# Apparent recent trends in hydrologic response in permafrost regions of northwest Canada

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## ABSTRACT

Yukon air temperature trends have been observed to change over the last several decades with an increase in both summer and winter air temperatures. An assessment of streamflow response was carried out to determine if there are apparent trends in permafrost regions as a result of the observed temperature changes. Degrading permafrost places a greater reliance on the interaction between surface and subsurface processes. Annual mean, maximum and minimum flows were assessed using the Mann–Kendall test to statistically validate observed trends. Annual mean flows are observed to have slight positive trends over the last three decades within continuous and discontinuous permafrost zones, with variable results within sporadic permafrost regions. These results are generally in keeping with similar trends in annual precipitation, which has increased slightly. Though not generally statistically significant, annual peak flows have largely decreased within continuous permafrost regions, and lesser so within discontinuous regions. Results are variable within sporadic permafrost zones. These trends are likely associated with increased annual precipitation; however, it is conceivable that there may be increased infiltration amounts as a result of degrading permafrost. Winter low flows have experienced significant apparent changes over the last three decades. The greatest changes in winter low flows appear to be occurring within the continuous permafrost zone, where flows from the majority of sampled streams have increased. Winter low flows trends in streams within the discontinuous permafrost zone generally exhibit positive significant trends, but are more variable. Winter streamflow trends within the sporadic permafrost zone are not consistent.

**Key words** | continuous, discontinuous, Mann–Kendall, 7-day low flow, sporadic permafrost, trend analysis

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## INTRODUCTION

The primary control over hydrologic response in northern regions is permafrost distribution, permafrost thickness and thickness of the active layer (Hinzman *et al.* 2005). Thick underlying permafrost and a thin active layer produce short pathways to the stream channel, with little or no interaction with subsurface processes. Ice-rich permafrost restricts rain or snowmelt infiltration to subsurface zones, resulting in surface storage in the form of ponds or wetlands. A thicker active layer enhances infiltration and associated groundwater recharge, which in turn would result in greater groundwater contributions to streamflow. Yukon hydrologic response follows this principle, and is closely tied to the underlying permafrost.

The warming climate appears to be resulting in a likewise change in the permafrost distribution of northern regions, including 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

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classes are warmer, and therefore more susceptible to thawing (Hinzman *et al.* 2005). Observations within the discontinuous permafrost regions of Alaska disclose the development of extensive areas of thermokrast terrain due to thawing permafrost (Romanovsky & Osterkamp 1999). These thermokrast features initially develop into small ponds, which eventually grow bigger, and initiate large taliks which penetrate the underlying permafrost, resulting in internal drainage. Shrinking pond surface areas have become a common occurrence in discontinuous and sporadic permafrost regions of Alaska and Siberia as a result of climatic warming (Jorgenson *et al.* 2001; Yoshikawa & Hinzman 2003; Smith *et al.* 2005). Increasing lake area seems to be generally observed within continuous permafrost regions. Thermokrast ponds expand due to permafrost degradation, increasing in area as long as permafrost and topographic conditions permit. Given sufficient time and permafrost degradation, expanding ponds within continuous permafrost regions would eventually drain (Smith *et al.* 2005).

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. There is some recent data that suggests the fluctuations could be outside the natural range of variability. Dawson City in central Yukon, which has the longest data record in northern Canada, experienced the warmest winter in its 110-yr record in 2003 (Janowicz 2003). Some trends have been observed in the last several decades. Winter and summer temperatures have increased in all regions, with greater winter temperature increases in northern Yukon, and greater summer increases in southwestern Yukon (Janowicz 2001). Winter precipitation has increased slightly in all regions, while summer precipitation is more variable, having decreased in northern Yukon and increased in southern Yukon. The greatest changes have occurred in western, mountainous regions, where both summer and winter temperatures and winter precipitation have increased significantly. These observed trends are within the range of projections developed by a Canadian Climate Centre global climate model (GCMII), which is based on a 100% increase of $CO_2$ in the atmosphere (Taylor 1997; Intergovernmental Panel on Climate Change 2001). There is also some evidence suggesting the trends may be associated with teleconnections between large-scale oceanic and atmospheric processes such as El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Barlow *et al.* 2001). Over the last century, the PDO appears to have shifted between positive and negative phases every 20–30 yr (Cayen 1996). A positive PDO is generally associated with lower than normal rainfall and higher than normal air temperatures, and a negative PDO is associated with higher than normal precipitation and lower than normal air temperatures. Inspection of the PDO index shows a major shift to have occurred in the 1970s, coinciding with the significant temperature increases observed in northern Canada during this time period.

