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Runoff Generation in a High Boreal Wetland in Northern Canada

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The stable isotope composition of water and major-ion concentrations were measured in a small catchment tributary to Manners Creek, situated in the zone of discontinuous permafrost near Fort Simpson, Northwest Territories. Hydrograph separation calculations based on $\delta^{18}O$ and $\delta^{2}H$ values of snow, active-layer water, and streamflow reveal that snowmelt contributions were secondary to active-layer storage contributions throughout the spring freshet period of 1990. At the time of peak spring runoff an estimated 40 to 50 % of streamflow was contributed by snowmelt, while over the entire spring period only 25 to 30 % of streamflow was contributed by snowmelt. Overland and pipe flow are shown to be important mechanisms of rapid snowmelt runoff from permafrost slopes.

Introduction

This study focuses on the hydrologic regime of the wetland-dominated terrain that blankets an approximate 400 km-wide corridor of Canada's Interior Plains extending from the Western Cordillera eastward to Great Slave Lake. This zone forms a significant portion of the Liard River catchment, the principle tributary of the Mackenzie River north of 60°N. Near-surface hydrology of this region is strongly influenced by the presence of discontinuous permafrost.

Accurate predictive modelling of runoff from such catchments requires a detailed knowledge of the various flow sources and pathways; information that cannot be readily obtained by standard hydrometric methods, which often fail to provide even simple estimates of total spring runoff in such complex terrain. As a first step in understanding the mechanisms of runoff generation, an alternate investigative approach is adopted incorporating the use of naturally occurring stable isotopes, oxygen-18 and deuterium, to trace the dynamics and interaction of snow, groundwater, and tributary discharge. ^{18}O and ^{2}H, which are incorporated within the water molecule ($^{1}H^{1}H^{18}O$, $^{1}H^{2}H^{16}O$) are almost ideal tracers due to systematic variations in their abundance in snow, rain, groundwater and other hydrologic components, and their conservative behaviour during mixing.

Hydrograph separation using oxygen-18 and deuterium has been widely applied in examining the role of basin storage in snowmelt and storm runoff generation (*e.g.* Dinçer *et al.* 1970; Fritz *et al.* 1976; Sklash *et al.* 1976; Sklash and Farvolden 1979; Herrmann and Stichler 1980; Fontes 1980; Herrmann *et al.* 1981; Ombradovic and Sklash 1986). Most studies have utilized a steady-state mass-balance relationship to partition overall discharge into volumetric quantities of "old" water (pre-storm or pre-melt groundwater) and "new" water (rainfall or snowmelt). According to Sklash and Farvolden (1979) the volume of new water, Q_N, contained within the instantaneous total discharge, Q_T, is given by

$$Q_N = Q_T \frac{\delta_T - \delta_O}{\delta_O - \delta_N} \tag{1}$$

where δ_T, δ_O, and δ_N are the isotopic compositions of stream water, old water and new water, respectively.

Isotope hydrograph separation has been used extensively to document the dynamics of groundwater discharge during storm and snowmelt events (Fontes 1980). In a wide range of hydrologic settings, groundwater has been shown to play an active or dominant role in event runoffs, commonly accounting for 30-70% of instantaneous volumetric outflow at the time of peak runoff.

Although isotope tracer studies have focused on catchments in sub-humid to humid climates, similar responses have been observed in permafrost terrain. For a southern Baffin Island catchment near Iqaluit, N.W.T., Ombradovic and Sklash (1986) demonstrated that up to 50% of instantaneous volumetric discharge and 60% of total stream discharge is comprised of old water (stored groundwater), indicating considerable interaction between meltwater and active-layer water during spring runoff. This is a significant result considering that freshet discharge in some permafrost catchments has been directly attributed to snowmelt runoff (*e.g.* Roulet and Woo 1986). Ombradovic and Sklash (1986) proposed that a high content of groundwater in the freshet runoff is the result of infiltration of meltwater which, in turn, displaces subsurface water from the melting active-layer. Hillslope runoff was inferred to be predominantly *via* subsurface flow pathways for both new and old water.

A similar approach to that of Ombradovic and Sklash (1986) was adopted in this study, however, the difficulty encountered in measuring discharge in the study catchment, primarily due to the presence of channel icings, prevented determination of absolute quantities of old and new water in the discharge. Instead, proportionate mixing of these components in the spring discharge was determined by solving for Q_N/Q_T in Eq. (1). For the hydrograph separation, average measured values of the isotopic composition of the snowpack are used for new water contributions (δ_N), and average measured values of the isotopic composition of groundwater, baseflow and icings are used for old water contributions (δ_O).

