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Snowmelt Runoff and Total Solids Production in a Discontinuous Permafrost Basin

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Edw. F. Chacho, Jr.
U.S. A. Cold Regions Research and Engineering Lab.,
Fort Wainwright, Alaska, U.S.A.

Snowmelt runoff and total suspended solids were measured for two years on Glenn Creek, a small, second-order, subarctic stream located near Fairbanks, Alaska, within the Yukon-Tanana Uplands physiographic province. The stream drains a 2.25-km^2 research watershed of which 70 % is underlain by permafrost. The two years of study represent very different snowmelt hydrographs due to differences in the snowpacks. In 1985, the snowpack was 180 % of the long-term average, while in 1988 it was only 56 % of the average. During both years, 60 % of the total snowmelt-season water yield had passed before a significant rate of solids yield was observed. Also in both years the peak in total suspended solids concentration lagged the stream discharge peak by three days. Diurnal fluctuations in discharge and total suspended solids concentrations are well-defined, including a peculiar occurrence of double diurnal peaks in the discharge hydrograph during portions of the snowmelt season. The diurnal fluctuations in solids concentration are shown to be consistent with water temperature fluctuations. In 1988, the percentage of organics in the total suspended solids was scattered from 0 % to 66 % during the snowmelt season.

Introduction

The literature on suspended solids discharge in northern rivers has been reviewed by Clark *et al.* (1988) and Clark (1988). A relatively large proportion of the studies was conducted on proglacial rivers (see, for example, Gurnell 1987). Relatively few studies have been reported for permafrost-dominated basins. The studies that have been reported are regional or restricted to the summer precipitation season. For example, the streams of the High Arctic (McCann *et al.* 1972), where the basins are nearly devoid of vegetated soils, and the Scandinavian subarctic (Threlfall 1986), where permafrost and the associated organic soil are not generally present, have streambeds that are composed of coarse sediments. Relationships from these studies are not directly transferable to the moss-covered basins of Interior Alaska, where the streams run through the fine silts and clays of loess deposits. In Interior Alaska, Slaughter *et al.* (1983), working on Caribou Creek, examined the relationship of total suspended solids and stream discharge for the precipitation runoff season only. Chacho (1990) reported on the discharge and total solids generation during a single snowmelt season on Glenn Creek, a small watershed in Interior Alaska. A search of the literature has not revealed additional studies that have examined in detail the temporal relationship between water and suspended solids discharge during the snowmelt season in a nonglacial, vegetated, permafrost basin. This paper examines the diurnal and seasonal variability of discharge and total suspended solids during the snowmelt runoff season on Glenn Creek, Alaska.

Site Description

Glenn Creek is a second-order stream located in a permafrost-dominated watershed 14 km north of Fairbanks, Alaska, at latitude 64°57'N, longitude 147°35'W at the southern edge of the Yukon-Tanana Uplands (Wahrhaftig 1965). The gaged area of the watershed is 2.25 km^2 and is uniformly distributed between the peak elevation of 493 m and 250 m at the basin outlet. The average basin slope is 0.184 m m^{-1} and ranges from near 0 to 0.6 m m^{-1}. About 30 % of the basin is covered by birch-aspen-white spruce stands on moderately well-drained silt loams covered with up to 15 cm of organic soil. This area is located on a south-facing slope where permafrost is not normally present. The remainder of the basin (70 %) is covered by black spruce stands on the north- and west-facing slopes and the valley floor. These areas are generally underlain by permafrost and consist of poorly drained mineral soils overlain by a 30-to-45-cm-thick organic mat. The entire length of the stream is contained within the permafrost portion of the basin. The stream type ranges from diffuse flow patterns among tussocks to a single channel incised up to 2 m. Where the channel penetrates the organic mat, the streambed and banks consist of silts and clays. A detailed description of the vegetation and geology of the basin is given by Dingman (1971). In previous studies at Glenn Creek, rainfall-runoff relationships have been described in detail by Dingman (1966, 1971, 1973) and related to slope hydrology by Chacho and Bredthauer (1983). Kane *et al.* (1981) discussed the results of lysimeter studies during the snowmelt season. Chacho (1990) reported on the water and suspended solids discharge during a single snowmelt season.

