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Hydrograph separations in an Arctic watershed using mixing model and graphical techniques

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Abstract. Storm hydrographs in the Upper Kuparuk River basin (142 km^2) in northern Alaska were separated into source components using a mixing model and by recession analysis. In non-Arctic regions, storm flow is commonly dominated by old water, that is, water that existed in the basin before the storm. We suspected that this may not be true in Arctic regions where permafrost diminishes subsurface storage capacity. Streamflow during the snowmelt period was nearly all new water. However, all summer storms were dominated by old water. Storms in a neighboring basin were dominated by new water but much less than was the snowmelt event. Thus a large increase in old water contributions occurred following the snowmelt period. This increase continued moderately through the summer in 1994 but not in 1995. We credit the seasonal changes in old water contributions to increased subsurface storage capacity due to thawing of the active layer.

Introduction

Permafrost is a ubiquitous presence in the Arctic that influences nearly all physical and biological ecosystem processes. Several studies have shown that permafrost has significant hydrological consequences which result primarily from the minimal subsurface storage capacity due to frozen ground [*Hinzman et al.*, 1993; *Dingman*, 1970; *McNamara et al.*, 1997; *Roulet and Woo*, 1988; *Woo and Steer*, 1983]. This is of particular concern to the NSF Land-Air-Ice-Interaction (LAII) Arctic Flux Study operating in the Kuparuk River basin in northern Alaska. The goal of the Arctic Flux Study is to estimate the regional fluxes of mass and energy in the Kuparuk River basin between the land, the atmosphere, and the Arctic Ocean [*Weller et al.*, 1995]. This requires a comprehensive understanding of the mechanisms and pathways by which water travels through the system. Hence we investigated the composition of storm flow in the Kuparuk River basin by asking the following questions: Is storm flow primarily composed of precipitation, called new water, or subsurface water previously existing in the basin, called old water, and what influence does permafrost have on storm flow composition? An understanding of both the partitioning of hydrographs and the mechanisms responsible for the partitioning is a prerequisite to understanding the relationships that exist between terrestrial and aquatic systems.

Several case studies in various nonpermafrost regions have shown that old water typically dominates storm hydrographs, including snowmelt events [*Buttle and Sami*, 1992; *Bottomley et al.*, 1986; *Dincer et al.*, 1970; *Eshleman et al.*, 1993; *Kennedy et al.*, 1986; *Kobayashi et al.*, 1993; *McDonnell et al.*, 1991; *Rodhe*, 1981; *Peters et al.*, 1995]. This may have significant influences on the transport of nutrients from the terrestrial to the aquatic system, a primary area of research in the Kuparuk River study. The old water reservoir in a basin with permafrost is severely restricted due to the frozen ground. Essentially all subsurface flow occurs in a shallow zone called the active layer that undergoes annual freezing and thawing cycles. Consequently, we suspected that storm flow may not be dominated by old water, as is commonly observed.

An analog for permafrost basins may be watersheds on the southern Canadian Shield, where impermeable bedrock underlies shallow soils. However, several workers have shown that storm flow is indeed composed primarily of old water in Canadian Shield watersheds, even with their diminished old water reservoirs [*Peters et al.*, 1995; *Bottomley et al.*, 1986; *Wels et al.*, 1991; *Hinton et al.*, 1994]. An important distinction between Canadian Shield watersheds and the Kuparuk River basin is that the subsurface reservoir and consequent basin storage capacity in the Kuparuk River basin increases as the ground thaws during the summer months from essentially zero depth in the spring to depths approaching those in the Canadian Shield watersheds late in the summer. Other studies have shown that certain hydrologic processes undergo coincident changes with the thawing active layer. *Hinzman et al.* [1991] showed that the portion of the soil profile that contributes to hillslope runoff increases through the summer. Further, *McNamara et al.* [1997] suggested that runoff/precipitation ratios may decrease as the active layer thickness increases. Thus we suspected that the systematic increase in active layer thickness would produce consequent changes in storm hydrograph compositions through the summer.

The specific objectives of this paper are (1) determine the proportions of old and new water in storm flow in the Kuparuk River basin during 1994 and 1995, (2) investigate the potential influences, particularly of permafrost, on storm flow composition. Storm flow compositions were determined from hydrograph separations using mixing model and graphical techniques. The influences on storm flow composition were investigated by constructing correlation matrices with variables including old water composition, precipitation characteristics, total flow, and storm date as a surrogate for active layer thickness. Runoff generating mechanisms were qualitatively evaluated using a technique developed by *Eshleman et al.* [1993] to compute contributing areas based on hydrograph separations. We focused on summer storms in the Upper Kuparuk River basin (Figure 1), with a limited analysis of snowmelt processes.

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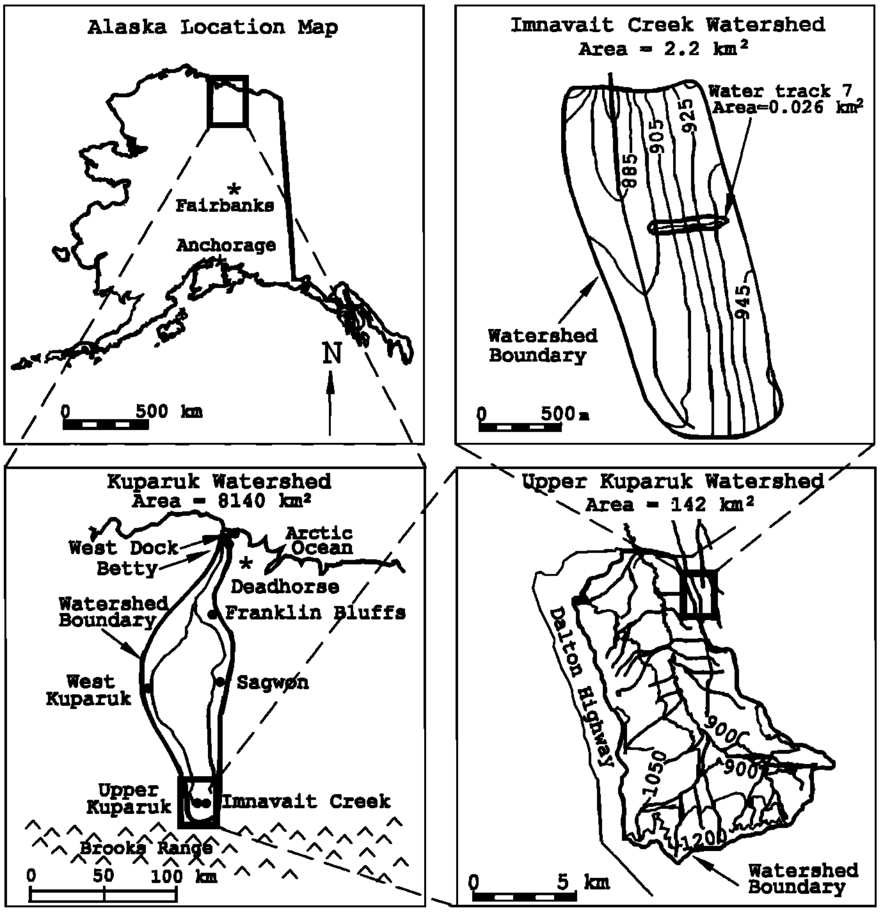

Figure 1. Map showing locations of the study sites in the Kuparuk River basin, northern Alaska. This study focused on the Upper Kuparuk River basin (142 km^2), with a limited analysis of Imnavait Creek (2.2 km^2).

Additional analyses were performed in the much smaller neighboring Imnavait Creek (2.2 km^2).

