The long-term response of stream flow to climatic warming in headwater streams of interior Alaska[1]

Jeremy B. Jones and Amanda J. Rinehart

Abstract: Warming in the boreal forest of interior Alaska will have fundamental impacts on stream ecosystems through changes in stream hydrology resulting from upslope loss of permafrost, alteration of availability of soil moisture, and the distribution of vegetation. We examined stream flow in three headwater streams of the Caribou-Poker Creeks Research Watershed (CPCRW) in interior Alaska over a 30-year period to determine (i) how stream flow varied among streams draining watersheds with varying extents of permafrost and (ii) evaluate if stream hydrology is changing with loss of permafrost. The three streams drained subcatchments with permafrost extents ranging from 4% to 53%. For each stream, runoff data were analyzed by separating base and storm flow contributions using a local-minimum method and with analysis of flood recession curves, Mean daily runoff during the ice-free season did not significantly vary among streams (mean = 0.57 $mm\cdot d^{-1}$), although the watersheds with lower permafrost had a greater contribution of base flow. Across years, flow was variable and was related with summer temperature in the watershed with low permafrost and with precipitation in the watershed with high permafrost. With climate warming and loss of permafrost, stream flows will become less responsive to precipitation and headwater streams may become ephemeral.

Résumé : Le réchauffement du climat dans la forêt boréale de l'intérieur de l'Alaska aura des impacts fondamentaux sur les écosystèmes lotiques par l'entremise de changements dans l'hydrologie des cours d'eau provoqués par la disparition du pergélisol dans les pentes, la modification de la disponibilité en eau du sol et la distribution de la végétation. Nous avons étudié le débit de trois ruisseaux situés en amont du bassin expérimental de Caribou Poker Creeks à l'intérieur de l'Alaska sur une période de 30 ans. L'étude avait pour but de (*i*) déterminer de quelle façon varie le débit des ruisseaux qui drainent des bassins où le pergélisol occupe différentes superficies et (*ii*) évaluer si l'hydrologie des ruisseaux change avec la disparition du pergélisol. Les trois ruisseaux drainaient des sous-bassins où le pergélisol occupait de 4 % à 53 % de la superficie. Pour chaque ruisseau, les données d'écoulement ont été analysées en séparant la contribution du débit de base et celle du débit d'orage à l'aide de la méthode du minimum local et de l'analyse des courbes de décrue. Le débit journalier moyen durant la saison où il n'y avait pas de glace n'a pas varié de façon significative entre les ruisseaux (moyenne = 0.57 $mm\cdot j^{-1}$) mais les bassins où il y avait le moins de pergélisol contribuaient davantage au débit de base. Le débit variait d'une année à l'autre; il était relié à la température estivale dans le bassin où il y avait peu de pergélisol et aux précipitations dans le bassin où il y avait beaucoup de pergélisol. Avec le réchauffement du climat et la disparition du pergélisol, le débit des cours d'eau va devenir moins sensible aux précipitations et les ruisseaux de tête pourraient devenir saisonniers.

[Traduit par la Rédaction]

Introduction

Climate change is predicted to have greater impacts or high latitudes compared with the rest of our planet Over the last 100 years, the mean surface temperature of the Arctic has increased at a rate 2-fold greater than the global mean (0.74°C·decade^{-1}; IPCC 2007). This warming is not equally distributed throughout the year but is most pronounced during the winter months (ACIA 2005). Consequently, permafrost in Alaska has warmed by 0.05-0.2°C·year^{-1}, which is possibly enough to start thawing discontinuous permafrost (Osterkamp and Romanovsky 1999).

Permafrost has a dominant control on watershed hydrology in the boreal forest of interior Alaska, Permafrost forms a relatively impermeable barrier and restricts subsurface tlows to the shallow active layer of soils. Over summer. as depth of thaw increases, subsurface flow paths through soils migrate deeper and can transition from organic- to inorganic-dominated soil horizons, Soil porosity also decreases along this vertical transition thereby reducing the subsurface runoff velocity from uplands to streams (Quinton and Carey 2008). In regions with discontinuous permafrost, such as interior Alaska, north-facing slopes and valley bottoms are commonly underlain with permafrost, whereas warmer

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south-facing slopes and ridge tops typically lack permafrost. Consequently, groundwater flowing through north- versus south-facing subcatchrnents travels through differenr subsurface flow paths, which has important implications for stream discharge (Bolton et al. 2000).

Stream response to storms differs for permafrost-free and permafrost-affected slopes (Bolton 2006). Stream flow from watersheds underlain with a large proportion of permafrost responds rapidly to precipitation, with rapid rising and falling limbs of storm hydrographs (Quinton and Carey 2008). In contrast, for streams that drain south-facing watersheds with little permafrost, precipitation can percolate into mineral soil layers resulting in greater residence time of water in catchments (Carey and Woo 2001). Stream hydrology may be sensitive to climate change and loss of permafrost with storm flows from watersheds with high permafrost potentially responding less rapidly to precipitation, and flow from watersheds with low permafrost. in tum, becoming ephemeral, particularly from smaller catchments. Stream biogeochemistry is intimately coupled to the response of stream flow to summer rain storms, winter snow, and recharge of soil and ground waters, as well as evapotranspiration (ET). The loss of permafrost under a warmer climate will potentially result in fundamental changes in the hydrologic regime and biogeochemistry of streams.

We examined the long-term hydrographic records of three headwater streams in the Caribou-Poker Creeks Research Watershed (CPCRW), which drained watersheds with varying extents of underlying permafrost to determine the sensitivity of upland stream hydrology to climate warming. Our objectives were to *(i)* determine how stream flow varied among streams draining watersheds with varying extents of permafrost and *(ii)* evaluate if stream hydrology is changing with loss of permafrost. We hypothesized that the rate at which precipitation and storm flows are transmitted to streams is governed by the extent of permafrost and thus the extent of a confining layer in watersheds. Moreover, the rate at which storm flows are released from storage will decline over the active season as the depth of seasonal soil thaw deepens and volume of storage zone increases. Lastly, we hypothesized that over longer time scales, with a loss of permafrost, stream flows will become less responsive to precipitation as volume of storage zone increases and storm flows will contribute less to overall stream discharge.

Methods

Study site

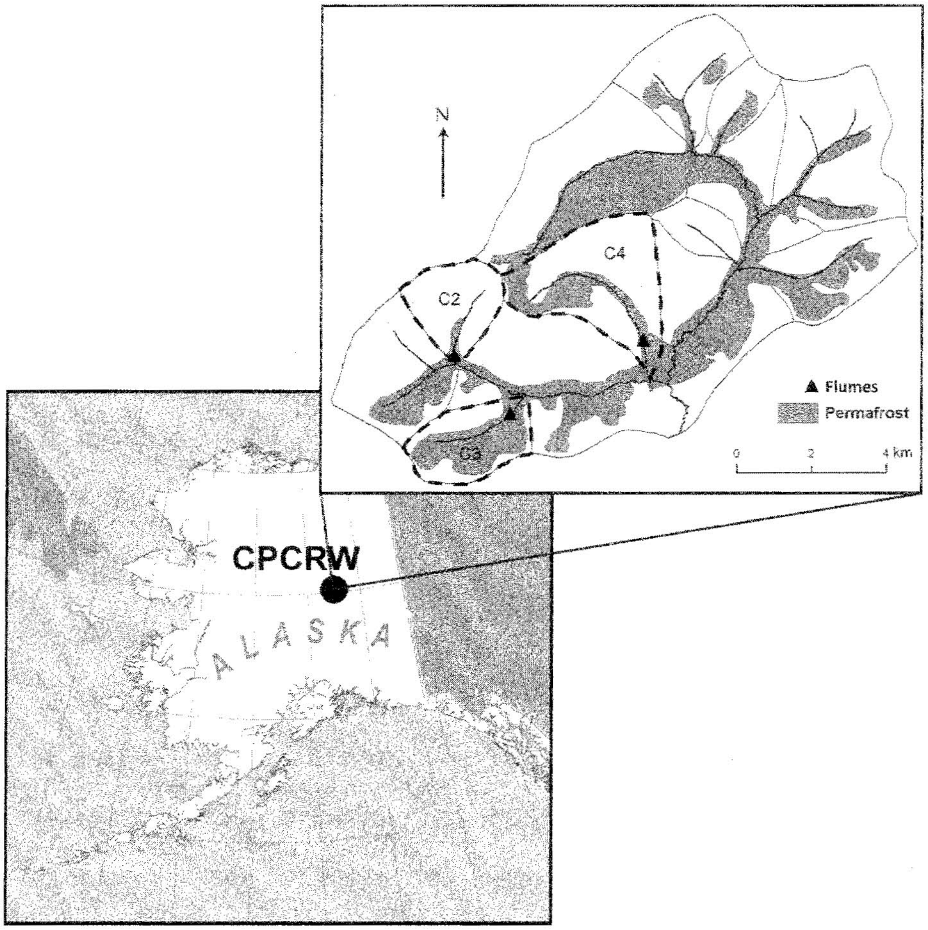
The CPCRW is located northeast of Fairbanks, Alaska (65°N, 147°W), where the climate is continental, with warm summers (mean = 16.4 °C in July). cold winters (mean = -24.9 °C in January), and low precipitation *(270* mm, of which 37% falls as snow; Slaughter and Viereck 1986). The CPCRW is a 104 km^2 watershed reserved for meteorological, hydrologic, and ecological research, and has not been directly affected by human activities. The CPCRW is part of the Bonanza Creek Long-Term Ecological Research (BNZLTER) program and has discharge records of summer stream flows dating from 1978 to present and precipitation records since 1993, Headwater streams of the CPCRW generally have ice-free flow from early to mid-May through late-September or mid-October.

The CPCRW is the only research watershed in the United States in the zone of discontinuous permafrost, where permafrost temperature is near 0 °C and thus vulnerable to loss with small changes in climate or surface-energy exchange (Osterkamp 1983). Within the CPCRW, *38%* of permafrost is unstable and thawing, and at least 2% has been lost over the past century (Hinzman et al. 2006). The distribution of permafrost within the CPCRW is governed by topographic aspect and elevation. Low sun angle creates large differences in solar input and soil temperature between north- and south-facing slopes, with permafrost generally absent on south-facing slopes but present on north-facing slopes and valley bottoms.