Measurements

From 1978 to 1988, streamflow had been measured near the outlet of the basin with a Parshall flume (229-mm throat width) and F-1-type water level recorder. In some years, a Campbell Scientific Instruments data logger was used to collect meteorological data and water temperature at the site, with the latter obtained by use of a thermistor installed at a fixed depth in the stream. The number of stream and meteorological parameters measured and the period of record has varied from year to year; in some years only the snowmelt runoff was measured, in some years only the summer precipitation events were measured, and in a few years the entire runoff season was measured.

During the 1985 snowmelt runoff season, an ISCO model 1680 automatic water sampler was installed at the flume, with the intake nozzle fixed at 20 mm above the floor of the flume inlet. Samples were collected primarily at 2-hr intervals, with infrequent, short sampling periods of 3-4 hr. The samples were returned to the lab, where specific conductance was measured and total solids concentration was determined by filtering the samples through pre-washed, tared Whatman 934-AH glass fiber filters, drying at 105°C and re-weighing. The organic or inorganic contents of the samples were not determined. Water temperature and meteorological parameters, other than precipitation, are not available.

During the 1988 snowmelt runoff season, the same sampler installation and sample reduction procedures were employed. In addition, the volatile portion of samples exceeding a total solids concentration of 20 mg L^{-1} was determined by ashing the filter and residue at 550°C and re-weighing (American Public Health Association 1971). In addition, a meteorological station was maintained at the site that collected data on incoming short-wave radiation, precipitation, air temperature and stream water temperature.

At the end of the summer, when air temperatures drop below freezing and rainfall events cease, water levels in Glenn Creek drop rapidly, and the stream usually freezes over by mid-October. Discharge ceases during the winter, evidenced by the flume freezing solid. However, the banks continue to drain, resulting in minor aufeis formation of 0.5 to 1 m thickness in the channel. At the initiation of the snowmelt season, the ice was manually cleared from the flume and from a reach of the channel above and below the flume to assure free flow through the flume. The short reach of the channel above the flume that was cleared of ice and snow had been completely lined with sandbags to eliminate scour in the channel due to possible early thawing as a result of the removal of ice and snow.

Clark *et al.* (1988) emphasized the complexity and variability in the relationship between discharge and sediment transport in northern basins where thermal mechanisms may play a dominant role. They further emphasized that a short-time-interval, systematic temporal sampling scheme may be required to adequately address the patterns of discharge and sediment transport during the snowmelt season. This was further emphasized in an earlier report on Glenn Creek (Chacho 1990), where high diurnal variability in stream discharge and total suspended solids, as well as water temperature, was reported. The sampling scheme used on Glenn Creek, stream discharge and water temperature at 15-min intervals and total suspended solids primarily at 2-hr intervals, seemed adequate to define the diurnal variability.

Results

Discharge Hydrographs

The hydrographs for the two snowmelt seasons during which total suspended solids were measured, 1985 (Fig. 1) and 1988 (Fig. 2), were significantly different because of a very large difference in the snowpacks. Based on the snow water equivalent measured on 1 April in Fairbanks (SCS 1985, 1988), the snowpack at the start of the snowmelt season in 1985 was about 3.2 times greater than that in 1988. In 1985 the snowpack water equivalent was 177.8 mm or about 180 % of the long-term average, while in 1988 it was only 55.9 mm or 56 % of the average. As a result, the total volume and peak flows of the 1985 hydrographs were much larger than those measured in 1988.

The air temperature data included in Fig. 1 is from Fairbanks, Alaska, as these data were not available at the study site in 1985. Due to differences in elevation, the air temperatures at Glenn Creek are slightly lower than in Fairbanks, consequently snowmelt at Glenn Creek lags the Fairbanks temperature record. Strong diurnal fluctuations in discharge were evident throughout the snowmelt season except on the receding limbs of the seasonal hydrograph (Fig. 1). The hydrograph was almost entirely snowmelt generated, except for a series of small rainfall events on 7-9 May that totaled 4.6 mm over the three-day period and on 19 May with 1.5 mm. A large rainfall event of 4.1 mm on 29 May, which occurred after a long recession in flow, was arbitrarily selected at the end of the snowmelt runoff season for this study.