Site Description

The Kuparuk River flows from the glaciated foothills of the Brooks Range through the tundra flats of the coastal plain to the Arctic Ocean near Prudhoe Bay (Figure 1). The entire region lacks trees, is underlain by continuous permafrost, and is covered with snow for 7–9 months each year. The snowmelt event is generally the dominant hydrologic event each year, which typically occurs over a 7–10 day period between early May and early June [*Kane et al.*, 1991]. Approximately 30–40% of the annual precipitation falls as snow from September through May. The average summer rainfall is around 18 cm in the foothills of the Brooks Range. The maximum snowfall is typically 10–14 cm of water equivalent. Summer temperatures are typically between 6° and 18°C, and winter temperatures are commonly around −15° to −25°C. Permafrost thickness ranges from around 300 m near the foothills to over 600 m near the coast [*Osterkamp and Payne*, 1981]. Hence the region is effectively isolated from deep groundwater. Subsurface flow occurs in a shallow zone above the permafrost called the active layer which undergoes annual freezing and thawing. Soils typically thaw to maximum depths of 25–40 cm but can thaw to 100 cm depending on several environmental factors including soil type, slope, aspect, and soil moisture [*Hinzman et al.*, 1991].

This study focused on the Upper Kuparuk River, a headwater basin which drains 142 km^2 in the northern foothills of the Brooks Range. The slopes in the basin are covered with till from two glacial advances, Sagavanirktok and Itkillik, from the middle and late Pleistocene [*Hamilton*, 1986]. At the intersection with the Dalton highway the Upper Kuparuk River is a fourth order stream on a U.S. Geological Survey (USGS) 1:63360 map. However, the hillslopes and tributary valleys contain a complex network of small streams that do not appear on maps at that scale. Two dominant streams join together at the base of steep hills in the upper basin forming the main channel which occupies a north-northwest trending valley. The main basin length is 16 km, with a channel length of 25 km. Vegetation in the basin consists of alpine communities at higher elevations and moist tundra communities, predominantly tussock sedge tundra, at lower elevations. Patches of dwarf willows and birches up to 1 m in height occupy portions of the banks. The average elevation of the basin is 967 m.

Imnavait Creek (2.2 km^2) is a small beaded stream occupying a north-northwest trending glacial valley which was formed during the Sagavanirktok glaciation (middle Pleistocene) [*Hamilton*, 1986]. The dominant vegetation in the Imnavait basin is tussock sedge tundra covering the hillslopes [*Walker et al.*, 1989]. An organic layer typically near 10 cm thick, but up to 50 cm thick in the valley bottom, overlies glacial till, where the soil rarely thaws deeper than the extent of the organic peat layer. The creek is essentially a chain of ponds, called beads, that formed where the stream has eroded and melted massive ground-ice deposits. The stream bottom rarely cuts through to mineral soil but maintains itself in the organic layer. Imnavait Creek flows another 12 km beyond our station before it joins the Kuparuk River.

The hillslopes in the Kuparuk River basin are drained by a network of water tracks. A water track is essentially a linear zone of enhanced soil moisture that flows directly down a slope and is best detected by a change in vegetation from the surrounding hillslope [*Hastings et al.*, 1989; *Walker et al.*, 1989]. Water tracks are generally spaced tens of meters apart on the hillslopes, although their density varies [*Walker et al.*, 1989]. Only intermittently do incised channels exist in water tracks, but they are significant components of the hillslope hydrologic cycle. They often end in peat covered valley bottoms through which water travels to the streams as diffuse subsurface flow through the active layer, or overland flow during extreme events.

Hydrograph Separation

Early techniques to separate storm hydrographs into source components involved graphical separation, or recession analysis, to determine the portion of storm flow that originates from groundwater or base flow. The shape of the hydrograph recession curve is used to decipher the timing and magnitude of surface and subsurface runoff. Newer, more physically based, techniques involve separating hydrographs into source components using naturally occurring tracers. Simple two-component mixing models are used to partition storm flow into old and new water assuming flow sources have distinct chemical or isotopic signatures, where old water is water that existed in the basin prior to a storm (i.e., soil moisture and groundwater) and new water is the rain or snowmelt contributed by a storm or snowmelt event. Commonly used tracers include oxygen isotopes, chloride, and specific conductivity. Advances in hydrograph separation techniques have expanded the two-component mixing model to include soil water and deep groundwater as separate components in a three-component model [*DeWalle et al.*, 1988]. The two-component mixing model is acceptable in this study due to the absence of a deep groundwater system.

We used specific conductivity as the primary tracer and compared those results to recession analysis of the same hydrographs. We used ^{18}O as the tracer for one of the hydrographs as a check on the specific conductivity approach and to evaluate flow sources during the snowmelt period. We used recession analysis when possible, but several storms contained multiple peaks, which made recession analysis impossible. Conductivity signals of new water and old water in Imnavait Creek were often too close to allow hydrograph separation by the mixing model. Consequently, we were only able to use recession analysis in Imnavait Creek.

Mixing Model

The mixing model is based on the steady state form of the mass balance equations for water and a conservative tracer,

$$Q_s(t) = Q_o(t) + Q_n(t) \quad (1)$$

$$Q_s(t)C_s(t) = Q_o(t)C_o(t) + Q_n(t)C_n(t) \quad (2)$$

where Q is the flow rate, C is the tracer concentration, t is time, and the subscripts s, n, and o refer to the total streamflow, the new component of the flow, and the old component of the flow, respectively. The streamflow attributed to old water at any time t is

$$Q_o(t) = Q_s(t)(C_s(t) - C_n(t))/(C_o(t) - C_n(t)) \quad (3)$$

and the new water flow is

$$Q_n(t) = Q_s(t) - Q_o(t) \quad (4)$$

Instantaneous proportions of total streamflow arising from either new or old water are $Q_n(t)/Q_s(t)$ and $Q_o(t)/Q_s(t)$, respectively. The values of Q_n, Q_o, Q_o/Q_s, and Q_n/Q_s are obtained by summing (3) and (4) over the duration of the storm.

The natural tracer technique requires that the tracer signatures be conservative; that is, they do not change through a storm, or the changes can be corrected for. The signatures of old and new water must also be distinct. Specific conductivity is not entirely conservative because rain water dissolves solutes as it passes through the soil. However, we believe our technique, described below, corrected for changes in specific conductivity due to soil contact.

Definition of End Members

Given the potential for spatial heterogeneity of soil water chemistry, it is difficult to obtain an accurate chemical signature of the old water component. For this reason a common method for estimating the old water component is to assume that the stream water during the low flow periods between storms represents an integrated sample of the old water in the basin. A continuous record of specific conductivity during low flow periods then provides a simple estimation of the old water component. However, Figure 2 shows that the specific conductivity of the Upper Kuparuk River during low flow periods increased through the season so that poststorm values were typically higher than prestorm values. We used linear interpolation between the prestorm specific conductivity and the poststorm specific conductivity to estimate the instantaneous old water signatures during a storm [*Hooper and Shoemaker*, 1986]. In cases where the poststorm conductivity was lower than the prestorm conductivity due to dilution from the next storm we used a constant conductivity through the storm equal to the prestorm conductivity for the old water signature. For the ^{18}O old water signature on storm 7 we used a constant value through the storm equal to the stream ^{18}O content immediately prior to the storm.

The new water specific conductivity was more difficult to estimate. Typically, the signature of precipitation for the event is used as the new water end-member. However, *Pilgrim et al.* [1979] showed that the specific conductivity of dilute water changes with soil contact time and is not a reliable end-member. They developed laboratory relationships for the changes in specific conductivity and found that the conductivity changed dramatically during the early stages, then approached equilibrium and increased more slowly. They then used these relationships to correct for the changing new water signature, successfully separating storm hydrographs using corrected specific conductivity.

