SEDIMENT LOAD AND CHANNEL CHARACTERISTICS IN SUBARCTIC UPLAND CATCHMENTS

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ABSTRACT

Sediment load in low-order streams of the unglaciated Yukon-Tanana Uplands of central Alaska may be related to drainage basin characteristics and to stream channel morphology. This has been investigated by analysis of selected physical, hydrological and water quality data for the 104 km^2 Caribou-Poker Creeks Research Watershed, located at 65°09′N, 147°30′W in a region of rolling to steep uplands and discontinuous permafrost. Channel morphology data are available for first-, second- and third-order streams. Sediment load for selected points was determined over 45 weeks during summers of 1978 and 1979. Consistent differences in sediment yield, hydrologic regime and channel morphology have been determined between permafrost and non-permafrost drainages.

INTRODUCTION

The taiga of central Alaska lies in the zone of discontinuous permafrost. This means that permafrost — earth material continually at temperatures below 0° — is found in some but not all locations. In the vicinity of Fairbanks, Alaska (latitude 65°N), permafrost is typically found on north-facing slopes and in topographically shaded sites, as well as in low-lying, poorly drained locales, while soils on south-aspect slopes are only seasonally frozen. Frozen soil thaws from the surface downwards each summer, resulting in a zone of seasonal thaw, the "active layer". The active layer may reach a depth of 60 to 90 cm or more during summer in undisturbed permafrost soils in interior Alaska, depending on local conditions. On undisturbed south-facing permafrost-free slopes, seasonal freezing may penetrate to 1.5 to 2.0+ m, again depending on local conditions.

In this region of discontinuous permafrost most hydrological research has concentrated on major rivers. With the exception of Emmett (1972), little or no data are available concerning hydraulic geometry, sediment loads or basin and channel characteristics of upland taiga stream systems.

There is increasing interest in accelerated "development" or management of interior Alaska's resources, ranging from mineral deposits to forest products, petroleum, fisheries, and recreation areas. Resource management or development activities frequently involve upland slopes and/or headwaters stream systems. Basic understanding of these systems under "pristine", undisturbed as well as "managed" conditions, is needed.

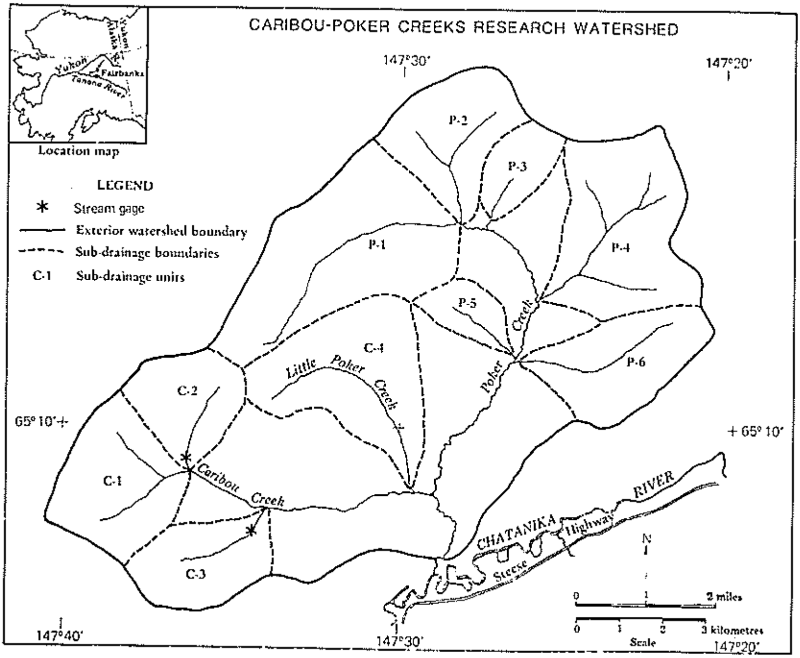
OBJECTIVE

This study was initiated to evaluate the interaction of drainage basin characteristics, channel characteristics, and suspended sediment load in an upland subarctic watershed. The underlying hypotheses were (1) that permafrost distribution might have a marked effect on channel characteristics, and (2) that streams draining permafrost landscapes might have sediment loads different from those of streams draining non-permafrost landscapes.