The patchy distribution of solar input and permafrost creates a mosaic of plant communities with different rates of hydrologic partitioning between ET and runoff (Bolton et al. 2004). Vegetation types in the study watersheds are typical of the majority of vegetated areas of interior Alaska (Viereck and Little 1972), Uplands are dominated by well-drained hardwood forests (paper birch *(Betula papyrifera* Marsh.), quaking aspen *(Populus tremuloides* Michx.)) on south-facing slopes, and black spruce *(Picea mariana* (P. Mill.) B.S.P.) with feathermoss *(Pleurozium schreberi* (Brid.) Mitt.), moss (genus *Hylocomium* Schimp. in B.S.G., other moss genera), and lichen understories on north-facing slopes. Uplands also have patchy understory of green alder *(Alnus viridis* (Vill.) Lam. & DC.). Valley bottoms are well defined in terms of geomorphology and vegetation (valley width ranges from 30 to 100 m), Soils in valley bottoms are typically saturated with extensive coverage of mosses (genera *Sphagnum* L. and *Hylocomium)* and dwarf shrubs (dwarf birch *(Betula nana* L), willow (genus *Salix* L), bog blueberry *(Vacciniwn uliginosum* L) and patchy coverage of mountain alder (*Alnus incana* ssp. *tenuifolia* (Nutt.) Breitung). Soils on south-facing slopes are typically shallow to moderately deep Inceptisols with thin organic horizons (5-9 cm) and loamy texture, whereas north-facing slopes and valley bottoms are typically poorly drained Gelisols with thick organic horizons (18-52 cm) with permafrost 45-60 cm below the surface (Ping et al, 2005). Geology of the CPCRW is dominated by quartz-mica schists, with some micaceous quartzites, garnet-mica schists. and phyllites (Chapman et al. 1971).

Discharge data for the present study were used from three streams in the CPCRW that drain the C2, C3, and C4 subcatchments of CPCRW (Fig, 1). During the ice-free season, now has been measured at hourly intervals in the C2 and C3 streams since 1978 and in the C4 stream since 1980. All three streams are instrumented with Parshall flumes and stage height has been recorded with Stevens chart recorders, and more recently by pressure transducers and data loggers. Stage height was related to stream discharge by developing rating curves, Because the Parshall flumes have tended to shift across years, rating curves were developed for all streams during most years of record. Data are nearly continuous across years, although several years are missing because of equipment failures. The subcatchments are similar in size with areas for the C2, C3, and C4 catchments of 5.2, 5.7, and 10.0 km^2, respectively, Permafrost extent in the

Fig. 1. Location of the Caribou–Poker Creeks Research Watershed in Alaska, as well as outlines of the major subcatchments, stream channels, and the distribution of permafrost within the research watershed. The three study watersheds are outlined by bold, broken lines.



three watersheds was variable with coverages of 4%, 53%, and 19% in C2, C3. and C4, respectively (Fig,

Methods overview

Patterns of stream discharge among the three streams and changes over time were examined with a hydrograph separation of base and storm flow discharge contributions, and an analysis of storm flow recession curves. Hydrograph separation and recession curve analyses were examined over the ice-free season and across years to test for longer term changes in stream hydrology. For all analyses we used data from the period of 1 June through 30 September (herein referred to as the "active season") and from years 1978 to 2007 for the C2 and C3 streams, and from years 1980 to 2007 for the C4 stream. The start of June was selected to avoid the period of snowmelt Only a few years had reliable snowmelt data, thus preventing an analysis of longer term trends in spring runoff. For all analyses, discharge data were standardized to watershed area and expressed as runoff ($mm \cdot d^{-1}$) to facilitate comparisons across streams.

Hydrograph separation

Hydrograph separation of base and storm flow components of stream runoff was conducted using the local-minimum method (Pettyjohn and Henning 1979; Figs. *2a, 2b*). For the local-minimum method, a sliding window was used to determine local minima in flow across an active season. For each stream, the size of the sliding window (I; d) was calculated from watershed area (*A;* krn-) as

$$[1] \quad I = 10A^{0.1}$$

The sliding window was adjusted for watershed size to account for differences in flow responses owing to differences in catchment contributing area. Base flow then was calculated by linearly interpolating runoff between consecutive nodes of minimum flow (Fig. *2a*). Storm flow was calculated as the difference between total runoff and base flow. Storm and base flows were examined among subcatchments and inter-annually to understand the role of permafrost on stream flow.