There have been a number of studies carried out in northern regions of North America on the impact of climate change on hydrologic response (Kite 1993; Burn 1994; Loukas & Quick 1996, 1999; Leith & Whitfield 1998; Whitfield & Taylor 1998; Spence 2002). A few broad-scale national and regional studies have included a partial review of Yukon hydrometric response. Whitfield & Cannon (2000) and Whitfield (2001) assessed climatic and hydrologic variations between two decades (1976–1985; 1986–1995) for stations in British Columbia and Yukon. Hydrologic response was generally found to be characterised with higher year-round flows. Mountainous streams were found to have the timing of the freshet advanced, followed by lower summer and fall discharge. Zang *et al.* (2001) and Yue *et al.* (2003) assessed the streamflow records for 243 Canadian hydrometric stations making up the Reference Hydrometric Basin Network, including some Yukon stations, over the period 1967–1996. While most of these stations were in southern Canada, they found winter low flows in northern British Columbia and Yukon to have increased significantly. Annual mean and peak flows were observed to have increased in glacerised basins of southern Yukon and northern British Columbia. Burn *et al.* (2004), in the comparison of streamflow of the Liard and Athabasca Rivers in the mountainous headwater regions of the Mackenzie River basin, found both streams to exhibit increases in winter discharge and some increase in the snowmelt freshet. Dery & Wood (2005) investigated the discharge of 64 Arctic or subarctic Canadian rivers from 1964–2003. They found a general 10% decline in mean annual discharge to the Arctic and North Atlantic Oceans over that period, which is consistent with the decline in annual precipitation in northern Canada over that period. The decline in streamflow was less pronounced in northwestern Canada where the results were not statistically significant. Their work indicated there were links between annual discharge and Arctic Oscillation, El Nino/South Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) at interannual to decadal timescales.

There has been only limited work to date on the impact of climate change specific to Yukon hydrology. Janowicz & Ford (1994) used the CCC GCM temperature and precipitation projections, and a correlation approach to assess the impacts of climate change on the water supply to the upper Yukon River. Their analyses indicated that annual inflows to the glacierised upper Yukon River would increase by 39%, primarily in the summer months, due to increasing temperature and precipitation. Janowicz (2001) carried out an analysis of streamflow to assess the response of the observed temperature and precipitation changes on peak flows, which normally occur as a result of spring snowmelt. The assessment revealed that there has been a dramatic change in mean annual flood (MAF) in some regions of the Yukon over the last 20 years, with a progressive decrease in the parameter moving from south to north. The greatest increases in MAF were observed to occur within the sporadic permafrost zone, from predominantly glacierised systems in western Yukon. Smaller increases were noted in southeastern Yukon. These increases correspond to the observed increase in both summer temperatures and winter and summer precipitation. Peak flows from central and eastern Yukon, within the discontinuous permafrost zone, exhibit very little change. Within the continuous permafrost zone, peak flows were observed to decrease progressively moving northward to the Arctic coast. In an assessment of streamflow discharge for the Yukon River basin, Walvoord & Striegl (2007) found no discernable trends in spring, summer, fall and annual discharge, while there was a general increase in winter discharge. A corresponding trend in annual precipitation was not observed. The observed changes in winter discharge are thought to be a result of enhanced groundwater inputs to streamflow. Janowicz (2007) carried out an assessment of winter low flows using records from 21 hydrometric stations evenly distributed between continuous, discontinuous and sporadic permafrost zones in Yukon Territory and adjacent areas of northern British Columbia and western Northwest Territories. Continuous permafrost zones exhibited the greatest positive trend in minimum winter streamflow. Winter streamflow trends within the discontinuous zone are positive but more variable, while trends in the sporadic permafrost zone are not consistent.

This paper summarises the results of a study carried out to assess apparent trends of annual mean, maximum and minimum flows in the Yukon and adjacent areas of northwestern Canada over the last few decades.

## SETTING

### Permafrost distribution and study area

Situated in northwestern Canada, much of Yukon Territory is underlain by permafrost. The territory is subdivided into three zones, depending on the relative amount of underlying permafrost (Figure 1). Continuous permafrost

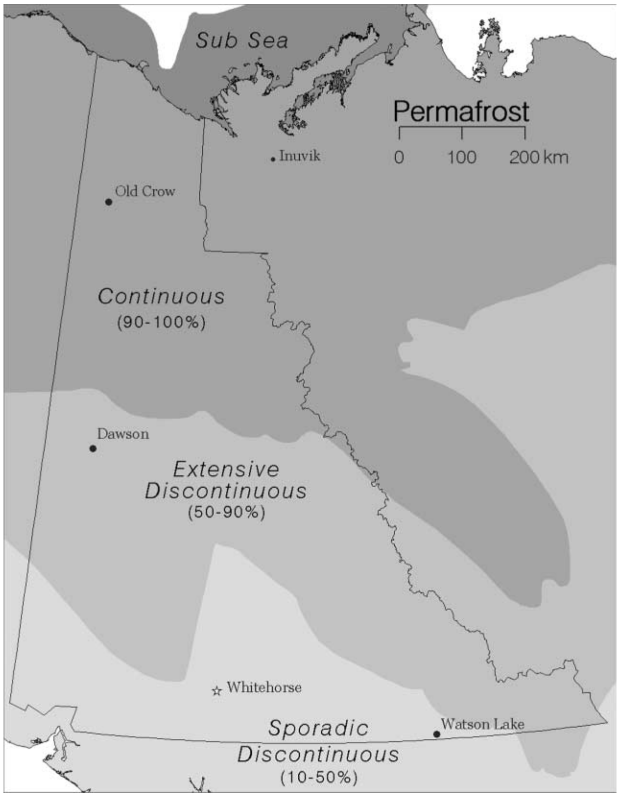

**Figure 1** | Study area and permafrost zones (from Smith *et al.* 2004).

areas have greater than 90% coverage, discontinuous areas have between 50–90% coverage and sporadic areas have 10–50% coverage (Brown *et al.* 1997). The continuous, discontinuous and sporadic zones represent 30, 45 and 25% of the Yukon, respectively (NRC 1995). The analyses were carried out using data from Yukon Territory, northern British Columbia and the western Northwest Territory west of the 125th parallel of longitude, an area covering approximately 920,000 km$^2$.

## Hydrologic response

There are four distinct hydrologic response types exhibited by Yukon streams. The southwest Coast and Saint Elias Mountains regions represent a region of glacial response. Hydrologic response from the remainder of the territory is closely tied to, and coincides in location and extent to, the three permafrost zones: continuous, discontinuous and sporadic (Janowicz 2004).

Figure 2 provides an illustration of typified runoff hydrographs for the four hydrologic response types.

The glacial response type, situated within the sporadic permafrost zone, has the greatest annual volume of discharge in response to the relatively large annual precipitation amounts (500–2,000 mm) received by the Coast and Saint Elias Mountains (Wahl *et al.* 1987). Peak discharge normally occurs in July or August, coinciding in timing to maximum summer temperature. Minimum annual discharge occurs in March or April, coinciding in timing to minimum annual groundwater inputs. Minimum annual winter flows are relatively large in comparison to winter flows in all other Yukon areas as a result of higher winter temperatures and weaker permafrost effects.