PROCEDURES

Study Site

The Caribou-Poker Creeks Research Watershed (Figure 1) is a 104 km^2 catchment located in the Yukon-Tanana Uplands (Wahrhaftig, 1965) of central Alaska. Elevation ranges from 210 to 826 m above m.s.l. The basin is forested, with the exceptions of limited areas of alpine tundra on ridgelines and riparian shrub communities adjacent to stream courses. The climate is continental with a mean annual temperature of approximately −4°C and an annual precipitation of about 500 mm. Snow cover is normally continuous for more than 200 days per year.



This basin was selected for hydro-meteorological research in 1969

(Slaughter, 1971), and has been designated as one of the initial components of a nationwide (USA) system of Experimental Ecological Reserves (The Institute of Ecology, 1977).

Physical Characteristics

Landscape characteristics were initially evaluated on 1:63 360 topographic maps, the largest scale available for this area. Characteristics of first-, second-, and third-order channels were measured in the field with rod, level and tape during the 1976 summer. At most stations, two cross-sections were measured: one at a riffle, and one at an adjacent pool or lower-gradient reach. Channel measurement sites were distributed throughout the research watershed, to obtain a broad spectrum of stream order, drainage area and aspect.

Stream Analysis

Water samples for determination of suspended sediment concentration were collected at approximately weekly intervals during the summers of 1978 and 1979. In these very small streams, use of a standard depth-integrating sampler such as the DH-48 was not feasible; samples were acquired using hand-held 500 ml polyethylene bottles, with a 44 mm orifice. Care was taken to sample the deepest sector of the stream, and to manually "depth-integrate" the sample to the extent possible.

Suspended sediment concentration was determined (non-filterable residue) according to procedures of the "National Handbook of Recommended Methods for Water-Data Acquisition" (US Geological Survey, 1977). Because suspended sediment concentrations were consistently low, samples were vacuum filtered with 0.45 μ Millipore filters.

Streamflow was measured at two stations (C-2 and C-3) utilizing prefabricated Parshall flumes installed in the channel and equipped with water-level recorders. During the 1979 runoff season, recurrent recorder malfunctions resulted in loss of continuous record for the C-2 site; however, instantaneous discharge at time of water sampling was obtained.

Parshall flumes were chosen for the continuous-record sites to minimize disruption of channel and banks at the installation point, and to avoid creation of artificial ponding. Permafrost is present adjacent to and (presumably) beneath the channel in these small basins; any additional heat input to this frozen ground at the gauging site would lead to thaw and thermal degradation and could lead to impairment or loss of the station — this has been observed in similar small basins underlain by permafrost (Dingman, 1971).

RESULTS

Physical characteristics of the research area and individual sub-drainages are given in Table 1.

The primary impetus for this study was interest in possible differences between permafrost-dominated (north-facing) and relatively permafrost-free (south-facing) headwater catchments. Initial attention was devoted to data from subdrainages C-2 (south aspect) and C-3 (north/northeast aspect) (Figure 1). These basins have nearly equal drainage areas (5.2 km^2 and 5.5 km^2, respectively).

TABLE 1—Physical characteristics of Caribou-Poker research watershed (after Bredthauer and Hoch, 1979).

Basin	Area km^2	Dominant Aspect	Elev. Range m	Relief m	Total Stream length km	Drainage Density km/km^2	Percent Permafrost
Caribou Creek	38.9	E	229–773	554	121.7	3.1	28.0
C-1	6.7	E	329–733	404	18.2	2.7	26.1
C-2	5.2	S	329–738	409	24.6	4.7	3.5
C-3	5.5	NE	305–770	465	20.8	3.6	53.2
C-4	9.7	SE	240-773	533	13.1	1.3	18.8
Poker Creek	56.6	S	229–826	597	199.9	3.5	30.5
P-1	13.1	NE	358–810	452	35.0	2.7	37.8
P-2	6.8	S	358–826	468	36.5	5.3	6.9
P-3	2.7	S	320–794	474	10.9	4.0	
P-4	10.1	SW	299–826	527	23.8	2.4	14.2
P-5	1.7	SE	274–774	500	4.9	2.9	
P-6	8.4	NW	273–755	482	27.7	3.3	17.8

A marked difference in hydrological response between these drainages was noted by Slaughter and Kane (1979). The permafrost-dominated catchment (C-3) is clearly "flashier", showing faster and higher storm response and lower base flows when compared with the south-aspect C-2 basin. This behaviour is attributed to the influence of permafrost terrain, which comprises over 50% of the C-3 catchment but only about 3% of the C-2 basin.

It was surmised initially that this differential flow response might be reflected in sediment load, with the flashier stream carrying the heavier load. Data of Table 2 tend to refute that concept — the south-aspect C-2 stream consistently (over two summers) had a slightly higher suspended-sediment concentration than did the northeast-aspect C-3 stream. While this relationship was reversed on several individual sampling dates, the pattern was consistent. This difference was significant ($p=0.20$) when evaluated by "t-test" of means (Snedecor, 1956); this relatively low significance level stems primarily from large variance about the observed means.

These measured suspended-sediment concentrations were in general agreement with levels measured concurrently at other points in the research area without simultaneous streamflow measurement (Hilgert, pers comm). We would suggest that the more consistent flow from the south-aspect basin, coupled with a deeper, non-permafrost soil mantle on south slopes (Rieger *et al.,* 1972) provides greater opportunity for sediment entrainment and transport during the course of a runoff season.

TABLE 2—Suspended sediment and streamflow data, 1978 and 1979 summers.

Date (month-day-year)	Station C-2		Station C-3	
	S.S. (mg/l)	Q, m^3/s	S.S. (mg/l)	Q, m^3/s
5-16-78	0.16	—	0.12	—
5-22-78	0.08	—	1.24	—
5-30-78	0.04	—	0.08	—
6-09-78	0.08	—	0.16	—
6-14-78	0	—	0.08	—
6-21-78	0.06	0.016	0.12	0.024
6-28-78	0.96	0.040	0.22	0.133
7-06-78	0.04	0.021	0.04	0.020
7-12-78	0.36	0.020	0	0.011
7-18-78	0.08	0.019	—	0.010
7-26-78	0.53	0.018	0.10	0.006
8-01-78	0.59	0.014	0	0.003
8-09-78	0.32	0.013	0.13	0.002
8-16-78	0	0.019	0.18	0.003
8-23-78	0	0.018	0.26	0.068
8-31-78	0.02	0.014	0.40	0.014
9-07-78	0.08	0.015	0	0.027
9-13-78	0	0.015	0	0.016
9-20-78	1.74	0.014	1.50	0.012
9-28-78	0	0.021	0	0.078
10-4-78	0	Frozen	0	Frozen
4-27-79	12.2	—	6.4	—
5-02-79	5.0	—	1.0	—
5-11-79	0.8	—	0	—
5-16-79	2.0	0.040	0	0.025
5-24-79	0	0.011	0	0.020
5-30-79	0	0.012	0	0.018
6-05-79	1.6	0.008	1.0	0.017
6-13-79	2.1	0.076	0	0.030
6-19-79	1.4	0.025	0	0.025
6-26-79	1.4	—	1.6	0.027
7-03-79	0	0.222	0	0.027
7-09-79	0.8	0.118	1.6	0.053
7-17-79	0.8	0.020	1.0	0.053
7-24-79	0.2	0.040	—	0.053
7-31-79	0	0.038	0	0.050
8-08-79	0	0.023	0	0.047
8-14-79	1.2	0.017	0.2	0.042
8-21-79	1.4	0.015	0	0.014
8-29-79	0	0.015	0.2	0.036
9-05-79	8.2	0.022	—	0.031
9-11-79	0	0.017	0.2	0.030
9-17-79	0	0.017	2.2	0.027
9-26-79	0.8	0.014	0	0.025
10-9-79	1.6	0.020	0.8	0.022

Attempts to relate suspended sediment concentration to streamflow (discharge) were unsuccessful. While a general trend toward increased suspended-sediment concntration at high flows is discernible for both basins, the extremely wide scatter of observed data points severely limits the utility of this relationship. For this reason, we did not construct flow-duration or derived sediment-duration curves for these drainages.