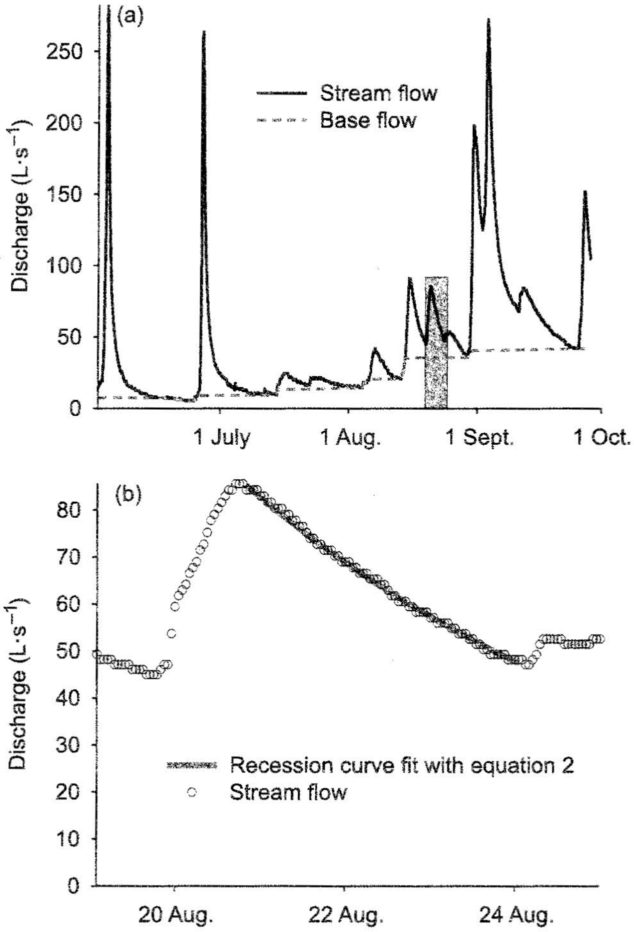
Flood recession analysis

Flood recessions were analyzed for all floods lasting longer than 12 h. For each flood, a recession coefficient (*k:* d-1) was calculated as

$$[2] \quad Q_t = Q_0 e^{-kt}$$

where Q is discharge ($L \cdot S^{-1}$) and t is time (d; Nathan and McMahon 1990; Fig. *2b*). Flood recessions were further ana-

Fig. 2. (*a*) Example hydrograph from the C3 stream for 1995 illustrating the results from the local-minimum method of hydrograph separation and (*b*) the flood recession analysis for one flood from 20–24 August 1995.



lyzed for each stream and year by comparing recession coefficients *(k)* with the day of year *(t)* using linear regression to determine if recession coefficients changed in magnitude over the active season. From our hypotheses, we predicted that recession coefficients for individual storm recession curves would decline over the active season as volume of storage zone increased with increasing depth of thaw. Because recession curves have a negative slope, the predicted change over the active season translates to recession curve coefficients becoming more positive in magnitude, and the regression of recession coefficients versus day of year having a positive slope.

Additional data and statistical analyses

A 3-fold approach was used to analyze the stream now data. First, comparisons were made among the three streams. Second, intra-annual patterns were examined for changes in stream flood response over the active season. Third, for each stream, inter-annual patterns were analyzed to determine if stream hydrology changed over the period of record. Inter-annual analyses included examining if seasonal changes in now varied across years,

Precipitation data were obtained from the National Weather Service at the Fairbanks International Airport. Data were used from the airport because a complete record spanning the period of stream flow measurements was not available from the CPCRW.

Differences among watersheds were tested with one-way analysis of variance using time-weighted active season means. Tukey's post hoc rest was used to test for significant differences among means. Inter-annual patterns in stream hydrology from the hydrograph separation and the seasonal recession response were tested with multiple linear regressions with year, precipitation, temperature, total snow accumulation from the previous winter (as water equivalents). and previous mean winter temperature as independent variables. To test for an intra-annual change in storm flow response, the storm flow recession curve coefficients *(k)* were regressed against the day of year. For all statistical analysis, a *P* value of 0.10 was used for significance. A value of 0.10 was selected because the goal of the study was to detect longer term trends in a data set that is inherently variable owing to inter-annual variation in climatic conditions.

Results

Precipitation, total stream flow, base flow, and storm flow

From 1978 through 2007, daily precipitation during the active season averaged 1.75 $mm{\cdot}d^{-1}$ (Table 1) but varied nearly 4-fold from a low in 2004 of 0.66 $mm{\cdot}d^{-1}$ to a high of 2.49 $mm{\cdot}d^{-1}$ in 1990 (Fig. 3)..Runoff did not significantly vary among the three streams $(P = 0.46)$, averaging 0.57 $mm{\cdot}d^{-1}$ (Table 1, Fig. 4). Although the mean daily stream flow was similar, the contribution of base flow and storm flow significantly varied among streams. The mean daily base flow from the watershed with high permafrost averaged 0.23 $mm{\cdot}d^{-1}$ compared with 0.46 and 0.49 $mm{\cdot}d^{-1}$ in the C2 and C4 streams, respectively (Fig. 4). Compared with total runoff, the base flow contribution in the watershed with high permafrost was only 44% of total flow, whereas in the watersheds with lower permafrost, base flow accounted for 81% of Bow, on average (Table 1). Relative to precipitation, total stream flow from watersheds was, on average. 32% of active season precipitation.

