones in southwestern Yukon was carried out to determine if there are apparent trends as a result of recent temperature and precipitation changes. Study results revealed a slight positive trend of mean annual discharge throughout the study region, while trends of annual maximum flow were observed to be more variable, with the majority of station records exhibiting a positive trend and two stations having significant negative trends. Positive trends in annual minimum flows were generally observed for all the stations within the study region,

As permafrost properties change with climate warming, hydrological response in the northern regions would likewise presumably change. Degrading permafrost increases the thickness of the active layer, decreases the overall thickness of the permafrost, and in certain areas eliminates the presence of underlying permafrost entirely. These actions place a greater reliance on the interaction between surface and subsurface processes. Melting glaciers and ice caps are likewise altering hydrological response by increasing runoff and altering its distribution.

Glacierized basins with little permafrost seem to exhibit a classic glacial response trend, while those with significant amounts of permafrost show more classic permafrost responses and trends. Other glacierized basins with variable amounts of permafrost have overlapping signals, having mixed streamflow trends which are difficult to interpret.

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