Previous studies have suggested that use of snowpack values for δ_N ignores the compositional changes that may occur as rainfall is added to snow during the course of the melt period (Hooper and Shoemaker 1986). In the present study rainfall effects are considered to be a minor source of error in δ_N as only trace precipitation was recorded during the entire melt period. Other studies have indicated that the processes of sublimation, melting, and meltwater percolation in a snowpack may alter meltwater compositions (Moser and Stichler 1980). No detailed sampling of temporal variations in melt water was conducted during this study. Errors inherent in assuming a simple two-point mixing system proposed in Eq. (1), although slight, are evident where small discrepancies in Q_N/Q_T estimates based on oxygen-18 and deuterium are observed. Overall, a good agreement between the two tracers suggests that the model assumptions are reasonable. The determination of relative contributions of old and new water in streamflow is shown to be valuable in assessing the relative importance of runoff mechanisms throughout the spring period. In particular, we establish that overland flow and pipe flow on permafrost slopes are rapid sources of peak runoff, and that groundwater interaction occurs even in the spring when the ground is frozen. Where available, physical measurements are also shown to support these conclusions. In comparison, geochemical tracers are less effective in monitoring the freshet runoff response due to non-conservative behaviour from contact with substrate mineral phases. However, HCO_3^- and SO_4^{2-} are shown to be useful qualitative indicators of runoff transit times and flow depths.

Study Area

Manners Creek drains an estimated 300 km^2 of wetland terrain, near Fort Simpson, N.W.T. (Fig. 1). Permafrost in the region exists predominantly beneath north-facing slopes and in areas with thick peat accumulation. These terrain types account for an estimated 10-25% of the regional land surface (Kay *et al.* 1983; Rennie *et al.* 1981).

Two main topographic zones are present in the catchment (Craig 1991). Extensive, flat headwater regions (Zone 1) are dominated by organic fens and small lakes. Local unsaturated areas occur where sand and peat ridges rise above the water table. Vegetation in the fens and along lakeshores consists of anchored or floating mats of sedge with minor dwarf birch and tamarack. Sand and peat ridges are vegetated by white spruce-aspen forest and black spruce-spagnum forest, respectively.

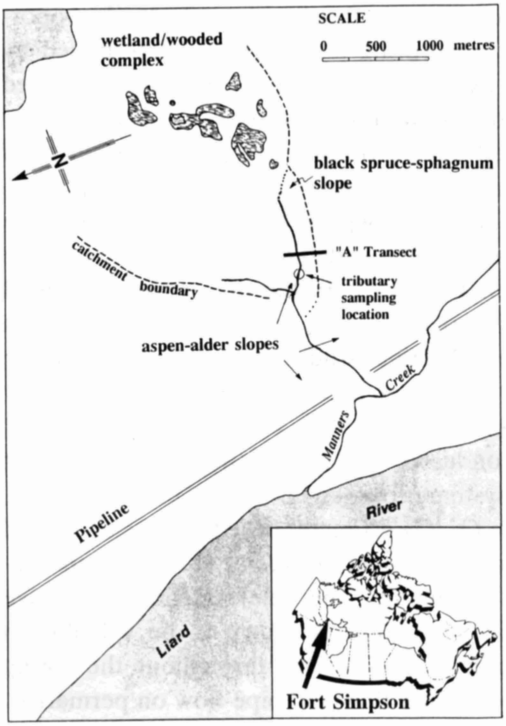

Fig. 1.
Location map of the Manners Creek study catchment near Fort Simpson. Northwest Territories (redrawn from Craig 1991).

Steeper, incised regions (Zone 2) occur lower in the drainage network where a regular pattern of tributary channels links Manners Creek and headwater regions. Topographic gradients range from 1 m/km in the headwater regions to 5 m/km in incised regions of the catchment.

Surficial deposits include organic muskeg (0.5 to 3.0 m) which blankets unconsolidated sediments consisting of sand or silty sand (0.5 to 4.0 m), and a deeper clay to silty clay unit ($\geqslant$ 15 m). Muskeg is discontinuous or absent on sand ridges and south-facing slopes.