We estimated the new water signature by measuring the specific conductivity of runoff in a small hillslope water track which drains an area of 0.026 km^2 on the west facing slope of the Imnavait Creek basin. We assumed that the conductivity in the water track during the falling limb of a storm hydrograph

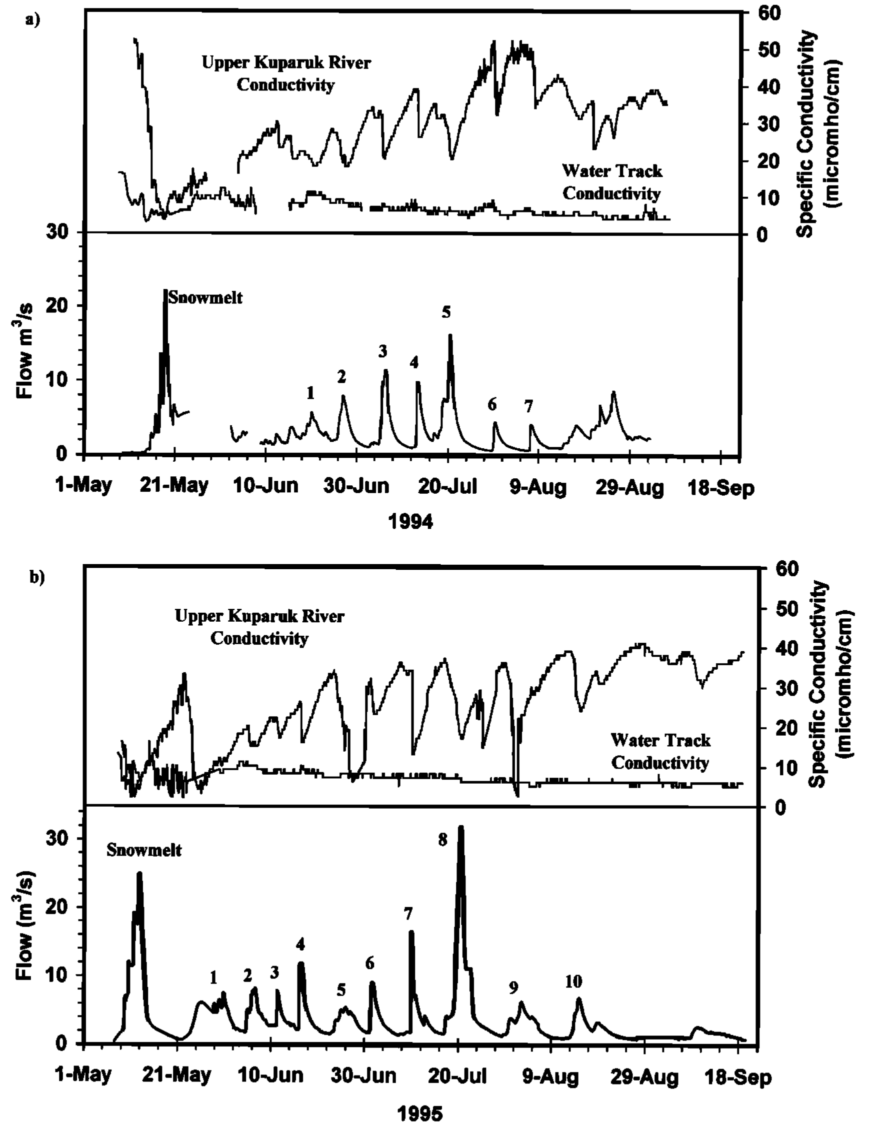

Figure 2. Hydrographs and specific conductivity records in the Upper Kuparuk River basin for (a) 1994 and (b) 1995. The storms analyzed in this study are numbered chronologically.

was not significantly influenced by old water and that the increase in specific conductivity of the water track during the falling limb of a hydrograph represented the slow increase in specific conductivity as the rain water approaches equilibrium with the soil. Hence, for each storm in the Upper Kuparuk River basin, the conductivity of the corresponding storm on the water track at peak flow was used as the new water end-member. A potential error in this method is that the water track runoff may indeed have been influenced by old water. If so, our estimates of new water conductivity may be too high, which would result in erroneously low computations of old water contributions. However, the specific conductivity in the water track ranged between 6 and 9 μmho/cm, which is close to that of local precipitation. Therefore underestimation of old water contributions will not be significant. The specific conductivity of the water track was distinctly lower than the Kuparuk River for all summer storms, which allowed us to use the two-member mixing model for all storms. We used the ^{18}O content of a bulk precipitation sample collected through the duration of the storm for the ^{18}O content of new water on storm 7.

Recession Analysis

Graphical hydrograph separation has received considerable criticism as there is no physical basis for its assumptions [*Freeze*, 1972]. *Dingman* [1994, p. 384] called the technique "convenient fiction." However, recession analysis can provide a qualitative way to evaluate runoff mechanisms when tracer techniques cannot be used. The technique becomes difficult to use on complex hydrographs such as those from overlapping storms or from a rain on snow event. Hydrograph recessions typically follow an exponential function. If plotted on a semi-logarithmic graph with discharge on the logarithmic scale, the recession should be a straight line [*Linsley et al.*, 1982]. However, the actual recession typically occurs in separate log linear segments with different slopes for the different sources of runoff. In a two-member system, surface flow and subsurface flow, the break in slope is assumed to be the point where surface runoff ceases. The remaining recession is due to subsurface base flow. The old water recession curve is obtained by projecting the line representing base flow recession backward in time to the corresponding peak of the hydrograph. A linear fit from the initial storm response to the old flow peak completes the old flow hydrograph. The proportion of old water contributing to the storm is calculated by dividing the area under the old water hydrograph by the area under the total hydrograph.

Field Methods

Streamflow was monitored at the Upper Kuparuk River basin and Imnavait Creek outlets using stilling wells with Stevens F-1 water level recorders mounted with variable resistance potentiometers to obtain digital data. Campbell Scientific CR10 data loggers recorded stream stage every minute and averaged over hourly increments. An H-type flume was used at Imnavait Creek to aid discharge measurements. Discharge measurements were made following USGS standards at several different stages to produce rating curves from which continuous records of discharge were calculated. Two complete meteorological stations recorded precipitation, wind speed and direction, air temperature, relative humidity, and various radiation terms. Hydrographs were produced for both basins from the initiation of snowmelt in early May to just prior to freeze-up in mid-September. To monitor active layer thickness, thaw depths on a ridge top and on the west facing slope in the Imnavait Creek basin were estimated by tracking the 0° isotherm using thermistors at various depths between 0 and 150 cm.

Specific conductivity was logged hourly at the Upper Kuparuk River, Imnavait Creek, and the water track using Campbell Scientific conductivity probes. Water samples for oxygen isotope analysis were collected every 3 hours during several storms using an Isco automatic sampler and by hand during snowmelt and between storms in the summer. Snowpack meltwater was collected by digging a snow pit and inserting a high-density polyethylene tray at the base of the snowpack before the initiation of melt. The pit was then covered with foam board to reduce melting of the pit wall. All of the meltwater in the tray at the end of each day was collected using a plastic syringe. Water samples for oxygen isotope analysis were collected with no head space in glass scintillation vials and stored in a cool, dark room until they were analyzed. Isotopic analysis of rain was completed only on samples collected for storms in August 1994. Only bulk precipitation samples were collected through the storms. Consequently, we are unable to address the isotopic variability of rain. Oxygen isotope measurement was performed at the University of Alaska Fairbanks Water and Environmental Research Center by extracting CO_2 from the water samples using a vacuum extraction line, then analyzing the gas for ^{18}O content on a VG Isogas series 2 mass spectrometer.

Results

Summer Storms

Both 1994 and 1995 were unusually wet summers with frequent storms. In 1994, 275 mm of rain fell at our gauge in the Upper Kuparuk River basin, and 274 mm fell in 1995. The 9-year average recorded at a nearby gauge in Imnavait Creek was 183 mm. Figure 2 shows the resulting hydrographs for the Upper Kuparuk River basin and identifies the storms used in this study. Storms 1, 2, 3, 4, 6, and 7 from 1994 and storms 2, 3, 4, 6, 7, 8, and 10 from 1995 were separated into source flow components using the mixing model with specific conductivity as the tracer. Storms 2, 3, 4, 6, and 7 from 1994 storms and storms 3, 4, 6, and 7 from 1995 were separated using recession analysis. Storm 7 from 1994 was also separated using ^{18}O as the tracer in the mixing model.

Figures 3a–3c show the results for storm 7 of 1994 as an example of each technique. The old water contribution for this storm calculated by the conductivity mixing model, the ^{18}O mixing model, and recession analysis was 79, 81, and 81%, respectively. These favorable comparisons confirm that hydrograph separation using specific conductivity as a tracer is acceptable. The old water and new water conductivity values used in the calculations are shown on the plots. The calculated old water contributions for each storm using chemical and recession separation are shown in Table 1. The old water contributions from the mixing model ranged from 65 to 81% in 1994 and 53 to 83% in 1995 with averages of 72 and 68%, respectively. These results indicate that old water dominated storm hydrographs in the Upper Kuparuk River basin. Recession analysis yielded similar results. Points would fall on the diagonal line on Figure 4 if the two techniques produced identical results. Although there is some scatter and clustering, there is fairly good agreement between the two techniques, which lends credence to the widely used but physically unjustified graphical method of hydrograph separation. *Kobayashi et al.* [1993] also found that tracer techniques and recession analysis produced similar results.

Eshleman et al. [1993] found a negative correlation between precipitation intensity and old water contribution to storm flow. Table 2 shows that no such correlation existed in the Kuparuk River basin at the 5% significance level ($\alpha = 0.05$). Table 1 contains the supporting precipitation data. Other potential influences on old water contribution include total runoff, total rainfall, rainfall duration, and active layer depth. We used storm date as a surrogate for depth of thaw to test for seasonal trends as a result of active layer thawing. Table 2 shows that the only significant correlation to old water contribution was storm date in 1994. There were no significant correlations to old water contribution in 1995.

Additional results based on the tracer separations following the format of *Eshleman et al.* [1993] are included in Table 1. The new water contributing area (NWCA) is an estimate of the area of the basin that produces direct runoff during a storm and is computed by dividing the new water flow volume by the corresponding total rainfall for the event. The new water contributing portion (NWCP) is the NWCA divided by the total watershed area and is an estimate of the percentage of the watershed that produces direct runoff during a storm. In 1994, NWCP in the Upper Kuparuk River basin ranged from a high of 34% early in the season with a decreasing trend to a low of 5% later in the season. In 1995, NWCP ranged between 73% early in the season to 18% at summers end, although there was no seasonal trend between the two extremes.

The specific conductivities for Imnavait Creek were too close to those for the water track to use the mixing model technique for separating Imnavait Creek hydrographs. This could mean that storm flow in Imnavait Creek is primarily composed of new water, or that old water in the basin has undergone very few chemical transformations during its residence in the basin. Thus we used recession analysis to calculate

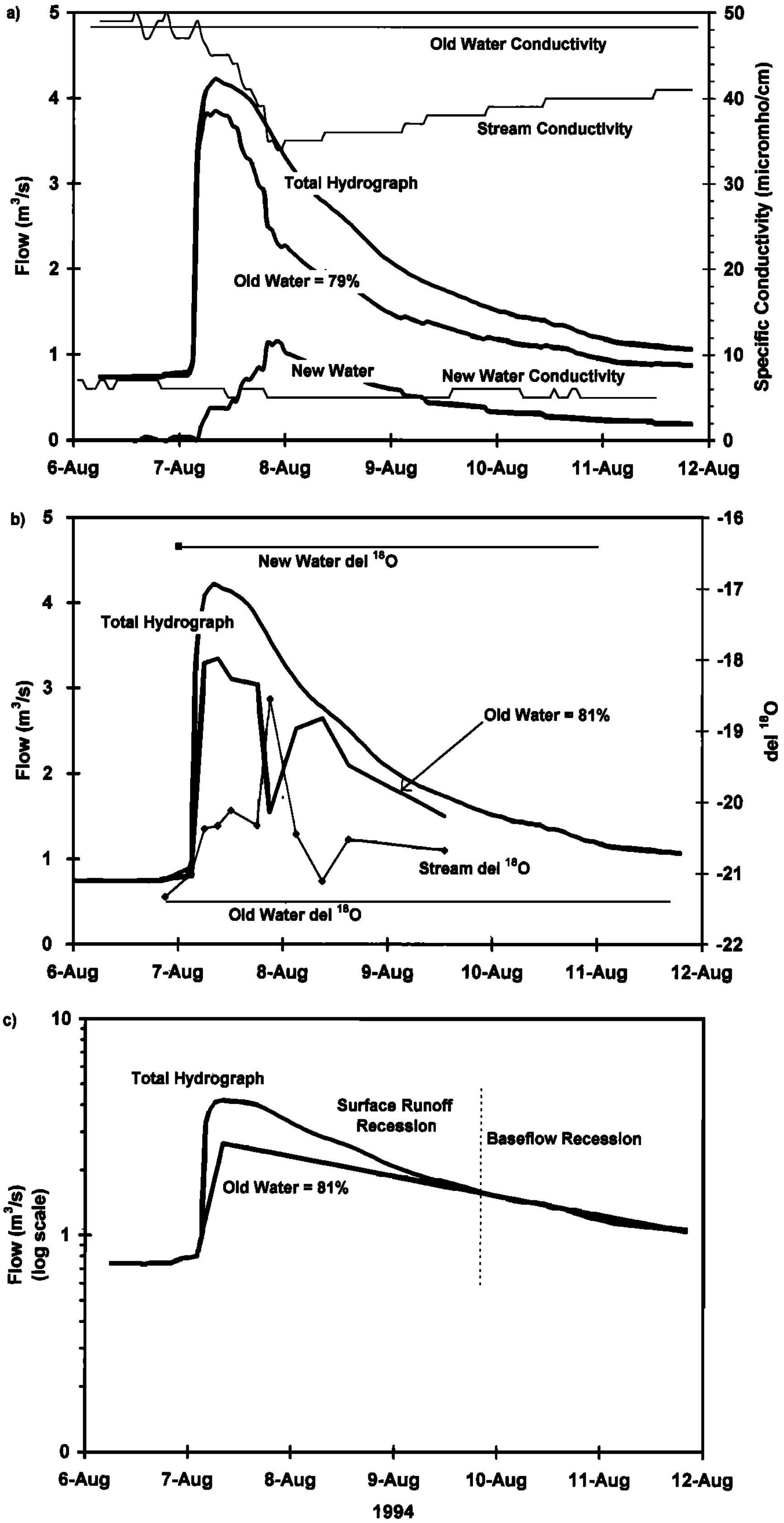

Figure 3. Storm 7, 1994 hydrograph separations. (a) Specific conductivity as a tracer resulted in a calculated old water contribution of 79%. (b) Oxygen isotopes as a tracer resulted in a calculated old water contribution of 81%. (c) Recession analysis resulted in a calculated old water contribution of 81%.