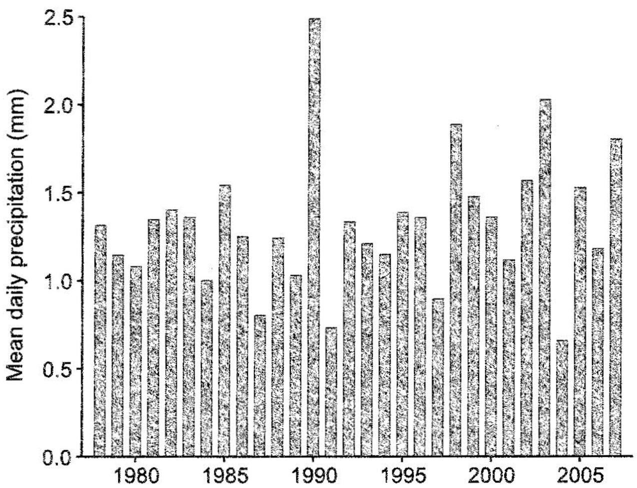
Total stream flow, base flow, and storm flow did not significantly change across years in any of the streams (Table 2). Runoff was variable across years, with the variability most pronounced in the smaller catchments (Fig. Flow in the C2 and C3 streams, which drained the smaller watersheds, varied 6.9- and 7.3-fold across years, whereas flow in the C4 stream varied 3.7-fold. Stream Bow from the watershed with lowest permafrost *(C2)* tended to be related with temperature, whereas How from the watershed with high permafrost *(C3)* tended to be related with precipitation (Table 2). In the C2 stream, total stream tlow and base flow were significantly related with temperature (Table 2). In the C3 stream, total flow and storm flow were significantly related with mean daily precipitation during the active season (Table 2). Interestingly, stream flow from the watershed with medium permafrost *(C4)* was not significantly related with precipitation or temperature (Table 2). Lastly, in all

Table 1. Catchment area, permafrost extent, and hydrology of the three study watersheds.

	Stream		
	C2	C3	C4
Watershed area (km^2)	5.2	5.7	10.0
Permafrost extent (%)	4	53	19
Precipitation ($mm \cdot d^{-1}$)	1.75±0.075	1.75±0.075	1.75±0.075
Temperature (°C)	13.5±0.17	13.5±0.17	13.5±0.17
Runoff ($mm \cdot d^{-1}$)	0.58±0.056	0.52±0.044	0.60±0.046
Base flow ($mm \cdot d^{-1}$)	0.46±0.046a	0.23±0.024b	0.49±0.041a
Storm flow ($mm \cdot d^{-1}$)	0.12±0.014a	0.29±0.030b	0.11±0.009a
Base flow (%)	79±1.7	44±2.6	82±1.5
Runoff to precipitation ratio (%)	34±3.7	31±2.8	37±4.3
Storm flow recession (d^{-1})	29±2.0a	33±2.2a	18±1.7b

Note: Temperature and precipitation data are from the Fairbanks International Airport. Values are mean ± SE. Significant differences among streams are indicted with letters.

Fig. 3. Mean daily precipitation at the Fairbanks International Airport for the period from 1 June through 30 September from 1978 to 2007.



three watersheds, base flow was significantly related with the previous winter snowfall (Table 2).

Flood recessions

The rate of flow recession during storms was nearly 2-fold greater in the streams draining the smaller watersheds (C2 and C3) compared with the stream draining the largest watershed (C4). Storm flow recession averaged 0.31 d^{-1} in the C2 and C3 streams compared with a mean rate of 0.18 d^{-1} in the C4 stream. The rate of flow recessions did not significantly change over the active season in the C4 stream but did significantly decline in the two smaller streams (C2 and C3: $P < 0.05$; Fig,5). In the C2 stream, flood recessions declined 0.0016 $d^{-1} \cdot d^{-1}$ whereas in the C3 stream, recessions declined 0.0027 $d^{-1} \cdot d^{-1}$. Across years, the seasonal change in flow recessions was negatively related with precipitation in the C2 stream, whereas in the C3 stream, the season change in flow recessions was negatively related with temperature (Table 2, Fig. 6). Across years, the seasonal change in flow recessions significantly increased in the C2 stream (Table 2, Fig, 7). In other words, in the watershed with low permafrost, flood recessions underwent a greater change over the active season early in the period of record compared with later.

Fig. 4. Mean daily runoff and base flow runoff calculated using the local-minimum method in the C2, C3, and C4 streams of the Caribou–Poker Creeks Research Watershed (from 1978 to 2007 for C2 and C3 and from 1980 to 2007 for C4).

