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# Hydrometeorology, Suspended Sediment and Conductivity in a Large Glacierized Basin, Slims River, Yukon Territory, Canada (1993–94)

M. SAWADA[1] and P.G. JOHNSON[1]

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ABSTRACT. The Slims River was monitored for global solar radiation, air temperature, discharge, suspended sediment, and dissolved load in 1993 and 1994. Peak seasonal discharge occurred late in the summer and reflects a typical glacierized basin hydrograph, with increased bare ice surfaces contributing strongly to discharge in July and August. Air temperature, rather than global solar radiation, was most strongly correlated with discharge in both years, but during sustained ablation, air temperature becomes a poor index of meltwater production. Precipitation was infrequent and of low magnitude. The variance in suspended sediment concentration could be explained only in part by discharge; frequent clockwise hysteresis and seasonal sediment concentration peaks unrelated to discharge variations also contributed to this variance. High concentrations of $Ca^{2+}$ and $Mg^{2+}$ in meltwaters reflect the lithological influence of carboniferous sedimentary rocks in the basin. Conductivity and individual cation concentrations decreased during both seasons and were inversely related to discharge. Diurnal conductivity amplitude was greatest during glacier melt, and frequent clockwise hysteresis was observed in both years.

Key words: conductivity, discharge, glacier, hydrology, hysteresis, sediment transport, Slims River, Yukon

RÉSUMÉ. En 1993 et 1994, on a installé des appareils sur la rivière Slims pour mesurer le rayonnement solaire global, la température de l’air, le débit, les sédiments en suspension et la charge dissoute. Le débit saisonnier de pointe se produisait tard durant l’été et reflète l’hydrographe typique d’un bassin englacé, où les surfaces de glace vive plus étendues en juillet et en août contribuent fortement au débit. Au cours de ces deux années, la température de l’air plutôt que le rayonnement solaire global était très fortement corrélée au débit, mais la température de l’air devient un index médiocre de la production d’eau de fonte durant une période d’ablation intense. Les précipitations étaient rares et de faible intensité. La variance dans la concentration des sédiments en suspension pourrait s’expliquer en partie seulement par le débit; une hystérésis dextrorse fréquente et des pointes non reliées à la variation du débit dans la concentration saisonnière de sédiments contribuaient également à cette variance. De fortes concentrations de $Ca^{2+}$ et de $Mg^{2+}$ dans l’eau de fonte reflètent l’influence lithologique des roches sédimentaires carbonifères dans le bassin. La conductivité et la concentration en cations individuels diminuaient durant les deux saisons et étaient inversement reliées au débit. L’amplitude de conductivité diurne était la plus grande durant la fonte glaciaire, et on a observé une fréquente hystérésis dextrorse au cours des deux années.

Mots clés: conductivité, débit, glacier, hydrologie, hystérésis, transport solide, rivière Slims, Yukon

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## INTRODUCTION

Human use of areas affected by glacial runoff has produced a growing need to understand and predict the hydrological regimes of glacierized basins. In such basins, the contribution of icemelt to river flow is greatest during dry hot summers, and icemelt can compensate for lack of rainfall in semiarid regions (Fountain and Tangborn, 1985). Thus icemelt directly affects hydroelectric power production (e.g., Østrem, 1973; McGowan and Sturman, 1996), agricultural activities, and water supplies (e.g., Butz, 1989) that rely on glacial meltwater. Additionally, understanding glacial hydrological regimes along a number of spatiotemporal scales is fundamental for modeling exercises that aim to predict how meltwater production will change in response to changing climate (Davidovich and Ananicheva, 1996; McGowan and Sturman, 1996; Melack et al., 1997; Singh and Kumar, 1997). The majority of empirical studies on glacierized basin hydrology have focused on small glacierized basins (Table 1). While Table 1 is by no means exhaustive, it suggests a need for similar studies in larger glacierized basins. Considering the importance of predicting runoff from glacierized basins in the face of global warming and increased population pressure in areas influenced by glacial meltwaters, a fundamental question is the degree to which large and small glacierized basins exhibit consistent hydrological, sedimentological, hydrochemical, and hydrometeorological behavior.

We present the results from two field seasons of monitoring the Slims River, which emanates from the

[1] University of Ottawa, Center for Research on Cold Environments, Department of Geography, Ottawa, Ontario K1N 6N5, Canada; msawada@aix1.uottawa.ca; peterj@aix1.uottawa.ca

TABLE 1. Representative sample of studies on glacierized basin hydrology.

| Basin/Glacier/Location | Basin Size ($km^2$) | % Glacier Cover | Study Type[1] | Author |
|---|---|---|---|---|
| Moiry Glacier | | | HC | Lorrain and Souchez, 1972 |
| Tsijiore Nouve, Switzerland | 4.8 | 71 | S | Lemmens and Roger, 1978; Gurnell, 1982; Gurnell et al., 1988; Gurnell and Warburton, 1990 |
| Bas Glacier d'Arolla, Switzerland | 7.6 | 70 | S | Gurnell et al., 1988; Gurnell and Warburton, 1990 |
| Midtdalsbreen, Switzerland | 9.6 | 77 | S | Willis et al., 1996 |
| Haut Arolla, Switzerland | 11.74 | 54 | HC | Brown and Tranter, 1990 |
| Bondhusbreen - Norway | 15 | 83 | H,S | Hooke et al., 1985 |
| Erdalsbreen, Norway | 16 | 69 | S | Østrem, 1973 |
| Miller Creek, British Columbia, Canada | 21.6 | 25 | HC | Zeman and Slaymaker, 1975 |
| Peyto, