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Challenges from North to South
Des défis du Nord au Sud

Summer and winter flows of the Mackenzie River system

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ABSTRACT
The Mackenzie River Basin contains major hydro-physiographical regions representative of northern permafrost and non-permafrost zones. The regional environments exert influences, best expressed by the summer and winter hydrographs of headwater rivers. Summer flow is particularly responsive to the varied climatic, topographic and hydrologic settings of the Cordilleran mountains, the low gradient Interior Plains and the bedrock terrain of the Canadian Shield with myriad lakes. In winter, streamflow is sustained by groundwater discharge and by lake outflow. Most rivers in Mackenzie Basin show only weak flow trends in the summer but winter flows in the lower basin exhibit statistically significant rising trends between years, which may be attributed to permafrost degradation and increased autumn rainfall, though these hypotheses warrant further verification.

RÉSUMÉ
Le bassin du fleuve Mackenzie contient des régions hydro-physiographiques majeures représentatives des zones nordiques de pergélisol et d'autres sans pergélisol. Les environnements régionaux exercent une influence, mieux exprimée par les hydrogrammes d'été et d'hiver des fleuves nourriciers. L'été, l'écoulement est particulièrement sensible à la variation des paramètres climatiques, topographiques et hydrologiques des montagnes de la Cordillière, ainsi qu'au faible gradient des plaines intérieures et du substratum rocheux du Bouclier canadien avec ses myriades de lacs. En hiver, l'écoulement est maintenu par le débit des eaux souterraines et par la décharge du lac. La plupart des rivières dans le bassin du Mackenzie montrent de faibles tendances d'écoulement en été, tandis qu'en hiver, les écoulements dans le bassin inférieur montrent d'importantes tendances à la hausse d'une année à l'autre. Ces dernières peuvent être attribuées à la dégradation du pergélisol et à une augmentation des précipitations à l'automne. Ces hypothèses méritent cependant d'être vérifiées davantage.

1 INTRODUCTION

Mackenzie River is the largest northward-flowing river in Canada. Many northern settlements along the river course, agriculture in the southern section, hydro-power production and resource development in various parts of the basin draw upon the river system for water supply. Furthermore, barge traffic along the main river requires information on summer flow, while the management of aquatic ecological well being can benefit from information on the summer and winter flow status. Spring freshets, generated by snowmelt and accentuated by ice breakup, have been well investigated (Prowse and Carter 2002; de Rham et al. 2008). The present study focuses on comparing the flow conditions during the summer and the winter seasons. One recent concern is the changing tendency of river flow in Arctic basins. Possible factors, including the role of permafrost, will be examined.

Occupying an area of 1.8 million km^2, the Mackenzie Basin covers about one-fifth of the total land surface of Canada. Rivers that cross different parts of this vast basin acquire flow characteristics according to the diverse hydro-physiographic conditions of the regions they traverse. With the large latitudinal and altitudinal extents of the basin, the arrival of spring and autumn differs by weeks or even months between its northern and southern extremities. To enable comparison of flow among rivers, a common time frame is adopted for the definition of summer (taken as the months of June to September) and winter (from November 1 to the end of March). For this study, daily streamflow data are acquired from the HYDAT database, the National Water Data Archive compiled by Water Survey of Canada.

2 SUMMER FLOW AND BASIN ENVIRONMENT

The Mackenzie Basin can be distinguished into four major hydro-physiographical provinces as shown in Figure 1, with permafrost underlying the northern basin. The summer flow regimes of rivers in these regions are influenced by basin attributes such as topography, land cover, and glaciers and lakes. Northern mountains of the Western Cordillera lie within the continuous permafrost zone whereas permafrost occurs preferentially beneath some lower slopes in the discontinuous permafrost belt and is present only at high altitudes further south. Several sets of natural and artificial environments affect the hydrographs, as demonstrated by the examples in Figure 2. Athabasca River at Jasper (Fig. 2a) in the south receives runoff contributions from snowmelt, rainfall and glacier melt, causing the hydrograph to fluctuate frequently in the summer. Liard River at Upper Crossing (Fig. 2b) is >7° latitude further north and without runoff contribution from glaciers. Its spring freshet arrives later than for the Athabasca, and the recession to summer flow is often interrupted by rain-driven hydrograph rises. The hydrograph of Peace River at Hudson Hope (Fig. 2c)

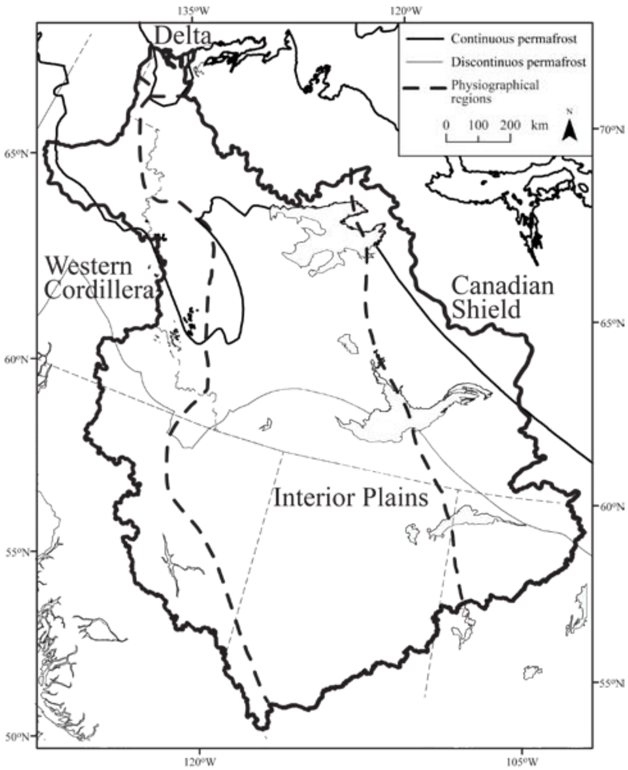

Figure 1. Hydro-physiographic regions of Mackenzie River Basin and southern limits of continuous and discontinuous permafrost.

reflects the effect of water release from Williston Lake for hydropower production, sometimes yielding more flows in the winter than in summer.

In the east lies the Canadian Shield with rolling topography. The crystalline bedrock is largely impervious, but major fracture zones are exploited by valleys, infilled with soil and often occupied by lakes and wetlands. The considerable storage volume of large lakes or chains of lakes dampens flow fluctuations and their outflow tends to be relatively even (e.g. Camsell River shown in Fig. 2d). The Interior Plains generally have low gradients, with continuous permafrost in the northern tundra, discontinuous permafrost in the Subarctic, and permafrost-free further south. Lakes and wetlands occupy many areas with pitted topography, with annual evaporation from open water surfaces ranging from >500 mm in the south to <200 mm in the tundra (Lins et al. 1990). The Plains present little obstruction for north-south airflow that can alternately bring forth dry or wet conditions, giving rise to large intra- and inter-annual fluctuations in summer flow for Plains rivers such as the Hay (Fig. 2e).

At the northern extremity of the Mackenzie Basin lies the Mackenzie Delta. It is an extension of the Interior Plains and consists of a watery maze of distributaries and myriad lakes. The Delta is flooded in the spring and dries out gradually in the summer except when storm surges bring about inundation from the seaward side and backwater effect extending to the upper Delta (Marsh and Schmidt 1993).

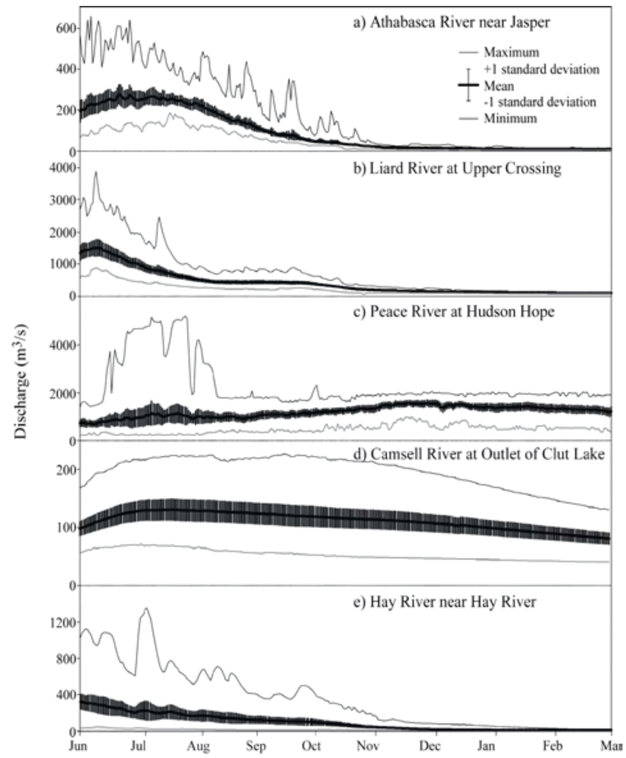

Figure 2. Long term (1972-2012) hydrographs showing the means, standard deviations, maxima, and minima for every calendar day between June and March. Examples are provided for rivers from mountainous regions: (a) Athabasca at Jasper, (b) Liard at Upper Crossing, (c) Peace at Hudson Hope; from Canadian Shield: (d) Camsell River; and from Interior Plains: (e) Hay River.

3 WINTER FLOW AND ICE SEASON

Extreme cold conditions prevail in the winter, when the land is blanketed with snow and shallow water bodies turn into ice, decoupling most hydrologic activities from atmospheric impetus such as evaporation, storms or mid-winter warm spells. River condition varies: some rivers cease to flow and their channels are infilled with drifted snow or icing, while those rivers with continuous flow acquire a cover of ice. The ice covered duration is taken as the period between freeze-up and breakup. As noted by Mackay (1960), the freeze-up date may be based on the formation of a given amount of ice on the river but a warm spell can destroy a fragile early ice cover. Breakup may be deemed as the initiation of ice movement or the clearance of ice at the observation site. Water and ice held in storage are discharged as part of the freshet. Mackay (1960) noted that breakup at Fort Good Hope can be correlated with the air temperatue of Fort Simpson for April and early May. Warmer spring may therefore translate to an earlier breakup, through both processes of thermal and mechanical breakup. The latter is initiated by hydrodynamic forces that lift and fracture the ice, and should be taken into consideration together with ice-melt in spring (Hiks and Beltaos 2008).

The timing of freeze-up and breakup varies considerably within the Mackenzie Basin, depending notably on altitude and latitude. For most rivers, winter is a low flow period with the flow sustained by groundwater discharge. Exceptions are most rivers in the Canadian Shield where outflow from large lakes continuously maintain moderate flows.

4 FLOW IN MAIN STEM OF MACKENZIE

The Mackenzie River collects runoff from its separate tributary basins. Integration of tributary inflow with discharge of the main stem can take some distances. This is shown by Mackay (1970) who investigated the joining of Liard River with the Mackenzie in June 1968. Using water temperature, turbidity and chemical (sodium and chloride) concentration, he found that the waters of these two rivers were not fully mixed at least 480 km downstream from their confluence at Fort Simpson. The Liard is a main contributor of flow to Mackenzie River. Woo and Thorne (2003) calculated that the Peace and the Liard together provide about half of the of the Mackenzie annual total flow before the Delta, other rivers of the northern mountains about one-tenth, the Athabasca River about one-fifth, the Shield rivers yield another fifth, and the least amount comes from rivers of the Interior Plains.

In view of the complex origins of runoff from different hydro-physiographic provinces, the flow of the main Mackenzie River carries mixed hydrological signatures that prevent the deciphering of regional factors that influence streamflow trends. For this reason, main stem Mackenzie River is excluded from the trend study below.

5 RECENT STREAMFLOW TENDENCIES

Studies of Arctic streamflow have identified monotonic linear trends in the mean and extreme discharges during the recent decades (e.g. McClelland et al. 2004, Walvoord and Striegl 2007, Yang et al. 2014). Most of the Mackenzie Basin other than the northern Shield and northern Plains display negative summer flow trends though their correlation coefficients (r-values) are not statistically significant. The tendency is stronger in the south (Fig. 3a). Rivers fed by lakes in the northern Shield and northern Plains maintain significant positive trends in both summer and winter, as do the smaller rivers on the Plains around Fort Simpson. Most western rivers, from the Peace and continuing northward, undergo a switch to statistically significant positive r-values in October, yet negative correlation intensifies in the Athabasca. Of note is that the southern limit of permafrost approximately delineates a separation between positive and negative tendencies in summer flow (Fig. 3).

6 TREND-MAKING MECHANISMS

Various hypotheses have been advanced to account for streamflow trends. Here, we examine possible association of several mechanisms with the identified trends in the Mackenzie Basin. An increasing flow trend can be related to an increase in water supply and/or enhanced efficiency in flow delivery. Precipitation input, cumulative storage release and permafrost degradation can be contributing factors.