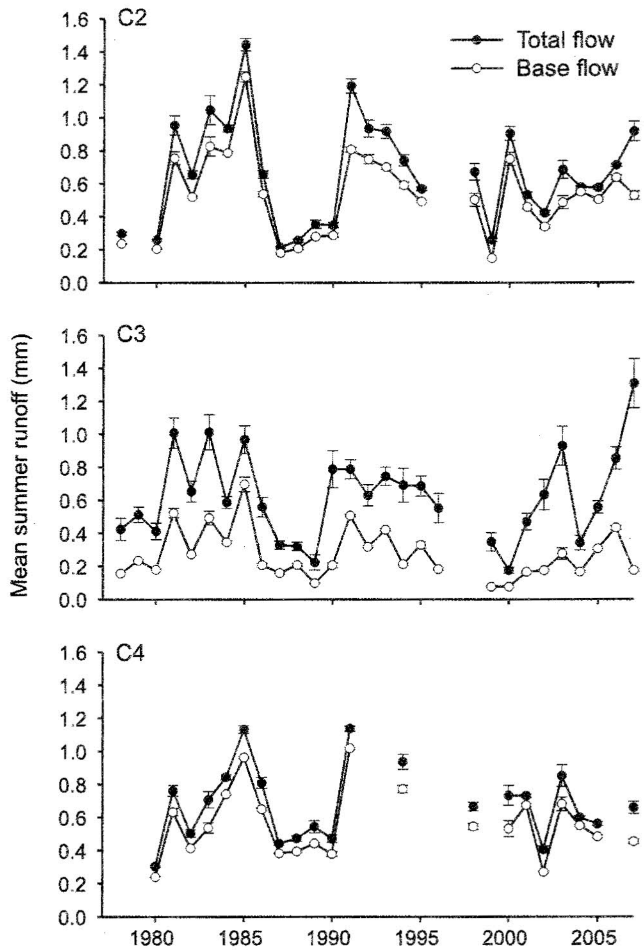


Table 2. Multiple regression coefficients for the mean stream flow, base flow, storm flow, and seasonal flood recessions. Mean base flow and storm flow were calculated from the hydrograph separation analysis, whereas seasonal flood recessions were calculated from recession curve analysis.

Parameter	Year	Summer precipitation (mm)	Summer temperature (°C)	Previous winter snow total (mm)	Previous winter temperature (°C)	r^2
C2						
Runoff (mm)	–0.003	**0.229***	**–0.106***	**0.003**†	–0.002	0.325
Base flow (mm)	–0.004	**0.200***	**–0.094***	**0.003**†	–0.003	0.370
Storm flow (mm)	0.001	0.029	–0.012	0.001	0.001	0.000
Flood recession ($d^{-1}\cdot d^{-1}$)	**0.013***	**–0.355***	–0.116	–0.001	0.003	0.190
C3						
Runoff (mm)	0.003	**0.216***	–0.001	0.001	0.020	0.015
Base flow (mm)	–0.002	0.067	–0.010	**0.002**†	0.017	0.292
Storm flow (mm)	0.004	**0.149***	0.009	–0.001	0.003	0.131
Flood recession ($d^{-1}\cdot d^{-1}$)	0.004	–0.066	**–0.204***	–0.001	–0.009	0.265
C4						
Runoff (mm)	–0.003	0.257	–0.040	**0.003**†	0.019	0.130
Base flow (mm)	–0.003	**0.244***	–0.017	**0.003**†	0.025	0.198
Storm flow (mm)	0.001	0.012	–0.023	–0.001	–0.006	0.000
Flood recession ($d^{-1}\cdot d^{-1}$)	–0.008	0.103	–0.029	–0.001	0.014	0.000

Note: Values in boldface type are significant at $P < 0.10$. *, $P < 0.10$; †, $P < 0.05$.

Discussion

Discontinuous permafrost and stream hydrology

The presence or absence of permafrost has a profound impact on water storage, water recharge, and runoff from hill slopes in upland catchments of the boreal forest. For hill slopes lacking permafrost, near-surface fluxes of water tend to be dominated by recharge during snowmelt and from summer precipitation, and losses owing to ET, deep ground water recharge, and stream now (Carey and Woo 1999). At the onset of winter, soils on hill slopes Jacking permafrost are typically relatively dry (Carey and Woo 1999). Over winter. moisture migration from soils to the overlying snowpack further desiccates soils (Santeford 1978), although the magnitude of water lost is small given the low moisture content at the onset of winter. Snowmelt is the dominant hydrologic event of the year. For hill slopes lacking permafrost, recharge is high during snowmelt and serves to be the dominant inflow of water into soil (Carey and Woo 1999), Over the summer, soil moisture is controlled by ET and precipitation. Potential ET frequently exceeds precipitation (Bolton et al. 2004), depleting soil moisture.

On hill slopes underlain with permafrost, soils are relatively moist at the start of winter compared with south-facing slopes owing to the permafrost acting as a confining layer (Carey and Woo 1999), Over winter, vapor derived from organic soil migrates upward creating hoar at the base of the snowpack (Santeford 1978). Also, water migrates within the soil toward the organic-mineral interface creating an ice-rich zone. With snowmelt, the ice-rich layer causes overland flow. For water that infiltrates, the depth of thaw is shallow, limiting subsurface flows to the near surface of the soil. As a consequence, on slopes with permafrost, lateral flows dominate during snowmelt (Carey and Woo 1999). Over summer. ET from coniferous stands of permafrost slopes is less than the hardwood stands of south-facing slopes and in most years similar to precipitation (Bolton et al. 2004). As a result, at the end of summer. soil moisture is likely greater on slopes with permafrost underlain compared with those lacking permafrost,

In all three watersheds of the present study, base How runoff was significantly related with snowfall the previous winter likely because of recharging of subsurface water storage during snowmelt (Table 2). In the watershed with lower permafrost, base flow also was related to summer precipitation (C2 and C4) and temperature (C2), indicating that base now is a function of not only winter recharge but also summer ET. During wetter summers. precipitation exceeds ET, reducing the seasonal draw-down in soil moisture and providing greater water availability for stream flow. In contrast, in the watershed with high permafrost. base now was not related to summer precipitation or temperature. indicating that ET had a reduced intfuence on stream base flow.