Table 1. Hydrograph Separation Results for the Upper Kuparuk River

Storm	Date	Total Discharge, m^3	Total Rainfall,* mm	Rainfall Intensity, mm/hour	New Water Discharge, m^3	New Water Mixing Model, %	Old Water Mixing Model, %	Old Water Recession, %	NWCA,† km^2	NWCP,‡ %
					1994					
1	June 17	2049238	19.8	0.25	837964	35	65	NA	42	29.7
2	June 25	2007369	17.2	0.43	841169	33	67	66	49	34.4
3	July 4	2505238	33.9	1.02	1000386	30	70	65	29	20.8
4	July 12	1543135	19.6	1.97	450912	31	69	63	23	16.2
6	July 29	1115632	28.2	4.97	216286	19	81	75	8	5.4
7	Aug. 7	873229	12.3	0.56	192928	22	79	81	16	11.1
average						28	72	70	28	20
					1995					
2	June 4	2035175	6.7	0.13	691960	34	66	NA	104	73.2
3	June 11	1150804	5.2	0.26	195637	17	83	88	38	26.5
4	June 15	2380086	17.8	1.77	809229	34	66	67	45	31.9
6	July 1	2106950	18.1	1.12	505668	24	76	77	28	19.7
7	July 9	2627313	20.0	0.06	1234837	47	53	47	62	43.5
8	July 17	7499286	39.8	0.45	3299686	44	56	NA	83	58.4
10	Aug. 12	2917276	28.7	0.24	758492	26	74	NA	26	18.6
average						32	68	70	47	33

NA, not applicable.
*Measured near Kuparuk headwaters stream gauge.
†New Water Contributing Area equal to new water flow volume/precipitation volume.
‡New Water Contributing Portion equal to NWCA/basin area.

storm flow compositions in Imnavait Creek. Most of the storm hydrographs in Imnavait Creek were complicated by multiple peaks, which made recession analysis unreliable. Hence we were only able to perform recession analysis on storms 3 and 6 in 1994 (Figure 5). Both storms in 1994 had old water contributions of 41%, indicating that new water dominated the storm hydrographs in Imnavait Creek. The lack of usable storms prohibited determination of whether or not a seasonal trend existed. However, storm 6 is late in the season and still has a relatively low old water contribution compared to the 75% for the recession analysis of the Upper Kuparuk River on the same date. NWCPs for storms 3 and 6 in Imnavait Creek were 14 and 13%, respectively.

Snowmelt

We were unable to perform accurate hydrograph separations during snowmelt due to the difficulties in obtaining representative end-member samples. However, the trends in ^{18}O content and conductivity in the streams during snowmelt enable reasonable approximations. The ^{18}O content in the Upper Kuparuk River, Imnavait Creek, and the water track increased dramatically throughout snowmelt in remarkably similar patterns (Figure 6). *Cooper et al.* [1993] reported similar data in Imnavait Creek. This initially appears to represent mixing of waters with distinct isotopic signatures. However, meltwater collected immediately under the snowpack that had not

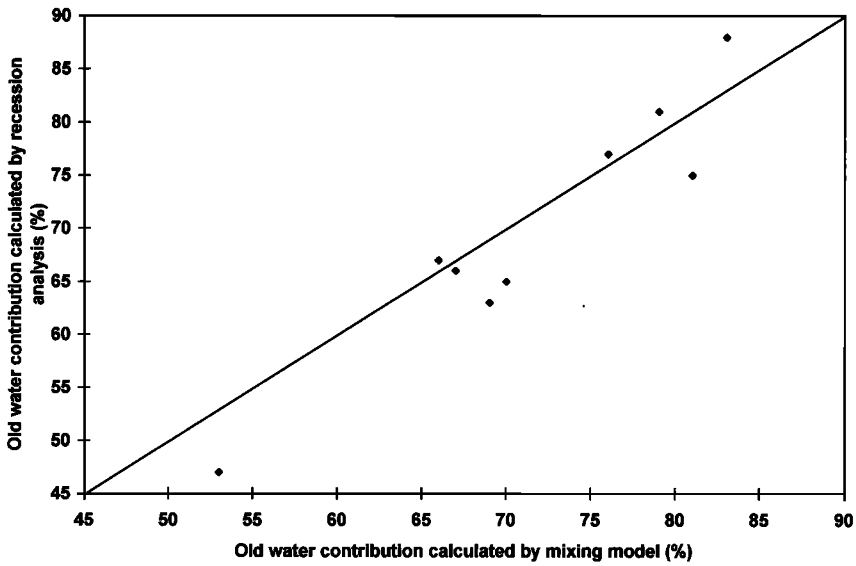

Figure 4. Plot showing the relationship between results obtained from the mixing model analysis and recession analysis. Points would fall on the diagonal line in a perfect relationship.

Table 2. Correlation Matrices of Potential Influences on Old Water Contributions to Storm Flow

	Storm Date	Total Flow	Total Rainfall	Rainfall Duration	Rainfall Intensity	Old Water
			*1994**			
Storm Date	1					
Total Flow	−0.85	1				
Total Rainfall	−0.07	0.37	1			
Rainfall Duration	−0.69	0.43	−0.47	1		
Rainfall Intensity	0.48	−0.36	0.71	−0.79	1	
Old Water	0.93	−0.77	0.17	−0.64	0.62	1
			1995†			
Storm Date	1					
Total Flow	0.46	1				
Total Rainfall	0.52	0.90	1			
Rainfall Duration	0.43	0.93	0.75	1		
Rainfall Intensity	−0.11	−0.22	0.16	−0.50	1	
Old Water	−0.14	−0.59	−0.46	−0.42	0.01	1

*Correlations between +0.62 and −0.62 are not significant at the 5% significance level.
†Correlations between +0.61 and −0.61 are not significant at the 5% significance level.

reached the soil had a similar trend. This suggests that enrichment of ^{18}O in streamwater during snowmelt is due to isotopic fractionation, as opposed to mixing of different source waters. *Cooper et al.* [1993] suggested this explanation to explain heavy isotope enrichment in their data but did not have the meltwater data to confirm their explanation.

Thawed soil moisture that originated from the previous fall precipitation is the potential old water source during snowmelt. *Cooper et al.* [1991, 1993] reported soil moisture ^{18}O contents around −20 parts per thousand (ppt) in 2 different years in the Imnavait Creek basin and reported that the variability around the basin was minimal. Further, the isotopic content of the water track through most of the summer of the *Cooper et al.* [1993] study was close to their estimation of soil moisture isotopic content. In 1994 the isotope content of the water track rose to a plateau around −20.5 ppt. These favorable comparisons suggest that this value can be used to approximate the potential old water source during snowmelt. That the ^{18}O contents in the Kuparuk River and Imnavait Creek remain distinctly lower than the estimated soil water value further suggests that these waters are almost entirely derived from melting snow.