Basin characteristics appear to more clearly reflect contrasts between north-aspect and south-aspect catchments. Bredthauer and Hoch (1979) measured drainage densities for the entire basin, utilizing all discernible inflections on existing contour maps and supplementing those with 1:18,000 scale aerial photography. Drainage density was consistently higher in predominantly south-aspect catchments than in north-aspect catchments. They attributed this to the extremely high moisture-retention capacity of the ubiquitous moss/lichen organic layer which carpets north-aspect landscapes underlain by permafrost. The deeper soil mantle and relatively shallow litter found on south-facing slopes provide increased opportunity for drainage development, increased stream length per unit area and thus increased opportunity for the stream to receive sediment. We have observed locally that north-facing slopes tend to be steeper than south-facing slopes (as has been noted elsewhere, e.g. French (1976), p 179). Lesser slope gradient and higher drainage density are consistent with suspended-sediment concentrations being higher in streams draining south-aspect landscapes — the more gentle slopes are expressions of greater weathering, increased soils development, higher drainage density, and increased subjection to geomorphic processes on warmer slopes.

A second question concerned the relation of channel parameters to aspect, order, and sediment regimen. The channel measurement results are tabulated in Table 3.

In hydraulic geometry analysis, width/depth ratio for channels at presumed bankfull flow has been utilized as a descriptor of relative channel shape (Leopold *et al.*, 1964). In this study, first-, second-, and third-order streams were surveyed. Bankfull cross-sectional data were stratified according to stream order. Comparisons of means for these classes (orders) of the width/maximum depth ratio showed inconsistent results; second-order channels had a lower average ratio than first-order streams, while third-order streams had the highest mean ratio (4.757). The same relative ranking occurred with the width/mean depth ratio; the ratio for second-order streams was lower than that for first-order, while third-order streams showed the highest ratio (7.256). Cross-sectional channel area (bankfull) did follow the expected pattern, progressively increasing with order. Simple "t-test" of means showed that bankfull cross-sectional area differences among these classes were statistically significant ($p=0.01$).

In comparisons of bankfull width/maximum depth ratios, channel cross-sections from permafrost-dominated sites consistently were different from channel cross-sections in either "mixed" (i.e., influence of permafrost in the catchment not clearly dominant) or non-permafrost-dominated settings. The difference in this ratio between "mixed" and

TABLE 3—Channel characteristics.

Site	Setting[1]	Basal aspect	Reach azimuth[2]	Stream order	Width/ max. depth	Channel area[3] (m^2)	Width/ mean depth	Channel slope
1	0	South	140°	1	2.758	0.85	4.475	0.118
2	0	South	190°	1	2.621	0.61	6.167	0.160
3	0	South	150°	1	3.056	0.76	5.170	0.159
4	0	South	150°	1	3.951	1.35	6.393	0.131
5	0	South	165°	2	2.780	0.41	5.343	0.050
6	0	South	165°	2	4.271	0.96	8.282	0.034
7	*	East	75°	2	1.882	1.31	3.380	0.036
8	*	East	75°	2	1.967	1.07	2.928	0.036
9	*	East	115°	3	2.478	1.01	4.129	0.167
10	*	Northeast	75°	1	1.951	0.46	4.390	0.068
11	*	Northeast	75°	1	3.318	0.36	6.731	—
12	?	East	95°	3	4.158	1.11	8.489	—
13	?	East	95°	3	2.489	1.91	4.028	—
14	*	North	10°	1	1.610	0.29	2.879	—
15	*	North	10°	1	0.933	0.21	1.374	—
16	*	South	170°	1	Ephemeral; active channel poorly defined			
17	*	East	75°	2	0.893	0.93	4.129	
18	*	East	75°	2	3.268	1.85	5.289	
19	0	Southwest	220°	1	6.302	0.22	9.364	0.169
20	0	Southwest	220°	1	4.876	0.68	6.839	0.110
21	0	South	180°	2	2.396	1.07	3.190	—
22	0	South	180°	2	1.929	1.08	2.933	—
23	?	East	110°	3	9.014	1.20	10.954	—
24	?	East	110°	3	6.411	1.68	10.427	—
25	8	West	280°	2	1.694	0.86	2.754	—
26	*	West	280°	2	1.937	0.75	2.908	—
27	0	South	250°	1	1.167	1.27	6.352	0.095
28	0	South	250°	1	2.453	0.77	5.289	0.095