Storm flow in the watershed with high permafrost was significantly related to summer precipitation, whereas storm flow in the watersheds with lower permafrost was not related with the weather variables analyzed (Table 2). In the watershed with high permafrost, summer precipitation is confined to the near surface, resulting in rapid delivery to the stream channel and increased storm flow contributions. In contrast, in the watersheds with lower permafrost, precipitation can infiltrate into soil and the water is not rapidly delivered to streams but instead feeds either base now or ET (Carey and Woo 1999).

The mean rate of runoff from the watershed with high permafrost was related to summer precipitation, whereas the mean rate of runoff in the watersheds with lower permafrost was related to both summer weather conditions and amount of soil water recharge from winter snow (Table 2). These couplings with seasonal weather conditions have interesting implications for stream flow from watersheds with varying extents of permafrost. Stream flow from watersheds with high permafrost will be most susceptible to changes in summer precipitation, whereas streams draining watersheds

Fig. 5. Stream flow recession response (d^{-1}) versus day of year for the Caribou–Poker Creeks Research Watershed from 1978 to 2007 for the C2 and C3 streams and from 1980 to 2007 for the C4 stream. In the C2 stream, flood recessions significantly ($P < 0.05$) declined 0.0016 $d^{-1} \cdot d^{-1}$, whereas in the C3 stream, recessions declined 0.0027 $d^{-1} \cdot d^{-1}$.

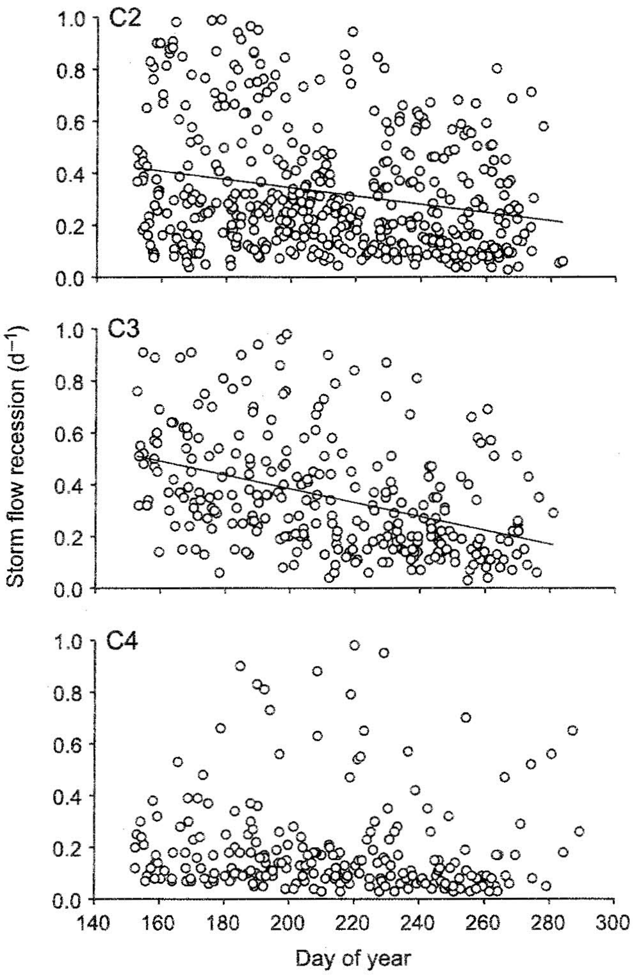


Fig. 6. Seasonal change in storm flow recessions in the C2, C3, and C4 streams versus mean active season temperature and precipitation. Fitted lines show significant ($P < 0.05$) changes in seasonal recessions.