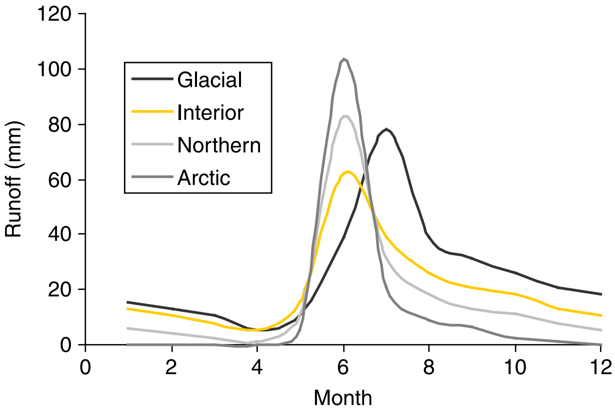

**Figure 2** | Hydrologic response zone hydrographs.

The Interior hydrologic response type is located within the sporadic and southern discontinuous permafrost zones, in an area which receives 300–600 mm of annual precipitation. It is characterised by peak flows in late May or early June in response to the snowmelt freshet. Secondary peaks occur during the summer months as a result of rainfall. Occasionally, smaller systems will have the dominant peak resulting from rainfall. Annual low flows occur in March or April, coinciding in timing to minimum annual groundwater inputs.

The Northern hydrologic response type is located within the northern portion of the discontinuous permafrost zones, and the southern portion of the continuous permafrost zone, in an area which receives 300–400 mm of annual precipitation. Further north the Arctic hydrologic response type is located entirely within the continuous permafrost zones, in an area which receives 150–300 mm of annual precipitation.

Patterns of annual streamflow of the Interior, Northern and Arctic response types are similar with respect to timing; however, the magnitude of total, peak and minimum annual discharge varies. While annual precipitation decreases with latitude, annual discharge increases slightly due to lesser amounts of evapotranspiration. Annual peak flows increase significantly with latitude as a result of the increasing dominance of the underlying permafrost which reduces the pathway to the stream channel. Conversely, annual minimum flows decrease with latitude due to lesser groundwater contributions to winter streamflow. Many smaller streams within the continuous permafrost zone are completely dominated by underlying permafrost, and have no observed flow during the latter part of the winter.

# METHODOLOGY

## Trend analysis

Data from all active and recently discontinued (<5 yr) Environment Canada hydrometric stations, on unregulated streams, with at least 25 years of record were used in the analyses. Because of the distinct seasonality of the station records, with annual minimum flows occurring in the winter or early spring and annual maximum flows occurring late spring or summer, independence between consecutive data in the time series is assured. A total of 43 station records were available for analysis (10 continuous, 13 discontinuous and 20 sporadic). Time series of three hydrograph characteristics–annual mean, maximum and minimum discharge–were assessed for trends. The 7-d average minimum annual low flow, which normally occurs in late winter or early spring, was used in the present study to represent annual minimum discharge. The 7-d average low flow parameter is a commonly used minimum flow measure which reduces the variability over a single value.

The Mann–Kendall trend test was used to assess trends in the three hydrograph parameters. First proposed by Mann (1945) and Kendall (1975), it is a non-parametric test used for the assessment of trends in time series. The Mann–Kendall test is a simple, robust tool which can readily handle missing values, but it does assume the observations to be randomly ordered in time. The standard normal variate value ($Z$) is calculated which 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 1 provides a summary of the trend analyses. The assessment of annual mean runoff indicated there was a slight positive trend, though not statistically significant, in the majority of hydrometric records within the continuous and discontinuous permafrost zones. One statistically positive trend, each for the continuous and discontinuous zones, was obtained. While summer and winter precipitation have generally increased and decreased respectively in permafrost regions, annual precipitation has increased slightly, which may provide the explanation for the corresponding slight observed increase in annual runoff in these regions. Results within the sporadic permafrost zone were more variable, with five statistically significant trends, which were divided between positive and negative trends. Annual precipitation has increased in this region as well, which provides the basis for the positive trends. The negative trends may be explained with greater rates of evapotranspiration in these watersheds, resulting in less runoff.

Annual maximum flows were observed to generally decrease within the continuous permafrost zone, though there were only two statistically significant records. Depending on drainage area, the majority of annual peak flow events are generated by snowmelt, while some smaller streams may have their annual peak flow resulting from intense summer rain events. With lesser amounts of winter precipitation, smaller peak flow events may be a result of likewise smaller snowmelt events. Alternatively it is conceivable that these trends may be explained by increased infiltration rates and longer pathways to the stream channel, associated with degrading permafrost. Figure 3, which is statistically significant at the 99% level, provides an illustration of annual maximum flow trends for the Porcupine River at Old Crow (09FD001). Similar results, though slightly weaker, were obtained for the discontinuous zone, and weaker yet for the sporadic zone.