Detailed investigations focused on a small tributary drainage area typical of incised regions of the Manners Creek watershed (Fig. 1). North-facing slopes with black spruce-spagnum forest were found to be underlain by permafrost, whereas south-facing slopes with aspen-alder forest were unfrozen (Fig. 2).

Although no hydrometric data are available for the Manners Creek watershed, streamflow records are available for five similar catchments near Fort Simpson ranging in size from 542 km^2 to 20,200 km^2. Wetland rivers commonly begin to freeze by mid-October and low to negligible flows occur throughout the winter months. Typically as little as 1-5% of annual discharge occurs through December to March. Icings are common in small streams where continued or periodic discharge of active-layer water occurs throughout the freeze-back period. Spring runoff generally begins in late April to early May, with discharge during these

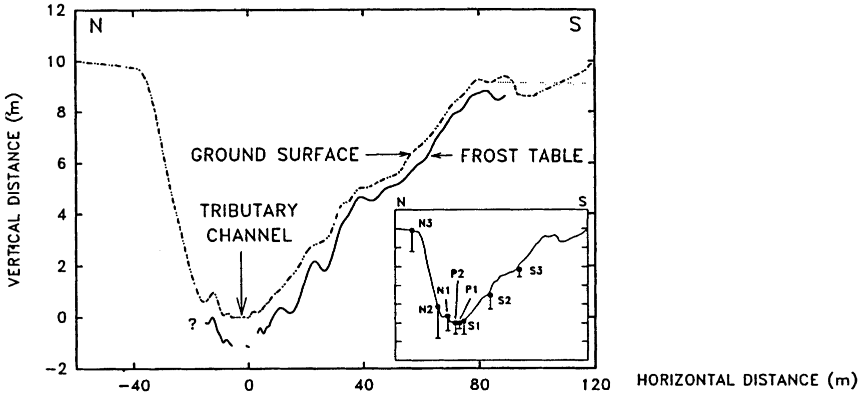

Fig. 2. Profile of the study tributary at 'A' transect showing the frost table depth in late August 1990. Note the shallow active layer beneath north-facing slopes and unfrozen conditions in south-facing slopes. Inset shows position and depths of monitoring wells.

months accounting for 30-60% of annual runoff. During 1990, when average annual runoff for these basins was 91 mm, the freshet period (April 15 to May 15) yielded 29 mm or 32% of the annual total (Environment Canada 1991).

Water Sampling and Analysis

Water sampling was conducted during the late-winter (March), spring-melt (April through June), and summer periods (July through September) of 1990. Reconnaissance investigations in July and September 1989, are described by Craig (1991). During 1990, water samples for oxygen-18 and deuterium analyses were gathered at various locations within the tributary basin, and at the mouth and headwaters of Manners Creek. Groundwater was sampled in wells installed along a representative transect ('A' transect; see Fig. 1). Streamflow samples were taken in the tributary immediately downstream of the 'A' transect wells. Sampling was conducted daily during the spring melt period and roughly at 10 day intervals in the later season. Water samples were returned to the Environmental Isotope Laboratory, University of Waterloo for measurement of $^2H/^1H$ and $^{18}O/^{16}O$ ratios by the methods of Epstein and Mayeda (1953) and Coleman *et al.* (1982), respectively. Prior to analysis, extraction of pore water from soil cores was accomplished by azeotropic distillation (Environmental Isotope Laboratory 1989). Isotopic composition is expressed in terms of $^2H/^1H$ and $^{18}O/^{16}O$ ratios, represented by "δ" values signifying the deviation in parts per thousand (‰) from a designated standard. Values are cited with respect to SMOW (Standard Mean Ocean Water), such that $\delta_{sample}=(R_{sample}/R_{SMOW}{}^{-1})\times 1000$, where R = $^2H/^1H$ or $^{18}O/^{16}O$ measured in sample and standard (see Fritz and Fontes 1980). Analytical uncertainties are $\pm 2‰$ for δ^2H and $\pm$ 0.2‰ for $\delta^{18}O$.

Water samples for major-ion geochemistry were filtered (0.45 μm), preserved, and returned to the National Hydrology Research Institute for analysis in accordance with the methods outlined in Environment Canada (1979).