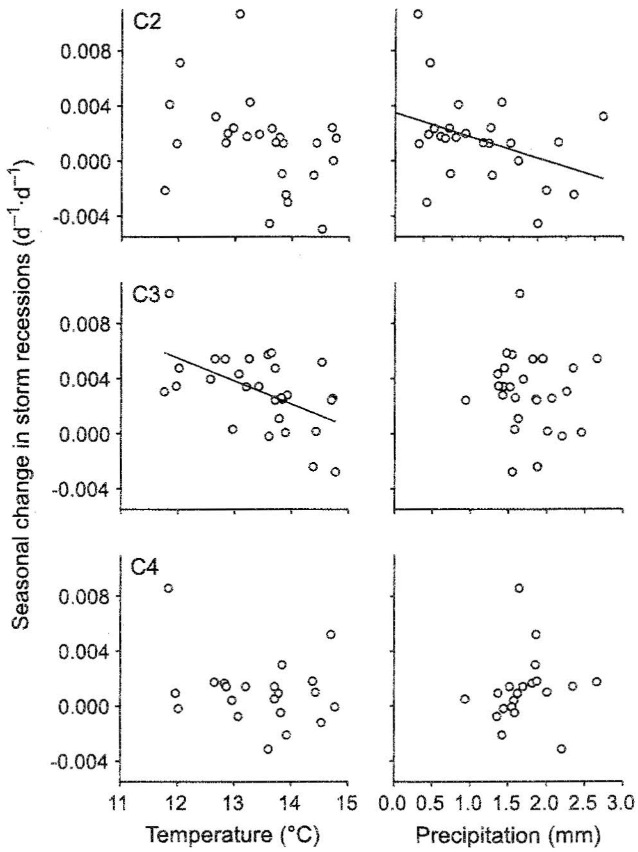
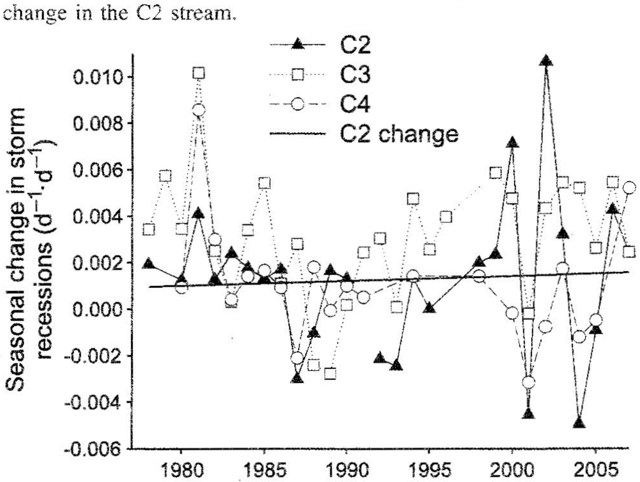


Fig. 7. Seasonal change in storm flow recessions in the C2, C3, and C4 streams versus year. The fitted lines show significant ($P < 0.05$) change in the C2 stream.



with lower permafrost may be most affected by changes in winter snow accumulation.

In addition to differences in mean runoff rate and the contributions of base and storm flows, the slopes of flood recessions varied among streams. Across all years, the slopes of flood recession curves declined over the summer in the C2 and C3 streams (Fig. 5). In other words, floods declined at a slower rate later in the active season. In the watershed with high permafrost (C3), the decline in flood recessions over the active season was related to mean active season temperature (Table 2, Fig. 6); the seasonal change in flood recession curves was greatest in cooler years. The decline in Hood recessions in the watershed with high permafrost is likely due to a deepening of the depth of thaw and increased hydrologic storage (McNamara et al. 1997: Bolton 2006). In the watershed with low permafrost (C2). the decline in flood recessions over the active season was related with mean summer precipitation (Table 2, Fig. 6); the seasonal change in flood recession curves was greatest in drier years. In the watershed with low permafrost, the seasonal decline in Hood recessions may be due to decreasing soil moisture over the active season and increased retention of precipitation in soil. In wet years, the soils remain relatively moist, which reduces the capacity of the soil to retain precipitation and results in more rapid Hushing of water from the catchment. Lastly, in the watershed with low permafrost (C2), the seasonal change in Hood recessions significantly increased across years (Table 2, Fig. 7). Although the cause for this increasing seasonal change in flood recessions across years is not clear, it may be due to an interaction among summer precipitation, temperature, ET, and seasonal soil thaw, which result in greater water storage by the soil later in the active season (McNamara et al. 1997: Bolton 2006). This increasing change, however, does indicate that stream flows from watersheds with low permafrost have become less responsive to precipitation over the period of record.

Climate sensitivity **of upland** stream **flow**

The loss of permafrost will have fundamental impacts on streams in the boreal forest of interior Alaska. Although we did not detect significant inter-annual changes in most measures of stream flow **in** CPCRW, we did observe distinct differences in summer runoff among streams. Over longer time scales, stream flow in Alaska is changing in response to the Pacific Decadal Oscillation (PDO; Hodgkins 2009). During the last warm phase of the PDO (1977-2006), flow in nonglacial rivers in Alaska increased during the winter and spring and declined during the summer compared with the cold phase from 1947 to 1976 (Hodgkins 2009). This change in river flow was attributed to a shift to earlier snowmelt during warmer years. The patterns among streams of CPCRW are consistent with inter-annual hydrologic changes observed throughout the subarctic including changes in the seasonal distribution of river flow (Walvoord and Striegl 2007), size of ponds (Riordan et al. 2006), glacial recession (Kaser et al 2006), and declines in snow-cover duration (Brown and Braaten 1998). In the Yukon River, the contribution of ground water to river discharge has increased 0.7-0.9%·year^{-1} over the past 30 years, whereas discharge has not changed (Walvoord and Striegl 2007). This increase in base flow was hypothesized to be due to climate warming, permafrost thaw, enhancement of groundwater infiltration, and a deepening of groundwater flow paths. Similarly, within the CPCRW, base flow in the streams draining the catchments with lower permafrost accounted for 79% and 81% of discharge (C2 and C4 streams, respectively) compared with only 44% in the watershed with high permafrost (Table 1). With climate warming and loss of permafrost, upland headwater stream flow will likely become less responsive to precipitation and streams may become ephemeral. Moreover, these changes in stream flow are one component of broader hydrologic change across the boreal forest of Alaska.

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