Cooper et al. [1993] reported that the lightest snow (lowest ^{18}O content) in the Imnavait Creek basin occurred in the valley bottom. This may explain why the ^{18}O values of the water track were distinctly higher than in Imnavait Creek and the Upper Kuparuk River but followed a similar pattern through the snowmelt period. The meltwater sampling location was in the valley bottom, while the weir on the water track where the samples were collected integrated the areas higher on the slope. If the runoff in the water track during the snowmelt period was entirely from meltwater heavier than meltwater in the valley bottom, then Imnavait Creek should be a mixture between the light meltwater collected in the valley bottom and the heavier meltwater from the water track. Figure 6 shows that the ^{18}O content of Imnavait Creek was indeed between the water track and the valley bottom meltwater. The Upper Kuparuk River had an almost identical pattern in ^{18}O content to Imnavait Creek. These patterns suggest that the isotopic contents of streamwater can be explained entirely by the mixing of fractionating meltwater sources without interaction with subsurface waters.

Without continuous data we could not partition the hydrographs for the snowmelt period. However, we calculated the old water contributions at one time instant, the latest time for which we have meltwater isotopic data. At that time, the meltwater had an ^{18}O content of −26.4 ppt, and the Kuparuk River had an ^{18}O content of −26.0 ppt. Using these values in the two-component mixing model (equation (3)) resulted in an old water contribution of 7%. If the valley bottom meltwater data was indeed lighter than the basin average, then the old water contribution would be even lower. It is possible that −20.5 ppt is a heavy estimate of the soil moisture and that fractionation occurs as soil moisture thaws, as well. If we subtract 2 ppt from the estimate of soil moisture ^{18}O content, which was the approximate range of fractionation in the snow meltwater data, then the old water contribution to snowmelt increases to 10%. This was on the rising limb of the hydrograph, where old water contributions are typically highest. *Cooper et al.* [1991] reported an old water contribution to storm flow of 14% at peak flow in Imnavait Creek.

The patterns in conductivity during the snowmelt period for the water track and the Upper Kuparuk River (Figure 2) confirm the above results. The high conductivity at the onset of snowmelt runoff results from solute exclusion in the snowpack. Ions migrate to the points of snowflake crystals during the freezing process. Initial meltwaters flush these ions and result in meltwater concentrations much higher than the bulk snowpack. The remaining snowpack is depleted of ions, and further meltwater therefore has low conductivity. After this process occurred early in the snowmelt period, the water track and the Upper Kuparuk River had nearly equal conductivities, which were similar to the conductivity of snowpack meltwater collected before it had contact with the soil. This further suggests that streamflow during the snowmelt period was almost entirely due to melting snow with little contributions from subsurface waters.

Hydrologic budget studies in Imnavait Creek confirm that there can be essentially no mixing of meltwater with underlying soils [*Kane et al.*, 1989, 1991; *Hinzman et al.*, 1991]. Approxi-

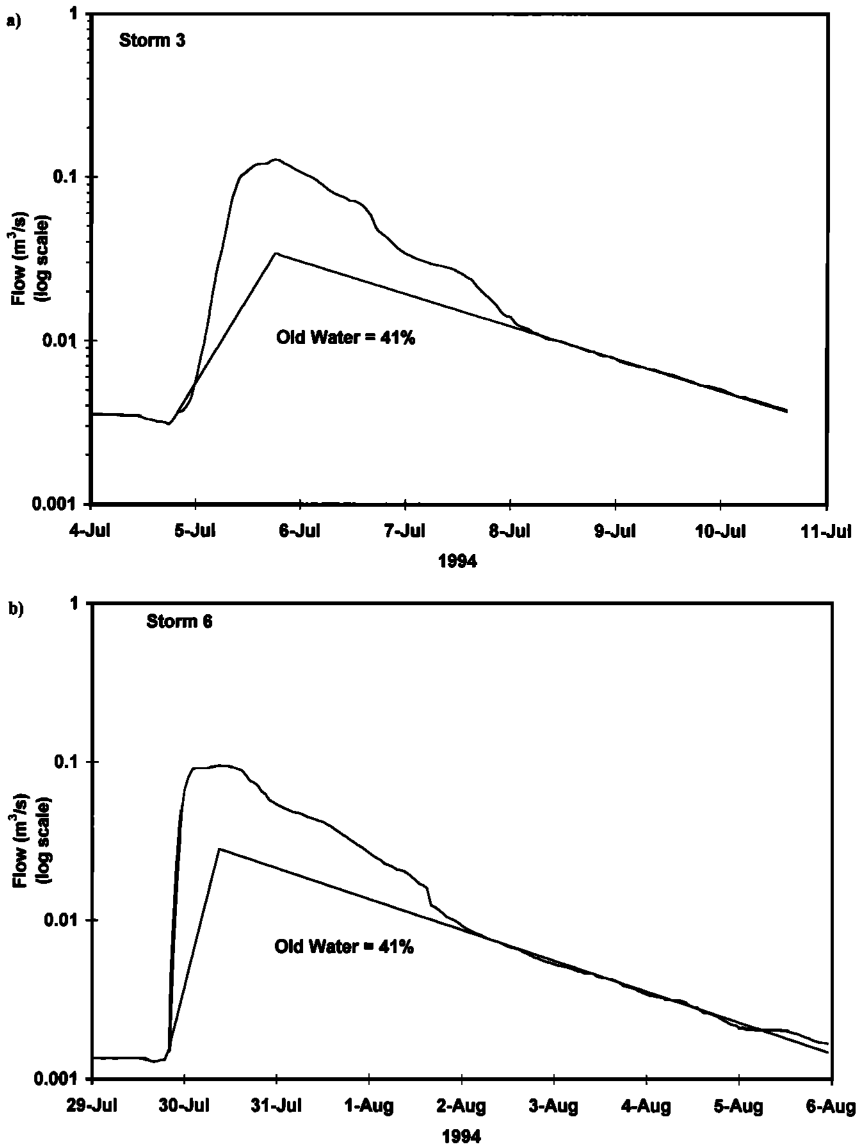

Figure 5. Individual storm hydrographs used for recession analysis in Imnavait Creek. The only suitable storms were (a) storm 3, and (b) storm 6.

mately 1.5 cm of meltwater infiltrates the desiccated surface soils before runoff ensues [*Kane et al.*, 1989], but this meltwater refreezes when it contacts the colder soil and essentially eliminates infiltration [*Hinzman et al.*, 1991; *Kane and Stein*, 1983].

Discussion

Influences on Storm Flow Composition

Summer storm flow in the Upper Kuparuk River basin is dominated by old water, as is commonly observed in other regions, despite the presence of permafrost. However, whereas streamflow during the snowmelt period in other regions is dominated by old water, streamflow during the snowmelt period in the Upper Kuparuk River is almost entirely composed of new water. Hence there is a dramatic shift in storm flow composition from the snowmelt period to the earliest summer storms. This change can be credited to active layer thickness. Immediately following snowmelt, storage capacity of the soil is restricted to a thin layer in the surface organic soils. The fastest rate of increase in active layer thickness occurs early in the summer. Thus, soon after snowmelt, rainfall is able to infiltrate the mineral soils, which was not possible during snowmelt, and displace old water into the streams. The basin storage capacity and the potential old water reservoir continue to increase as the active layer increases through the summer. In the summer of 1994 a high correlation between storm date and old water confirmed that old water contributions increased through the summer (Table 2), although at a moderate rate. Figure 7a illustrates the seasonal trends in thaw depth and old water contributions in 1994. The lack of continued increase in old water contributions in the summer of 1995 suggests that other factors influenced storm flow compositions.