Strong positive trends in annual minimum flows were obtained for all three permafrost zones, with the greatest positive trends observed within the continuous permafrost zone. Winter baseflows are generally related to drainage area. In cold regions the relationship is more pronounced, with smaller drainages having less groundwater inputs to baseflow; therefore, smaller winter flows. While summer and winter precipitation have generally increased and decreased respectively in permafrost regions, annual precipitation has increased slightly and there has been a corresponding slight observed increase in annual runoff in continuous and discontinuous permafrost regions. Both precipitation and annual discharge increases are slight and cannot provide the basis for winter low flow increases. Summer and winter air temperatures have been observed to increase in most regions and may be attributed to the increase in winter low flows. Increasing air temperature results in permafrost degradation, which enhances the interaction between surface and groundwater systems, allowing for greater groundwater contributions to baseflow.

**Table 1** | Mann–Kendall trend statistics

| | | | | | Mann–Kendall $Z$ statistic | | |
|---|---|---|---|---|---|---|---|
| **Permafrost class** | **Station no.** | **Drainage area (km$^2$)** | **Record period** | **$n$ (yr)** | **Mean** | **Maximum** | **Minimum** |
| **Continuous** | 09FC001 | 13 900 | 1977–2006 | 28 | 0.99/- | − 0.12/- | 1.31/- |
| | 09FD001 | 55 400 | 1962–2006 | 41 | − 1.62/- | − 2.91/$^{***}$ | 1.51/- |
| | 10HB005 | 15 400 | 1976–2006 | 23 | 2.63/$^{***}$ | 1.16/- | 3.04/$^{***}$ |
| | 10LA002 | 18 600 | 1975–2006 | 32 | 1.32/- | 1.31/- | 4.89/$^{****}$ |
| | 10LC003 | 1310 | 1974–2006 | 32 | 0.86/- | 0.96/- | “0” |
| | 10LC007 | 625 | 1975–2006 | 32 | 1.54/- | − 0.03/- | 3.79/$^{****}$ |
| | 10MC002 | 70 600 | 1975–2006 | 31 | 0.27/- | − 0.94/- | 3.65/$^{****}$ |
| | 10MD001 | 5710 | 1976–2006 | 27 | − 1.25/- | − 1.96/$^{**}$ | “0” |
| | 10NC001 | 56 300 | 1970–2006 | 27 | − 1.48/- | − 0.68/- | − 1.65/$^{*}$ |
| | 10ND002 | 68.3 | 1977–2006 | 28 | 0.00/- | − 0.38/- | “0” |
| **Discontinuous** | 09AH003 | 1750 | 1975–2006 | 30 | − 0.39/- | − 0.39/- | 1.52/- |
| | 09AH004 | 6370 | 1983–2006 | 24 | − 1.39/- | − 1.34/- | − 1.19/- |
| | 09BA001 | 7250 | 1961–2006 | 45 | − 0.33/- | − 2.41/$^{**}$ | 1.70/$^{*}$ |
| | 09BC001 | 49 000 | 1953–2006 | 53 | 0.30/- | − 1.27/- | 2.21/$^{**}$ |
| | 09BC004 | 22 100 | 1973–2006 | 34 | 0.12/- | − 0.12/- | 2.82/$^{***}$ |
| | 09DD003 | 51 000 | 1964–2006 | 43 | 0.82/- | 0.17/- | 0.95/- |
| | 09EA003 | 7800 | 1966–2006 | 41 | 1.79/$^{*}$ | 0.55/- | 3.27/$^{***}$ |
| | 09EA004 | 1100 | 1975–2006 | 31 | 0.48/- | 0.25/- | 1.68/$^{*}$ |
| | 09EB003 | 2220 | 1982–2006 | 23 | 0.95/- | 0.82/- | 1.98/$^{**}$ |
| | 10EA003 | 8560 | 1961–2006 | 39 | 0.39/- | − 0.47/- | 0.94/- |
| | 10EB001 | 14 600 | 1964–2006 | 42 | 0.96/- | 1.32/- | 2.30/$^{**}$ |
| | 10GB001 | 20 200 | 1975–2006 | 23 | 1.11/- | 0.89/- | 1.03/- |
| | 10KB001 | 7400 | 1978–2006 | 21 | − 1.40/- | − 2.00/$^{**}$ | 1.00/- |
| **Sporadic** | 08AA003 | 8500 | 1953–2005 | 53 | 0.02/- | − 0.29/- | 0.26/- |
| | 09AA006 | 6810 | 1951–2006 | 55 | 3.00/$^{***}$ | 2.54/$^{**}$ | 2.59/$^{***}$ |
| | 08AA008 | 1250 | 1981–2006 | 26 | − 0.71/- | − 0.74/- | 1.16/- |
| | 08AA009 | 194 | 1981–2005 | 25 | − 0.58/- | − 0.21/- | 0.33/- |
| | 08AB001 | 16 200 | 1975–2006 | 32 | 1.87/$^{*}$ | 0.37/- | 0.52/- |
| | 09AA012 | 875 | 1958–2005 | 44 | − 0.16/- | 1.34/- | − 0.65/- |
| | 09AA013 | 992 | 1958–2006 | 45 | 0.16/- | − 0.53/- | 0.13/- |
| | 09AC001 | 6930 | 1949–2005 | 56 | 0.27/- | − 1.76/$^{*}$ | 1.67/$^{*}$ |
| | 09AC007 | 457 | 1989–2006 | 17 | − 0.84/- | − 0.78/- | − 1.03/- |
| | 09AE001 | 30 300 | 1944–2006 | 61 | − 0.85/- | − 1.61/- | − 1.33/- |
| | 09CA002 | 4950 | 1953–2006 | 53 | 0.43/- | 1.58/- | 4.29/$^{****}$ |
| | 09CA004 | 631 | 1981–2006 | 23 | 0.45/- | 0.03/- | 2.38/$^{**}$ |
| | 09CB001 | 6240 | 1975–2005 | 30 | 0.38/- | − 1.44/- | 2.75/$^{***}$ |
| | 10AA001 | 33 400 | 1961–2003 | 45 | − 2.04/$^{**}$ | − 1.53/- | 0.36/- |
| | 10BB009 | 211 | 1980–2005 | 26 | − 1.92/$^{*}$ | − 0.86/- | 0.13/- |
| | 10BA009 | 6900 | 1962–2005 | 44 | − 0.09/- | − 1.15/- | 2.70/$^{***}$ |
| | 10AC005 | 888 | 1964–2005 | 42 | − 0.27/- | − 1.57/- | 0.80/- |