6.1 Climate warming

A tendency for air temperature to rise in late summer can be detected in most of Mackenzie Basin (Fig. 4a), especially in the central and southern areas. Despite the weak trend, warmer conditions can enhance evaporation loss and degradation of permafrost. An increase in evaporation may account for a reduction of summer flow in non-permafrost areas while in permafrost terrain, limited CALM data (Circumpolar Active Layer Monitoring; http://www.gwu.edu/~calm/data/north.html) indicate that the active layer at Fort Simpson has deepened significantly between 1992 and 2014 and the active layer at Willowlake River has also thickened between 1993 and 2012. Both ground ice melt and thawing of northern wetlands, which opens pathways for flow connectivity, can lead to a positive tendency for summer flow in the northern Plains, as revealed by the rivers around Fort Simpson.

6.2 Fire

Forest fire directly impacts ground thermal regime and severe wild fire can increase the active layer thickness, as documented by Mackay (1995). With forest fire, the loss of vegetation and surface cover is accompanied by changes in ground thermal properties that affect insulation and heat conduction, the radiation regime as well as surface water balance. Comparing a burnt and an unburnt site in southern Yukon, Burn (1998) found that the burned site had higher ground temperature at all depths, and attained annual maximum thaw depth in October and November instead of mid-November. Permafrost degradation proceeded from both the top and the bottom, and active layer thickness reached 3.8 m compared with 1.4 m beneath the forest, representing permafrost thaw of 2.5 m between 1958 and 1997. While permafrost degradation is evident after a forest fire, a considerable extent of devastation is needed to provide sufficient water from intensified ground ice melt to sustain increased flow. Nevertheless, in discontinuous permafrost areas, degradation proceeds both vertically and along the edges of the permafrost bodies, as noted by Quinton et al. (2011), while groundwater movement can convey heat to further the thaw. Percolation would then be enhanced and subterranean flow conduits can be expanded, as suggested by St Jacques and Sauchyn (2009).

6.3 Precipitation

The precipitation trends of early and mid-summer do not form discernible spatial clusters but the trends of a number of stations shift in August to approximate those of