TABLE 3—Channel characteristics—continued

Site	Setting[1]	Basal aspect	Reach azimuth[2]	Stream order	Width/ max. depth	Channel area[3] (m^2)	Width/ mean depth	Channel slope
29	0	Southwest	225°	2	3.223	0.96	5.388	0.042
30	?	Southwest	240°	2	4.351	0.25	7.523	—
31	?	Southwest	240°	2	3.483	1.04	4.087	—
32	0	South	200°	3	7.851	3.06	12.084	—
33	0	South	220°	3	4.101	3.53	6.362	—
34	0	Southeast		1	Ephemeral; active channel poorly drained			
35	0	South	150°	2	1.609	0.62	2.728	
36	?	East	120°	3	3.628	2.96	4.412	0.117
37	?	East	110°	3	2.685	3.79	4.422	0.177

[1] Setting: 0 Indicates clear preponderance of permafrost-free sites in contributing catchment; stream channel may be within mapped permafrost soil type.

* Indicates large proportion of contributing catchment occupied by permafrost soils; stream channel in permafrost.

? Indicates limited areas of permafrost in contributing catchment; stream channel is in permafrost.

[2] Azimuth of stream reach for surveyed channel.

[3] Cross-sectional area, m^2, of bank-full channel.

"non-permafrost" settings was non-significant. In comparisons of bankfull width/mean depth ratios, channel cross-sections in permafrost-dominated sites consistently were significantly ($p = 0.01$) different from channel cross-sections in either "mixed" or non-permafrost settings. The same comparison did not show any significant difference between the "mixed" and non-permafrost settings in terms of bankfull width/mean depth ratios. The width/depth ratios for both maximum and mean bankfull depths do suggest a tendency for channels to increase in width more rapidly than in depth downstream.

In first- and second-order streams, channel cross-sections in permafrost-dominated settings had lower average width/depth ratios, for both mean depth and maximum depth, than did channel cross-sections in non-permafrost-dominated settings. Differences between cross-sections in permafrost and non-permafrost settings were statistically significant ($p = 0.05$) in the case of first-order streams, but were not statistically significant in the case of second-order streams. The sample of third-order streams was not large enough to test possible influence of permafrost. The results suggest that stream channels developed in permafrost-controlled settings tend to expend more energy in downward cutting than in lateral widening, given similar valley materials.

These observations are in agreement with the suggestion of Leopold *et al.*, (1964) that channels developed in "cohesive" materials tend to be narrower (and therefore deeper) than channels developed in relatively less-cohesive materials. Most of the stream cross-sections measured were in soils mapped as either Bradway Silt Loam or Karshner Silt Loam (pergelic cryaquepts) (Rieger *et al.*, 1972), including all those cross-sections classified as "permafrost-dominated setting". A number of the first-order streams in settings classified as "non-permafrost-dominated" were developed in Olnes or Gilmore Silt Loams (typic cryorthents, typic cryothents) (Rieger *et al.*, 1972). The Bradway and Karshner series are considered permafrost soils, while the Olnes and Gilmore series are free from permafrost. While all are silt loams, relatively cohesive material in terms of channel development, we would suggest that the permafrost soils (Bradway and Karshner) are effectively more cohesive due to the frozen condition than are the non-permafrost soils (Olnes and Gilmore). This is supported by the channel geometry data discussed previously, in that the bankfull width/depth ratios (for both maximum and mean depths) were greater for permafrost-free channel settings than for permafrost-dominated channel settings.

Sediment load was apparently not directly related to channel characteristics at any given point in the stream system. However, these results are internally consistent. Average sediment load through the summer was greater in streams draining permafrost-free catchments; channel geometry data indicated that streams in permafrost-free settings tend to widen more rapidly than deepening, relative to permafrost-dominated streams. Increased widening entails increased bank-cutting, hence greater production of sediment — hence the higher average sediment load in permafrost-free streams.

CONCLUSIONS

Channel shape and sediment load of low-order headwaters streams appear to be influenced by occurrence of permafrost in the contributing catchments. Permanently frozen soils are effectively more cohesive than unfrozen soils, resulting in a tendency for stream channels to deepen rather than widen. During summer, sediment load was lower in the streams draining a permafrost-dominated catchment. Higher sediment yield from a permafrost-dominated catchment is attributed to a deeper, more easily-worked soil mantle and greater opportunity for weathering, along with higher drainage density than in permafrost-dominated settings.

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