(*continued*)

**Table 1** | (*continued*)

| | | | | | Mann–Kendall *Z* statistic | | |
|---|---|---|---|---|---|---|---|
| **Permafrost class** | **Station no.** | **Drainage area (km$^2$)** | **Record period** | ***n* (yr)** | **Mean** | **Maximum** | **Minimum** |
| | 10CB001 | 2160 | 1946–2005 | 61 | $2.18/^{**}$ | $1.80/^{*}$ | $4.30/^{****}$ |
| | 10CD001 | 20 300 | 1945–2005 | 61 | 1.47/- | 0.42/- | $5.19/^{****}$ |
| | 10CD003 | 273 | 1979–2005 | 27 | 0.04/- | − 1.13/- | “0” |

”0”: zero flow.
Level of significance: $^{*}$0.10; $^{**}$ 0.05; $^{***}$ 0.01; $^{****}$ 0.001.

It is not possible to statistically validate all trends, since some of the study streams have had predominately “zero” winter flows in past decades, with increasing occurrences of measurable winter low flows in recent years. As with many statistical techniques, the Mann–Kendall tests are not able to handle “zero” flows. In regions of continuous permafrost many streams have “zero” flows. Of the study streams, the Rengleng River (10LC003) with a drainage area of 1310 km$^2$ and the Firth River near the mouth (10MD001) with a drainage area of 5710 km$^2$ have had nonexistent winter low flows in past decades, while some measurable flows during recent winter periods has been observed. The winter flow regime for Caribou Creek (10ND002), with a drainage area of 68.3 km$^2$, has remained unchanged, with “zero” flows throughout the entire 29 year monitoring period.

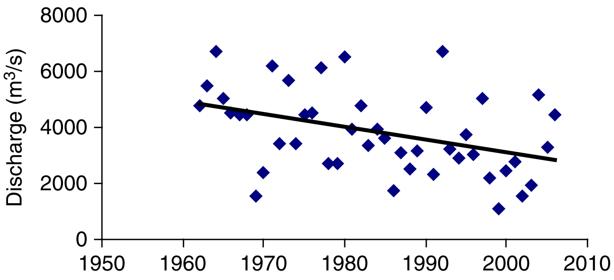

**Figure 3** | Annual maximum discharge: Porcupine River at Old Crow, 09FD001.

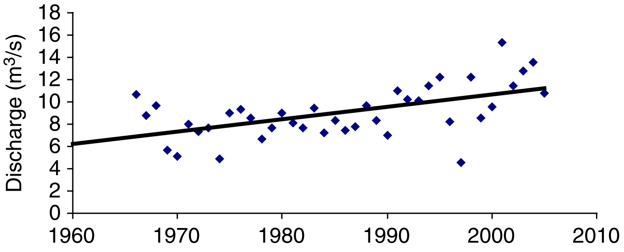

**Figure 4** | Annual minimum discharge: Klondike River above Bonanza Creek, 09EA003.

Trends of winter low flow regimes, with increasing flows, are generally exhibited by streams within the discontinuous permafrost zone. All but one of the thirteen study streams exhibit positive winter low flow trends, while seven of these have statistically significant trends. Figure 4 illustrates the increasing trend for the Klondike River (09FA003). Even the smallest streams within the discontinuous permafrost zone normally have winter flows, so drainage area is not as strong a factor in influencing winter streamflow as in the continuous permafrost zone.

Trends of increasing winter low flows are not generally strong within the sporadic permafrost zone. Seven of the twenty represented streams have statistically significant positive trends. Most of the remaining stations have positive trends, though three stations exhibit negative trends. Increasing winter streamflow trends have occurred from some mountainous regions with significant alpine permafrost, while some basins are transitional with the discontinuous permafrost zone. One station exhibits “0” winter flows. The generally weak positive trends may possibly be attributed to lesser permafrost coverage, which in turn is subject to lesser amounts of degradation and subsequently smaller impact on hydrologic response.

## CONCLUSIONS

An assessment of streamflow response was carried out to determine if there are apparent trends in permafrost regions as a result of observed temperature changes. As permafrost properties change with climate warming, the hydrologic response in 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. Annual mean, maximum and minimum flows were assessed. Annual minimum flows were represented by the mean 7-d low flow. The Mann–Kendall test was used to statistically validate observed trends.

Annual mean runoff indicated there was a slight positive trend, though not statistically significant, within the continuous and discontinuous permafrost zones, which may be explained by the corresponding observed increases in annual precipitation in these regions. Results within the sporadic permafrost zone were more variable, with no definitive observed trends. Though annual precipitation has also increased in this region as well, providing the basis for the positive trends, negative trends may be due to greater rates of evapotranspiration, resulting in less runoff.

Annual maximum flows were observed to generally decrease within the continuous permafrost zone. This may be due to likewise smaller snowmelt events associated with less winter precipitation. Alternatively these trends may be explained by increased infiltration rates and longer pathways to the stream channel associated with degrading permafrost. Similar results, though slightly weaker, were obtained for the discontinuous zone, and weaker yet for the sporadic zone.

Strong positive trends in annual minimum flows were obtained for all three permafrost zones. It is possible that these increases are a result of corresponding increases in both summer and winter air temperatures, which have been observed to increase in most regions, resulting in permafrost degradation enhancing the interaction between surface and groundwater systems, allowing for greater groundwater contributions to baseflow.

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