In 1988, diurnal fluctuations in discharge were also evident throughout the snowmelt season except on the receding limbs of the seasonal hydrograph (Fig. 2). The 1988 snowmelt runoff hydrograph was significantly affected by rainfall events. The small early-season peaks on 1-2 May were most likely due to rain-on-snow events of 30 April-3 May, which totaled 8.1 mm. A small event of 2.5 mm on 7-8 May had little effect. From 12 May-16 May, 17.0 mm of rain fell on the last remains of the snowpack, which produced the seasonal discharge peak. A rainfall event of 3.6 mm on 19 May was arbitrarily selected as the end of the snowmelt runoff season for this study.

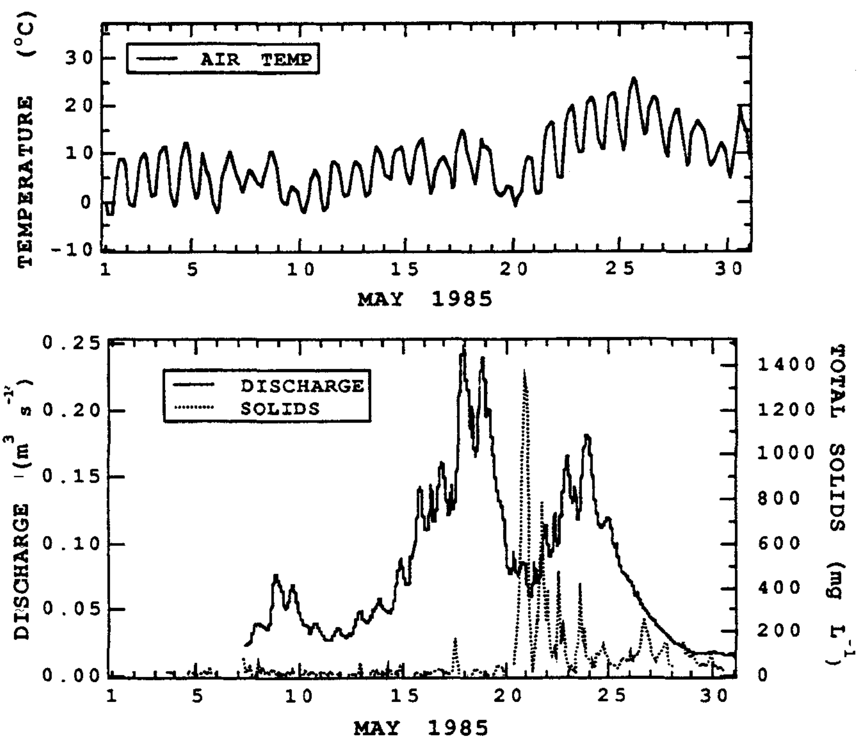

Fig. 1. Air temperatures at Fairbanks, Alaska, and discharge hydrograph and total suspended solids concentration for the 1985 snowmelt runoff season at Glenn Creek, Alaska.

Suspended Solids

The total suspended solids concentration, SS_t, for the 1985 snowmelt runoff season is shown in Fig. 1. Prior to 20 May, SS_t is very low, exceeding 50 mg L^{-1} only on 17 May, the day of the peak seasonal discharge. Significant SS_t does not begin until 20 May, when a rise in concentration from less than 50 mg L^{-1} to 1,337 mg L^{-1} occurred in a single day. The peak in SS_t occurred 17 days after snowmelt runoff was first detected in the stream and lagged the discharge hydrograph peak by 3 days. On 26 May, a secondary SS_t peak occurred, which lagged the 23 May hydrograph peak by 3 days.

In 1988, the magnitude and total volume of suspended solids transport are much lower than in 1985 due to the much smaller snowpack and snowmelt runoff (Fig. 2). However, except for the spike on 22 April, SS_t follows a similar pattern to that of 1985, where: concentrations remain low prior to the seasonal hydrograph peak, an SS_t peak exceeding 50 mg L^{-1} is coincident with the seasonal discharge peak, and the peak occurs on the hydrograph recession and lags the peak discharge by 3 days.