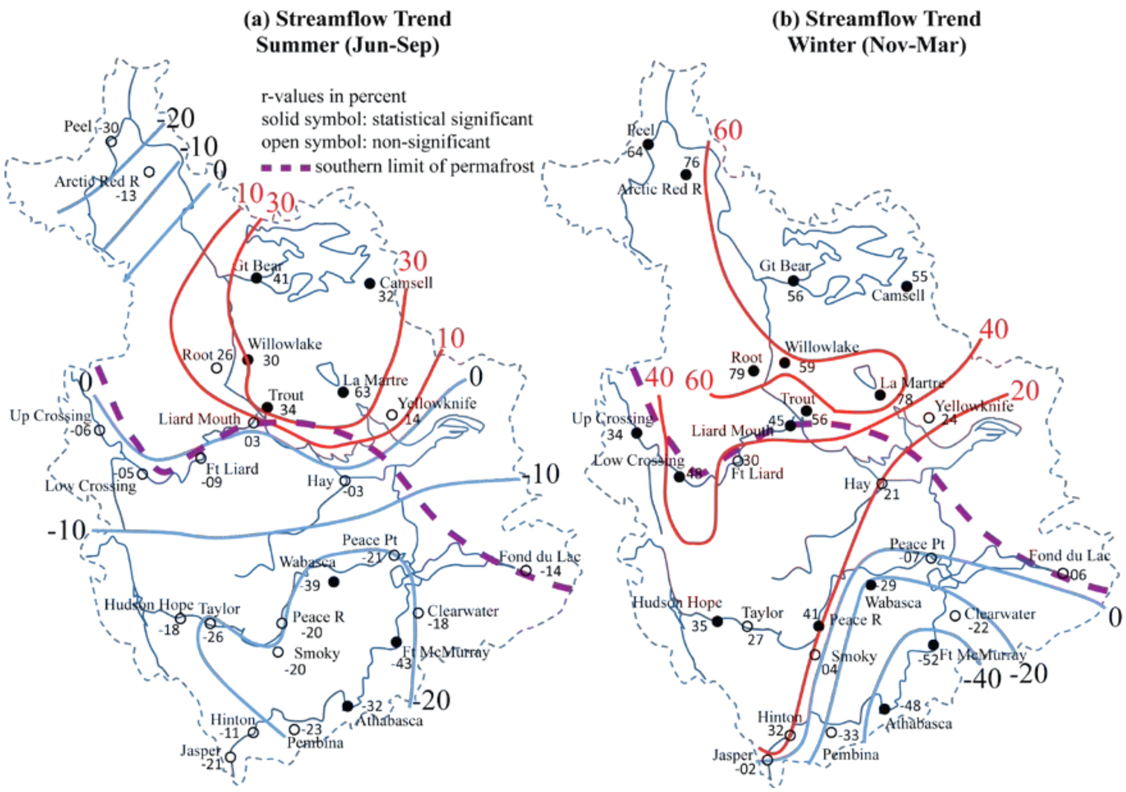

Figure 3. Streamflow trends indicated by correlation of flow with years (1972-2013); correlation coefficients are given in percent: (a) summer (June to September) and (b) winter (November to March). Also shown is the southern limit of discontinuous permafrost.

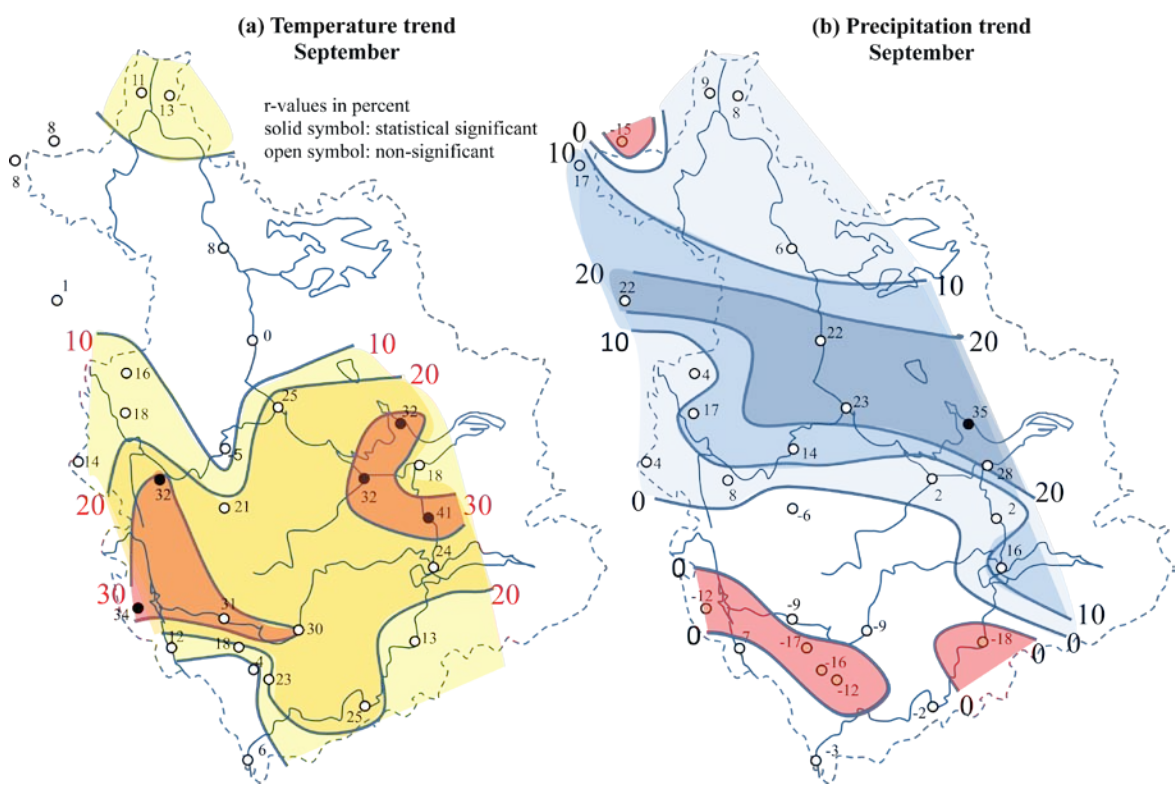

Figure 4. Trends of (a) September air temperature and (b) September precipitation across Mackenzie Basin.

the following month. By September a general pattern emerges, separating stations with declining tendency in the south from those with a positive trend elsewhere in the basin (Fig 4b). A positive precipitation tendency in both August and September suggests that such a spatial configuration is not random (coincidentally, these zones correspond roughly with the permafrost regions). The fall is when a cold air mass returns to the Subarctic, bringing frontal storms that deposit rain to raise autumnal streamflow and increase basin storage in support of winter baseflow.

Combining late summer precipitation with warming of the basin, it is plausible that most of the non-permafrost areas in the south have diminished pre-winter moisture storage due to elevated evaporation and reduced precipitation. In the north, however, increased late-summer precipitation and enhanced permafrost degradation (through ice melt contribution and subsurface flow connectivity) would enrich moisture storage that supports baseflow. The amount of baseflow in relation to the storage status prior to the onset of winter can be estimated by an empirical relationship between winter flow and the discharge on October 15, which is indicative of the pre-winter storage status (Woo and Thorne, 2014). Thus, storage provides a plausible link between the trends of autumn precipitation, late summer warming and enhanced winter flow.

6.4 Lake storage

Large lakes considerably retard outflow response to water gains and losses, atmospheric inputs and the impetus of inflow. However, the storage factor is complicated by the cumulative amount of net atmospheric input (precipitation minus evaporation), inflows including spring freshet, outflows including artificial release, storage capacity and antecedent storage of the past seasons and even of multiple years.

Most lake-fed rivers are located in the Plains and Shield regions. The Plains can be impacted by permafrost degradation but the Shield is dominated by bedrock that is relatively insensitive to permafrost change. Rivers in the north, such as Great Bear, Camsell, and Lac LaMartre, show decadal increase in streamflow, yet no such tendency is found in southern Shield rivers like Fond du Lac and Lockhart. Superimposed on these trends are multi-year cyclical variations, but the presence of a long-term trend, in both summer and winter, is attributable to gradual buildup of lake storage. The chief contributor may be increased precipitation in the fall (Spence et al. 2011), at a time when northward migration of frontal storms brings much precipitation to the Subarctic but when seasonal evaporation has declined.

Under human influence, more water may be released in winter than in summer from Williston Lake, depending on hydroelectric power demand, thus reversing the normal flow regime of Peace River. Usually being the principal contributor of winter flow to the Mackenzie, the Peace will carry its winter flow tendency to the main Mackenzie River.

6.5 Uncertainties

There are uncertainties regarding accuracy of streamflow data and reliability of results of analysis.
(1) The agents of permafrost degradation cannot be unequivocally ascertained. Wild fire may be instrumental in permafrost thaw, but fires are not regionally extensive. Climate warming is pronounced in winter, yet a temperature increase of several degrees during extreme cold may be ineffective in forcing the thaw.
(2) Permafrost degradation with its attendant effects on flow augmentation may occur througout summer and extend into winter, but the magnitude of change is small relative to the volume of summer runoff and the effect would escape statistical detection.
(3) Measurement of discharge under ice remains a challenge for stream gauging. Trend analysis requires historical data, yet the reliability of winter flow measurements depends on river size and winter severity (Rosenberg and Pentland, 1966).

These consideratins should not be dismissed in the investigation of winter flow trends.

7 DISCUSSION AND CONCLUSIONS

Warm season hydrological processes such as rainfall, snow and ice melt, surface runoff and evaporation cease to be active in the winter, when intense cold together with snow and ice cover restrict moisture exchanges between the land, the water surface and the atmosphere. Then, other than rivers with discharge dominated by lake outflow, streamflow of the Mackenzie system switches from a surface-flow controlled summer regime to a groundwater-flow dictated winter regime.

Hydrometric data from the past four decades indicate that summer flow has a weak negative trend, except in the northern Shield and Plains with myriad lakes. In winter, the negative trend intensifies in the southern corner but the trend in the north reverses to become positive. Given that the trends are genuine, possible mechanisms that lead to winter rise in river flow include precipitation increase in late summer that enhances basin storage to sustain higher baseflow, and permafrost degradation that augments contribution from ground ice melt and develops subterranean pathways to facilitate groundwater discharge. These factors need not be mutually exclusive and can reinforce each other. Permafrost, for example, is one of the environmental conditions that respond to air temperature but itself influences runoff production and delivery. In the absence of definitive confirmation of one or more hypotheses, continued investigation is warranted.

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