Eshleman et al. [1993] demonstrated that old water contribution to stormflow decreases as precipitation intensity increases. However, *Hinzman et al.* [1993] showed that vertical hydraulic conductivities in the Imnavait Creek near surface organic soils are so great that precipitation intensity rarely exceeds infiltration capacity and that runoff occurs more com-

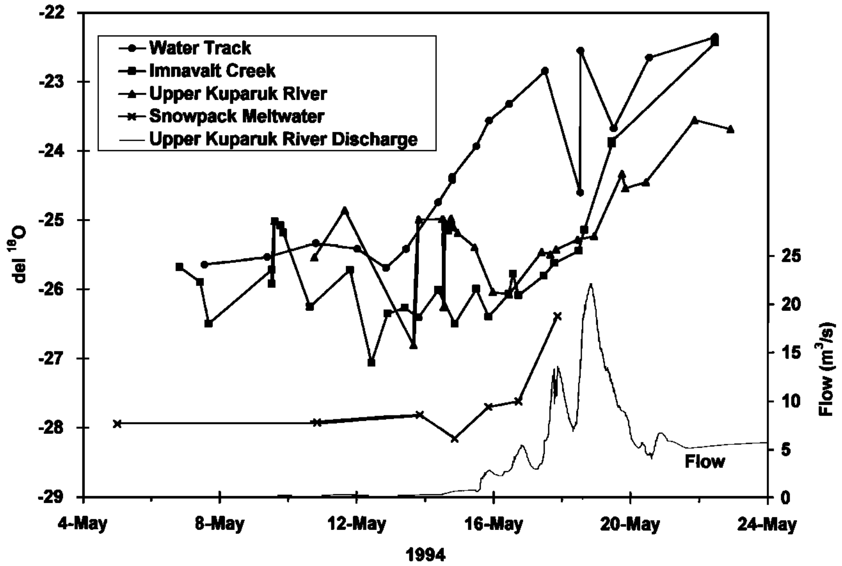

Figure 6. The ^{18}O contents for the Upper Kuparuk River, Imnavait Creek, the hillslope water track, and snowpack meltwater during the 1994 snowmelt period. The snowmelt hydrograph for the Upper Kuparuk River is shown for reference.

monly as a result of saturation of the active layer. *Roulet and Woo* [1988] arrived at a similar conclusion in the Canadian Low Arctic. They stated that in wetland soils, minimal runoff occurs until the soil saturates and the water table rises above the surface, effectively initiating a simultaneous response over the whole wetland area. This is a threshold response of runoff initiation, and it suggests that total precipitation combined with basin storage capacity should be more significant than precipitation intensity in determining hillslope response to precipitation events.

Basin storage capacity is dictated by the active layer thickness and soil moisture conditions. Thus the depth of active layer thaw, in conjunction with precipitation patterns, influences old water contributions to stormflow. *Hinzman et al.* [1991] showed that the soil moisture in the surface organic soil layer in Imnavait Creek is highly sensitive to recent precipitation patterns, while the soil moisture in the underlying mineral soil remains fairly constant. Therefore the influence of active layer depth on basin storage capacity is diminished once the thaw depth reaches the mineral soil. Thus, in the period immediately following snowmelt, increases in active layer thickness have dramatic influences on storm flow compositions. However, later in the summer, any influence of the active layer can be easily masked by soil moisture conditions as dictated by precipitation patterns.

New water contributing portion (NWCP) results showed similar patterns to old water contribution with a seasonal trend in 1994 (Figure 7b) but not in 1995. NWCP may be influenced by changes in the active layer thickness in the same manner as is old water contribution. However, a more significant result of the NWCP calculations is the difference between permafrost and nonpermafrost basins. *Eshleman et al.* [1993] reported NWCP values between 0.1 and 3% for the Reedy Creek watershed in the Virginia coastal plain which has a humid subtropical climate. Although these values range by a factor of 30, they are considerably lower than those we report from the Upper Kuparuk River (Table 1). This suggests much more interaction with the subsurface in nonpermafrost environments.

Flow Sources and Hillslope Response

Walker et al. [1996] constructed a hierarchic geographic information system (GIS) of the Upper Kuparuk River basin which showed that open water, including streams, lakes, and ponds comprise 0.5% of the basin. The computed NWCPs are significantly higher indicating that the new water storm flow response cannot be accounted for just by precipitation onto the channel network and that there is indeed interaction with the surrounding hillslopes. However, by adding the riparian wetland areas (1.4%), the well-developed hillslope water tracks (10.9%), and the poorly developed water tracks (21.9%), the total area of the extended channel network is 34.7% of the total basin area. This is remarkably close to the 34% early season NWCP in 1994 indicating that all of the early season new water storm flow can be accounted for by precipitation onto the extended channel network. The hillslope contributions to storm flow are likely coming from only the water tracks with very little interaction with the unchanneled hillslopes. Thus the water track network may act as the maximum potential saturated area during storms. The storage capacity in the water tracks increases as the season progresses which could account for the decrease in NWCP and the increase in old water contributions through the summer of 1994. By the end of the season the new water contributing area is probably restricted to narrow margins around the streams. The early season NWCP in 1995 was 73%, which is considerably higher than the area of the extended channel network. However, this storm was fairly close to the end of the snowmelt period when large snowdrifts persisted on the east facing slopes and at the higher elevations. Consequently, the runoff during this storm was likely a mixture of precipitation and meltwater, which would alter the contributing area of runoff generation. The mean 1995 NWCP was 33%, indicating that throughout the season new water storm flow can be accounted for by precipitation

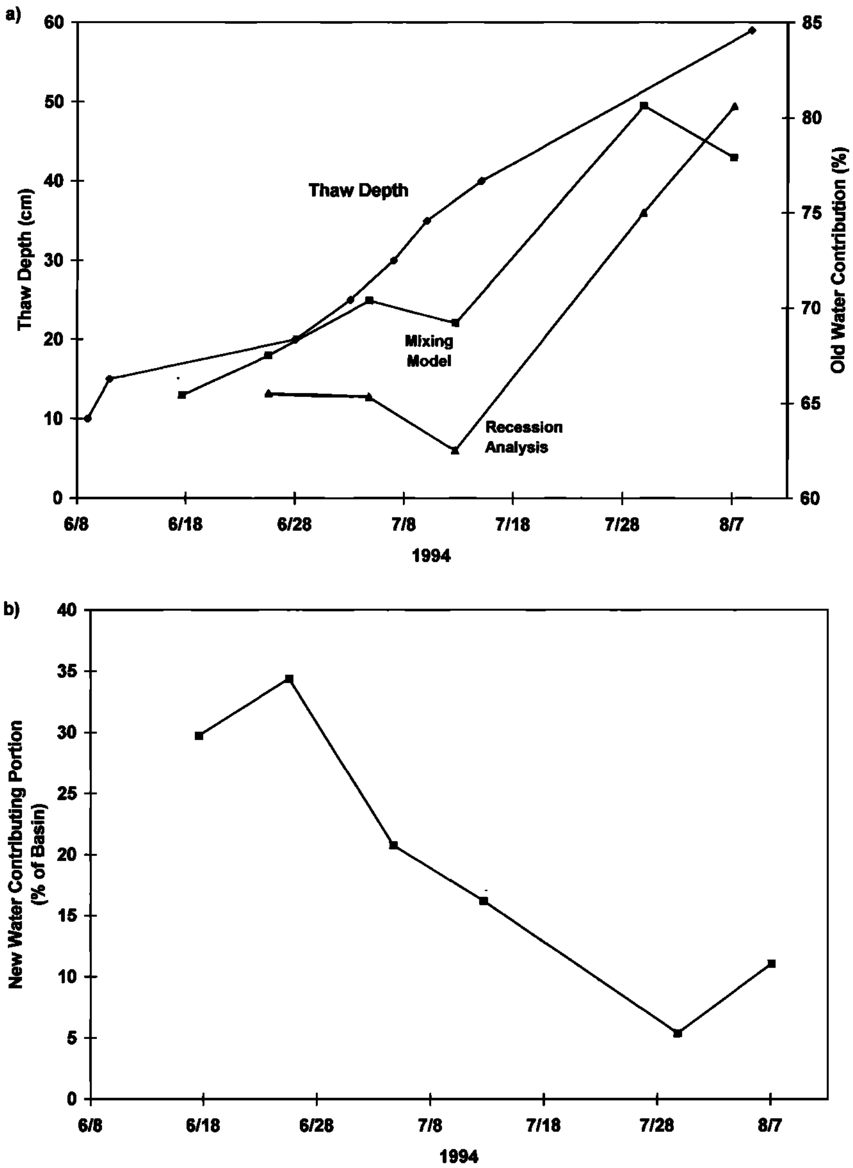

Figure 7. The 1994 seasonal trends in storm response in the Kuparuk River basin. (a) The contribution of old water to storm flow in the Upper Kuparuk River as calculated by the mixing model and recession analysis is plotted against the right axis. Depth of thaw is plotted on the left axis to illustrate the correlation to old water contributions. (b) The new water contributing portion (NWCP).