Comparison of Total Suspended Solids to Discharge

The seasonal relation between discharge and total solids concentration for the two years of record are similar. In 1985, the snowmelt runoff season lasted 28 days in which the peak discharge occurred 14 days after the initiation of streamflow and 90 % of the total snowmelt-season solids yield passed in a 10-day period. In 1988, the snowmelt runoff season lasted 32 days in which the peak discharge occurred 29 days after the initiation of streamflow and 66 % of the total snowmelt-season solids yield passing in a 5-day period. In both years, significant solids yield did not begin until 60 % of the total snowmelt-season water yield had passed.

At the beginning of the snowmelt runoff season, except for the short reach above the flume that had been cleared of ice, most of the flow appeared to take place on top of the snow and ice in the channel. This accounts for the early-season lack of suspended solids, as there was little contact of flowing water with the channel bed for thaw and erosion to take place. Therefore, there is no apparent explanation for the spike in SS_t on 22 April 1988 (Fig. 2) and it will be treated as an unexplained anomaly in the record at this time.

Thus it appears that solids generation lags water generation, in both total yield, where significant solids yield did not begin until 60 % of the total snowmelt-season water yield had passed, and instantaneous concentration, where the seasonal peak in SS_t consistently lagged the hydrograph peak by about 3 days. This observed lag agrees with Threlfall (1986) and Clark *et al.* (1988), who reported that ice/freezing armoring of the channel may cause sediment transport to lag the hydrograph peak in arctic and subarctic streams, particularly in headwaters or small basins.

Diurnal Fluctuations of Total Suspended Solids and Discharge

The 8-day period during which significant solids discharge had taken place in 1985, 20-28 May, has been expanded in Fig. 3 for closer inspection of the diurnal variability of the stream discharge and SS_t. The occurrence of double diurnal peaks in the snowmelt discharge hydrograph is apparent. This phenomenon occurs each year to varying degrees (*i.e.,* 25-29 April 1988, Fig. 1), and the diurnal timing of the peaks is generally consistent.

The 1985 seasonal SS_t peak occurring on 20 May corresponded very closely with the late-day or second diurnal discharge peak. The SS_t peak occurred 4 hr earlier on the successive day (21 May) and 4 hr earlier again on the next day (22 May), at which point the timing of the daily peak remained consistent for the remainder of the snowmelt runoff season. That includes the secondary SS_t peak on 26 May and the peak on the successive day, which occur on the recession limb of the hydrograph when double diurnal discharge peaks are no longer apparent. Therefore, it does not appear that the timing of the double diurnal discharge peaks affects the timing of the diurnal SS_t peak.

There were too few diurnal SS_t peaks in 1988 to perform a comparison of their timing to the timing of the diurnal discharge hydrograph. The 1988 seasonal SS_t

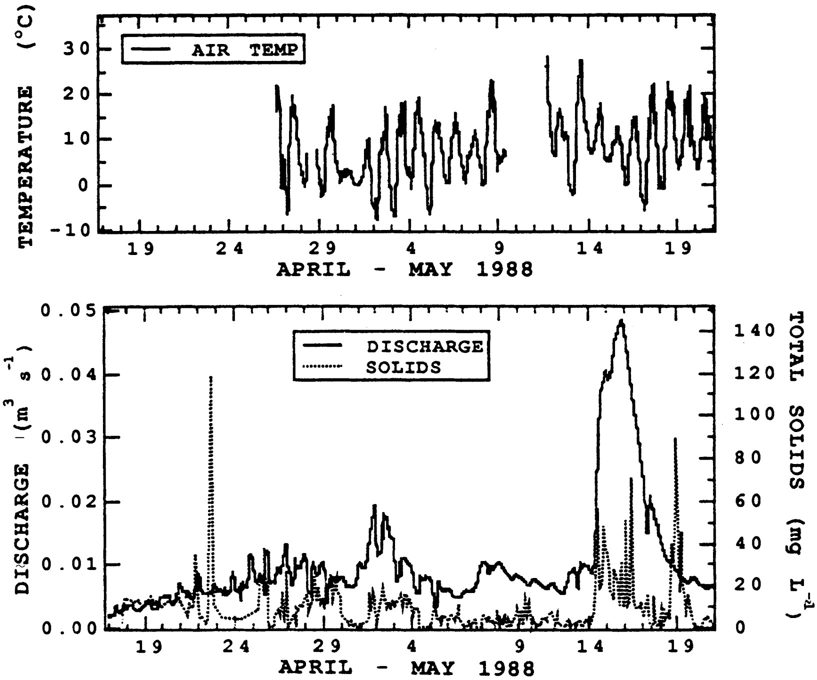

Fig. 2. Air temperatures, discharge hydrograph, and total suspended solids concentration for the 1988 snowmelt runoff season at Glenn Creek, Alaska.

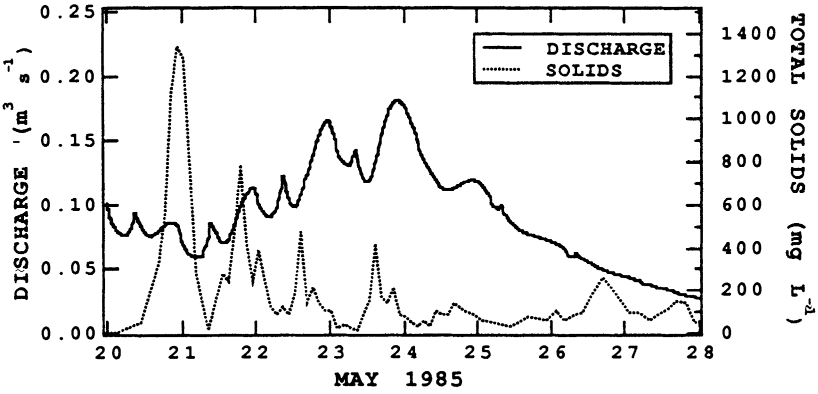

Fig. 3. 1985 Glenn Creek discharge hydrograph and total suspended solids concentration for the 8-day period, 20-28 May, of significant suspended solids discharge.

peak occurred late in a day of steady hydrograph recession and was not related to a diurnal discharge peak in any way (Fig. 2). It is of interest to note that the seasonal SS_t peak occurred at nearly the same time of day, near midnight (2400 hr), in both 1985 and 1988, when very dissimilar discharge hydropgraphs were observed.

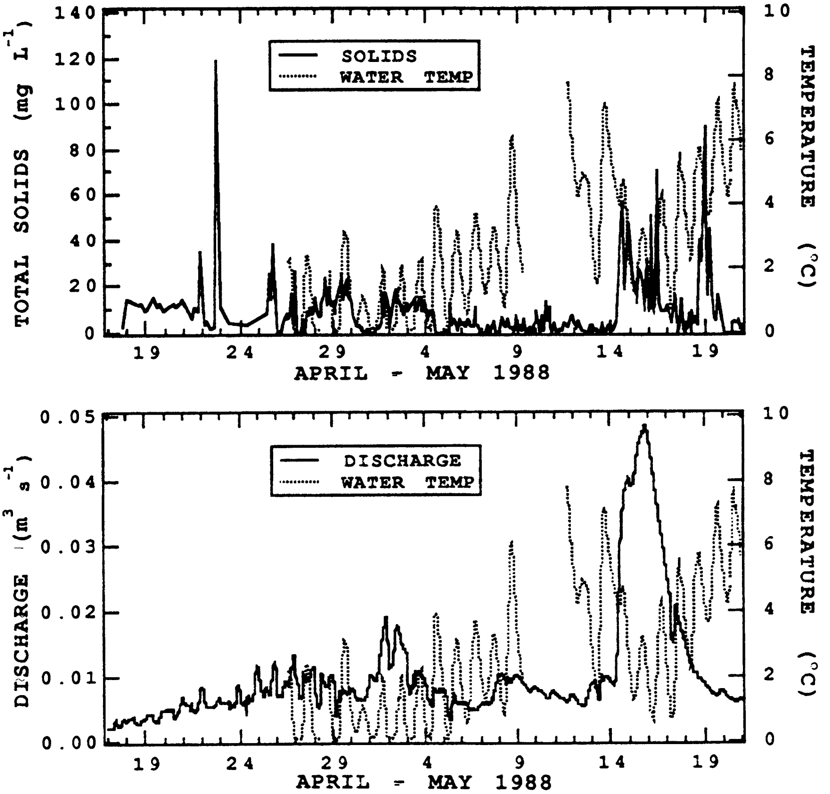

Fig. 4. 1988 Glenn Creek discharge hydrograph and water temperature; and total suspended solids discharge and water temperature.

Comparison of Discharge and SS_t to Water Temperature

To further investigate the diurnal fluctuations in discharge and SS_t, it is of interest to make the comparison to diurnal water temperature fluctuations. For example, if the double diurnal discharge peaks were a result of differences in travel times from distinct multiple source areas in the basin then double diurnal peaks or a wide flat peak in the diurnal water temperature might be expected. In addition, since the lag of SS_t to discharge on a seasonal basis may be attributed to ice/freezing armoring of the channel, it is of interest to investigate the relationship between diurnal fluctuations of SS_t and water temperature.

Although the snowmelt volume in 1988 was so low that hydrograph characteristics are not well-defined, it is apparant that, on the few days that double diurnal discharge peaks occurred, the trough between the peaks was not associated with a drop in water temperature (Fig. 4). The comparison of the diurnal variability of SS_t and water temperature shows that the seasonal SS_t peak lags the diurnal water temperature peak by 6 hrs (Fig. 4).

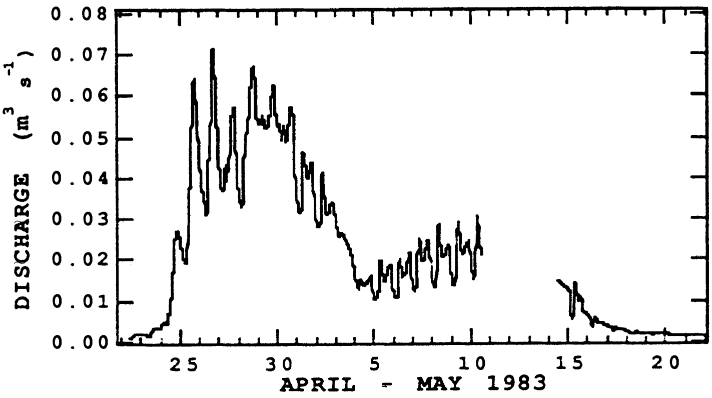

Fig. 5. Discharge hydrograph for the 1983 snowmelt runoff season at Glenn Creek, Alaska.

Due to the greater activity and variability in both discharge and SS_t in 1985, it is of more interest to compare the 1985 discharge and SS_t record to water temperature. Unfortunately water temperatures are not available for 1985. Water temperature data had been collected in previous years and is available for comparison to the hydrograph during the occurrence of double diurnal discharge peaks. Chacho (1990) reported that a search of data from previous years indicated that a portion of the 1983 hydrograph (Fig. 5) included strong double diurnal discharge peaks and displayed many similarities to the 1985 hydrograph during the 8-day period of significant solids discharge. The similarities include the development of strong double diurnal discharge peaks after the snowmelt runoff season peak discharge and their occurrence on the rising limb of a secondary peak in the discharge hydrograph.

A comparison of the double diurnal discharge peaks to water temperatures in 1983 (Fig. 6) shows clearly, as did the 1988 data discussed previously, that the trough between the diurnal discharge peaks is nearly coincident with the peak diurnal water temperature. The shape of the 1983 diurnal water temperature curves is consistent from day to day and, for the most part, follows what would be expected for the diurnal variability during the snowmelt runoff period. The temperature data shows no indication that the double diurnal peaks in the discharge hydrograph are a composite of runoff from two sources in the watershed with different times of concentration. At this time the cause of the double diurnal discharge peaks is unknown and awaits further analysis.

Based on the similarities in the seasonal and daily discharge hydrographs discussed above, it is assumed that, for qualitative comparison purposes, the water temperatures measured on 4-12 May 1983 (Fig. 6) are similar to those that occurred on 20-28 May 1985 (Fig. 3). The 1985 SS_t and 1983 water temperatures are compared in Fig. 7. Since this is an assumed match between data from two different

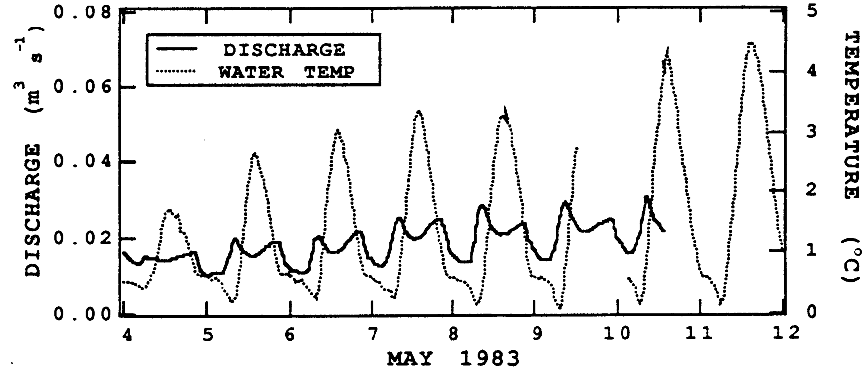

Fig. 6. 1983 Glenn Creek discharge hydrograph and water temperature for the 8-day period, 4-12 May.

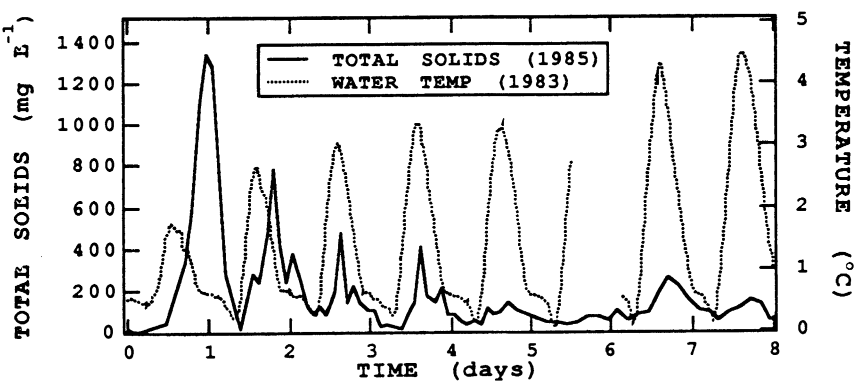

Fig. 7. Comparison of 4-12 May 1983 water temperatures and 20-28 May 1985 total suspended solids concentration at Glenn Creek, Alaska.

years, detailed or quantitative analysis is not warranted. However, a few qualitative observations can be addressed. First, after a short adjustment period, the timing of the diurnal peaks of water temperature and SS_t are very similar. As discussed above, the timing of the SS_t peaks gradually shifts over the first 3 days of this period, with the result that the SS_t peak initially lags the water temperature peak by about 8 hr, but by the third day the timing of the diurnal peaks matches very closely. Second, both water temperature and SS_t drop to near zero values at the end of each day (Fig. 7), even though the diurnal minimum discharge may remain relatively high, such as on 21-24 May (Fig. 3), or the discharge declines steadily over the entire day, such as 25-28 May (Fig. 3). The apparent correlation between these two characteristics of the SS_t and water temperature diurnal variability indicates that the timing of solids discharge during the snowmelt season is less a function of stream discharge and more a function of heat flow in the watershed.

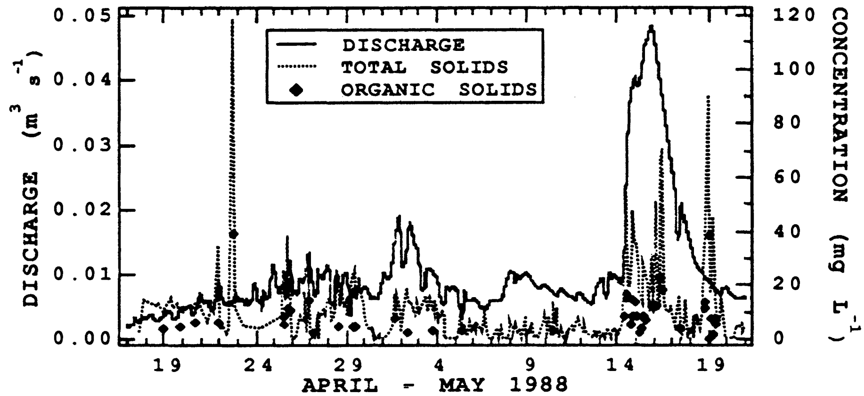

Fig. 8. Discharge hydrograph, total suspended solids and suspended organic solids concentration for the 1988 snowmelt runoff season at Glenn Creek, Alaska.

This does not necessarily mean that SS_t is directly related to water temperature, only that it appears that the factors which influence water temperature may also influence SS_t, whether it be to melt through the ice cover and thaw the streambed within the channel banks or to thaw the watershed surface sufficiently for erosion and entrainment of solids by surface runoff to take place.

Organic-Inorganic Solids Discharge

The source of solids production during the snowmelt runoff season must play a major role in the timing of solids discharge. In a permafrost-dominated basin, where the thaw depth is very shallow during the snowmelt season, nearly all surface and subsurface runoff occur in the upper organic soil layers (there may be isolated, localized areas where subsurface channels penetrate the organic soils and erode the underlying mineral soils). The stream channel is generally deeply incised, penetrating the organic soils, and the entire flow area is contained in the mineral soils. Therefore, the composition of the solids discharge may differentiate between in-channel and watershed sources of solids production. High organic solids concentration would be indicative of a watershed source, and high inorganic or sediment concentration would be indicative of an in-channel source.

In 1988, the organic portion of the samples with SS_t exceeding 20 mg L^{-1} were determined as volatile solids (Fig. 8). With the exception of two samples (54 % on 27 April and 66 % on 19 May), the percentage of organics in the total solids load was less than 50 % during the entire snowmelt runoff season, indicating that the majority of the solids production was from within the stream channel. The small snowpack and low snowmelt runoff apparently restricted overland and shallow subsurface flows on the watershed which limited the generation of organic solids. An average or larger snowpack may produce much different results.

Summary and Discussion

Three snowmelt hydrographs were presented, 1983, 1985 and 1988 (Figs. 6, 1 and 2, respectively). The snowmelt hydrographs were nearly the same length: 1983, 30 days; 1985, 28 days and 1988, 32 days. The hydrograph peak occurred after 5 days in 1983, 14 days in 1985 and 29 days in 1988, illustrating the variability in the timing of the snowmelt season hydrograph peak, as it occurred at the beginning, middle and end of the snowmelt runoff season.

In the two years that total suspended solids were measured, 60% of the total snowmelt discharge volume passed before significant solids yield began. The majority of the total suspended solids passed in a short time; in 4 days in 1985, 22% of the total discharge volume accounted for 71% of the total suspended solids yield, and in 3 days in 1988, 30% of the total discharge volume accounted for 56% of the total suspended solids yield.

The total suspended concentration was low (less than 50 mg L^{-1}) during the early portion of the snowmelt runoff season. In both 1985 and 1988, after initiation of the rising limb of the seasonal hydrograph peak, a small spike in suspended solids concentration was observed. The peak in suspended solids concentration lagged the discharge peak by 3 days in both years and a secondary suspended solids concentration peak also lagged a secondary discharge peak by 3 days.

Double diurnal discharge peaks were observed in the three snowmelt hydrographs presented. The double diurnal discharge peaks are not correlated with diurnal water temperature fluctuations. Chacho (1990) had reported earlier that the double diurnal discharge peaks were not explained by diurnal changes in specific conductivity. The cause of the double diurnal discharge peaks has not yet been explained.

During the periods when high solids yields were observed, the diurnal peak of the total suspended solids concentration initially lagged the diurnal water temperature peak, but shifted over a 3-day period to match the timing of the water temperature peak. Total suspended solids concentration and water temperature dropped to near zero values each day, indicating that watershed heat flow influences the production of solids discharge.

In 1988, the organic and inorganic portions of the total solids samples were measured. Low flow and low total suspended solids concentration in 1988 restricted the determination of source areas of solids production. The percentage of organics in the samples ranged from 0% to 66%, with no apparent relation to discharge or magnitude of solids concentration.

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Edw. F. Cacho, Jr.

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Address:
U.S. Army Cold Regions Research and Engineering Laboratory,
Building 4070,
Fort Wainwright, Alaska,
U.S.A. 99703-7860.