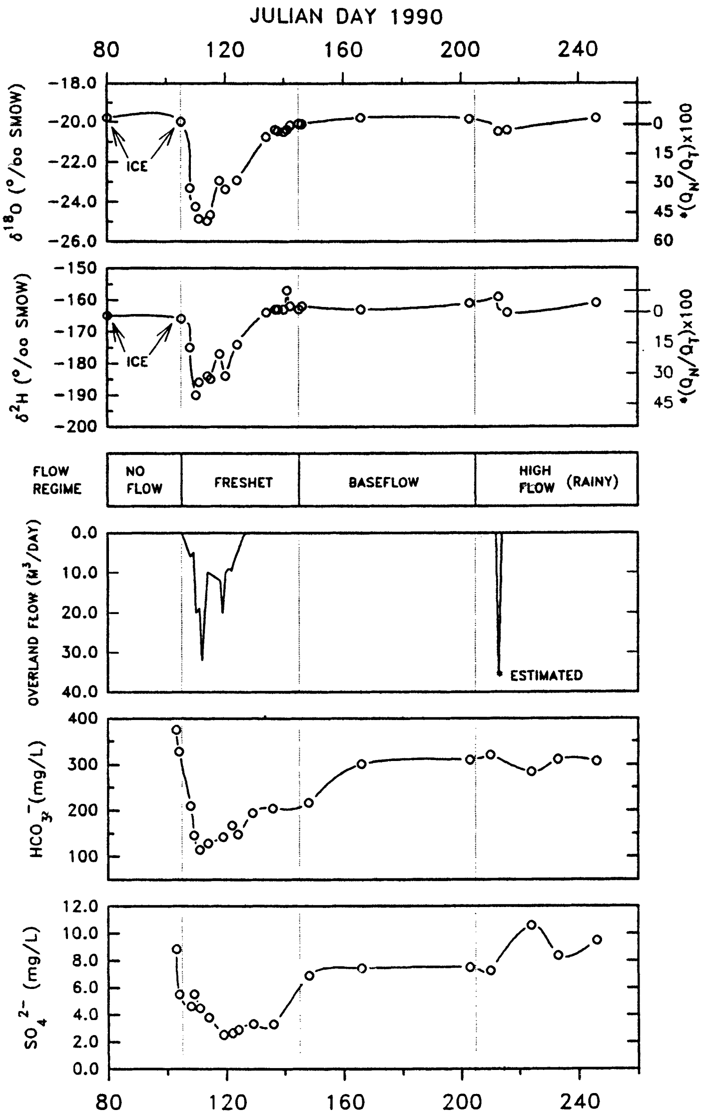

Fig. 3. Temporal variations of isotopic and geochemical contents in streamflow. Also shown, overland flow discharge from a permafrost-slope runoff plot (redrawn from Reedyk 1991). See text for description. * Approximate snowmelt water contribution as indicated by the instantaneous δ^{18}O or δ^{2}H value of streamflow. Refers to freshet period only.

Water Chemistry

Chemical parameters have often been used to perform hydrograph separations where conservative or near-conservative mixing relationships can be established for old and new water sources (*e.g.* Ombradovic and Sklash 1986, Fritz *et al.* 1976). In the study catchment, such an analysis is not warranted as it is apparent that concentrations of HCO_3^- and SO_4^{2-} and other major ions in snow are modified during the course of runoff by interaction with overburden materials (Craig 1991). The existence of complicated geochemical interactions is revealed by the poor correlation of streamflow HCO_3^- and SO_4^{2-} with streamflow $\delta^{18}O$ and δ^2H concentrations, and overland flow contributions (see Fig. 3). Nevertheless, geochemical parameters provide useful background information on runoff sources and pathways.

Mineral-water interaction in the study basin has been described by Craig (1991). Surface waters and shallow active-layer waters are generally close to saturation with calcite ($CaCO_3$), and dolomite ($CaMg[CO_3]_2$), reflecting dissolution of abundant soil carbonates in surficial sand layers. In addition, deep active-layer waters display high SO_4^{2-} concentrations resulting from dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) in underlying clay and clay-silt layers.

A general correlation was observed between streamflow HCO_3^- and SO_4^{2-} concentrations and the tributary flow regime (see Fig. 3). Similar correlations were observed for Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and Total Dissolved Solids (Gibson 1991; Craig 1991). Relatively high HCO_3^- and SO_4^{2-} concentrations were measured during baseflow periods when streamflow was fed predominantly by flow through the active-layer sand unit. In contrast, low HCO_3^- and SO_4^{2-} concentrations were observed during the spring freshet period when streamflow was fed by both active-layer water and snowmelt runoff via overland and pipe flow pathways. In addition, an increase in streamflow SO_4^{2-} concentrations was observed during the later thaw season in response to deepening of the active layer within clay and clay- silt layers.

Results

Winter Storage

Tributary flow during the spring melt period originated from three primary sources; namely, snow, icings, and groundwater. Physical and isotopic inventories of these winter storages were conducted prior to spring melt. $\delta^{18}O$ and δ^2H values of the various waters are summarized in Table 1. The mean snow water equivalent in the tributary catchment was 110 mm and six integrated snowpack samples had fairly uniform values of $\delta^{18}O$ and δ^2H, averaging −29.6‰ and −228‰. Icings, which occurred mainly in the tributary channel were typically 5-7 m wide and 1-2 m thick, with an average water-equivalent volume of 5 m^3 per metre of channel.

Table 1 – Summary of isotopic compositions of selected waters.

Source		n	$\delta^{18}O$ (1 σ)	$\delta^{2}H$ (1 σ)
Snow		6	−29.6 (0.6)	−228 (7)
Icings		9	−20.7 (0.5)	−168 (9)
Baseflow		8	−19.9 (1.2)	−161 (4)
Groundwater (post-freshet)	A. non-permafrost slopes	0	N.A.	N.A.
	B. permafrost slopes	13	−20.6 (0.4)	−164 (5)

Icings were cored and depth profiles were sampled for stable isotopes. The $\delta^{18}O$ and $\delta^{2}H$ content of icings (−20.6‰, −168‰) was found to be similar to late summer active-layer water (−20.6‰, −164‰).

No water samples were obtained from non-permafrost slopes where monitoring wells remained continuously dry. Samples of a late summer permafrost slope soil profile had average $\delta^{18}O$ and $\delta^{2}H$ values of −20.6‰ and −164‰, similar to active-layer water sampled in monitoring wells in late summer (−20.6‰, −165‰). This is slightly enriched compared to mean annual precipitation (−21.0‰, −174‰; see Gibson *et al.* 1993). Average tributary baseflow had moderately higher average $\delta^{18}O$ and $\delta^{2}H$ values than active-layer groundwater (−19.9‰, −161‰), which is attributable to admixture of evaporated surface water (see Gibson *et al.* 1993).

Snow and Active-Layer Contributions to Streamflow

In 1990, spring tributary flow began on 15 April (Julian Day 105) over channel icings. Peak tributary flow was observed between 20 and 24 April (JD 110-114), and declined gradually over a period of several weeks. Although no detailed discharge record is available, rough measurements were made using a Price Type AA current meter. Maximum daily discharge in the small tributary catchment during the melt period is estimated at 800 to 1,000 m^3/day, with an average daily discharge ranging from 300 to 400 m^3 (Reedyk 1991).

Temporal variations in streamflow $\delta^{18}O$ and $\delta^{2}H$ are shown in Fig. 3. $\delta^{18}O$ and $\delta^{2}H$ reached minimum values of −25.0‰ and −190‰ during the peak discharge period and slowly returned to values typical of baseflow (−19.9‰, −161‰) by 15 May (JD 135). If snowmelt was the dominant source of runoff during the freshet period, tributary $\delta^{18}O$ and $\delta^{2}H$ values should have been close to that of snow (−29.6‰, −228‰). As $\delta^{18}O$ and $\delta^{2}H$ values were considerably heavier, it is apparent that runoff also contained water derived from the active layer. Active-layer contributions to streamflow were evidently significant at the time of peak discharge and became more and more dominant as the freshet period progressed.

Calculations were carried out using Eq. (1) to quantify proportionate mixing of new and old water contributions to streamflow. In the calculations used for the separation, $\delta^{18,2}{}_N = -29.6‰, -228‰$ and $\delta^{18,2}{}_O = -20.4‰, -166‰$; δ_N representing the mean snowpack composition, and δ_O representing an average of the mean compositions of baseflow, icings, and active-layer water. At the time of peak runoff new water represented 40 to 50 % of the streamflow, whereas over the entire freshet period new water represented only 25 to 30 % of the streamflow.

Contributions of icing ablation to streamflow were examined by Reedyk (1991) concurrent with this study. Reedyk (1991) determined that icing ablation accounted for approximately 6 % of freshet streamflow, which suggests that the majority of old water was derived from active-layer sources.

Runoff Sources and Pathways

Contributions of non-permafrost slope waters are considered to be minimal in view of the unsaturated conditions observed throughout the 1989 to 1990 period. Snowmelt occurred earlier here than on permafrost slopes, with no observed overland or subsurface flow. A deep water table (> 3.4 m) within clay to silty clay would further indicate only minor potential for deeper groundwater flow.

On permafrost slopes, snowmelt occurred during 15 April to 1 May (Julian Day 105-120). Shallow active-layer water sampled in monitoring wells during the melt period was found to have $\delta^{18}O$ and δ^2H values intermediate between late-season active-layer water (old water) and snow (new water), suggesting mixing of these components. Rapid rise in water tables within the shallow active layer (≈ 0.15 m) resulted in runoff *via* overland flow (flow in rills between saturated depressions), and pipe flow (flow in 5-10 cm diameter, 1-10 m long frost cracks situated at or above the mineral soil/organic layer contact). The characteristics of overland flow and pipe flow were comparable to those described in previous studies in similar environments (Woo 1988, Woo and DiCenzo 1988). The timing of overland flow discharge from a small runoff plot is shown in Fig. 3. Although no pipe flow measurements were made, the timing and isotopic similarity of pipe flow and overland flow suggests a similar generation mechanism. $\delta^{18}O$ and δ^2H values of overland flow and pipe flow were found to be heavier than snowpack values, indicating a significant old-water content (Table 2). Q_N/Q_T evaluated from Eq. (1) indicates that 50 to 60 % of instantaneous overland and pipe flow discharge is derived from over-winter active-layer storage (*i.e.* water existing prior to snowmelt). Evidently, mixing of snowmelt and *in situ* water occurred in the shallow active layer. As storage capacities were exceeded in the early freshet period, old and new water were delivered to the tributary by surface routes and shallow subsurface routes in pipe structures. Following cessation of overland and pipe flow, the isotopic composition of streamflow rapidly returned to baseflow values. In light

Table 2 – New water proportions in permafrost slope runoff. Note: Q_N/Q_T from Eq. (1). Range indicates $\delta^{18}O$ and δ^2H estimates, respectively.

Runoff component	n	$\delta^{18}O$ (1σ)	δ^2H (1σ)	Q_N/Q_T
Pipeflow	3	−25.6 (0.6)	−195 (7)	0.54-0.47
Overland flow	2	−24.8 (0.1)	−190 (1)	0.46-0.39
Permafrost slope groundwater (freshet)	3	−22.3 (0.9)	−176 (7)	0.22-0.20

of the isotopic similarity between tributary baseflow and late season active-layer waters, replenishment of the tributary during quiescent periods was evidently occurring *via* the active-layer soil matrix. Visual observations during a rainy period in the later thaw season revealed that overland and pipe flow pathways had reactivated, however no detailed isotopic sampling was conducted during this time (see Fig. 3).

Discussion

The high content of old water in streamflow throughout the freshet period of 1990 reveals that groundwater contributions were significant even in the early spring when the ground was frozen below about 0.15 m depth. In view of the striking correlation between variations in overland flow and $\delta^{18}O$ and δ^2H values in the tributary (see Fig. 3) we conclude that overland flow from permafrost slopes was the primary source of peak streamflow.

From the separated hydrograph we have estimated that new water contributions accounted for 25 to 30 % of streamflow during the freshet period in the study catchment. Twenty-five to thirty percent of measured freshet runoff from wetland-dominated catchments in the area is equivalent to 7-9 mm of runoff, based on spring runoff of 29 mm (Environment Canada 1991). Assuming that only permafrost slopes (10 % of the study basin area) were contributing to streamflow, and using measured snowpack water equivalents ($\approx$ 110 mm), we estimate that up to 11 mm of basin runoff could be generated from snow sources on permafrost slopes. This suggests that permafrost slopes were capable of sustaining the entire quantity of snowmelt in streamflow during the freshet period.

A similar calculation indicates that 20-22 mm of spring freshet runoff was from old water sources. Old water contributions from icings are estimated to account for approximately 2 mm of this runoff, with the majority of old water, approximately 198-218 mm, originating from active-layer sources on permafrost slopes.

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