onto the extended channel network. These results suggest that the mechanisms that are occurring on the unchanneled hillslopes are overwhelmed by the water tracks and are not significant in the basin response except in extreme events.

A good agreement between NWCP and the extended channel network was also found by *Eshleman et al.* [1993] in Reedy Creek, where runoff generation is dominated by saturation overland flow. Perhaps then a common mechanism of runoff generation exists among watersheds in these different regions, despite radically different hydroclimatological conditions.

The commonly accepted groundwater ridging hypothesis proposed by *Sklash and Farvolden* [1979] states that old water originates in narrow margins around the streams. In the Kuparuk River basin the water tracks are ephemeral streams that exist as zones of enhanced soil moisture during dry periods. It is likely then that old water contributions come directly from moisture existing in the water tracks that are replenished during storms. We have suggested that the unchanneled hillslopes are not significant components of new water runoff, and it is likely that they are not significant as old water sources as well. We must clarify our above explanations relating hillslope thaw depth to storm flow response by stating that those processes described are occurring within the hillslope water tracks as well. It is important to note that water tracks are distinct geomorphologic features of drainage basins in the Arctic, not simply zones of preferential saturation during storms. Essentially, water tracks function as both hillslopes and channels. Early in the season, the thaw depths in both the unchanneled hillslopes and the water tracks are near zero. In the following summer months the water tracks thaw deeper than the adjacent tundra regions. Hence the old water reservoir per unit of surface area is greater in the water tracks, thereby enhancing the relationships between thaw depth and runoff described above, and lending further support to our statement that old water storm contributions come primarily from water existing in the water tracks and saturated valley bottoms.

The distinct differences in specific conductivity between Imnavait Creek and the Upper Kuparuk River suggests that there is a source of solutes present in the Kuparuk basin that is not present in Imnavait Creek. The specific conductivity of Imnavait Creek is rarely greater than local precipitation, suggesting that there is no significant interaction with underlying mineral soil and that the old water source exists in the organic soil horizon. A spring located in the Kuparuk River headwaters 8 kilometers upstream of our gauging station was sampled periodically through the summer, and the specific conductivities closely followed the low flow stream concentrations. *Kreit et al.* [1992] suggested that this spring water originates from precipitation within the basin that percolates through coarse glacial sediments. Also, many of the small streams and water tracks in the headwaters of the Upper Kuparuk River have specific conductivities similar to those of the spring. The water discharging from the spring and in the upper streams is likely from the same source as the old water contributions to storm flow.

Small streams and water tracks may have differing chemical signatures depending on the bed material. Water tracks that exist only in the upper organic soil layer have very low specific conductivities and will retain signatures close to new water throughout a storm, as in Imnavait Creek. Water tracks and streams that cut through to mineral soil pick up more solutes and develop an old water signature similar to what we see in the Upper Kuparuk River. The consequence is that we may overestimate the new water contributions in peaty channels. The Upper Kuparuk River basin contains both peaty and stony channels. However, that our recession analysis and mixing model results are similar for the Upper Kuparuk River suggests that our storm flow separations are not significantly influenced by this potential error. Further, this supports our explanation that the source of old water is from soil moisture within the water tracks and ephemeral streams and that the differing old water signatures between basins do not require different explanations of storm response.

The above discussion raises the question why Imnavait Creek storm flow is not dominated by old water. This may be due simply to the density of hillslope water tracks and the presence of a large wetland in the valley bottom of Imnavait Creek. GIS mapping of the Imnavait Creek basin indicates that 56% of the basin is either part of the channel network, riparian wetland, or water track providing a very large potential saturated area for quick flow of new water compared to 35% in the Upper Kuparuk River basin [*Walker et al.*, 1996]. The NWCPs for Imnavait Creek (14 and 13% for storms 3 and 6 in 1994) are considerably less than the potential saturated area, even though new water dominates the storm runoff. This suggests that a relatively small portion of the basin contributes a majority of the runoff during storms. That contributing portion may be the broad wetland in the valley bottom which occupies 12% of the basin and remains saturated most of the summer. A likely scenario is that the water tracks provide a mixture of old and new water to the wetland valley bottom, which produces a saturated surface in the valley bottom from which continued precipitation runs off. A lower portion of the Upper Kuparuk basin is valley bottom wetland (1.4%), thus more of the water tracks connect directly with the streams without passing through a wetland.

Summary

We suspected that permafrost may alter the composition of storm flow in the Kuparuk River basin from the common observation in other regions that old water dominates storm hydrographs. Further, we suspected that the gradual increase in subsurface storage capacity due to thawing of the active layer would impose seasonal trends on storm flow characteristics. Using both a chemical mixing model and graphical recession analysis, we found that storm flow in the Upper Kuparuk River basin in 1994 and 1995 was indeed dominated by old water contributions. However, Imnavait Creek storm flow was dominated by new water contributions. The difference between the two basins may be a result of the differences in the potential saturated portions of each basin. Favorable comparisons between the specific conductivity mixing model, ^{18}O mixing model, and recession hydrograph separation techniques support our use of specific conductivity as a tracer and lend credence to the physically unjustified recession analysis technique.

In 1994, old water contributions to storm flow in the Upper Kuparuk River increased moderately through the summer. Those seasonal trends were not apparent in 1995, and no seasonal trends were observed in the storm flow dynamics of Imnavait Creek in either year. However, there were large differences in the compositions of storm flow between the snowmelt period and the first summer storms each year. Thus, in the period immediately following snowmelt, increases in active layer thickness have dramatic influences on storm flow compositions. Later in the summer the influence of the depth of the active layer can be masked by soil moisture conditions as dictated by precipitation patterns.

New water contributing portion (NWCP) was much greater in the Upper Kuparuk River basin than in the basin without permafrost studied by *Eshleman et al.* [1993], which suggests that more interaction occurs between the surface and subsurface in basins without permafrost. Further, NWCP decreased through the summer of 1994, which agrees with the increase in old water contributions. As the storage capacity of the basin increases through the thawing season, more new water enters the soil, as opposed to going directly to runoff, and mixes with old water to produce runoff.

We credit both new water and old water sources to hillslope water tracks and suggest that very little interaction occurs between unchanneled hillslopes and streams. The small amount of interaction between the two zones is diminished even more with the increasing storage capacity in the unchanneled hillslopes as the season progresses. That storm flow composition has even moderate dependence on active layer thickness has implications that a warming climate may impose significant changes in the hydrology of watersheds in the Arctic, which may then influence the timing and magnitude of the delivery of nutrients to the aquatic system.

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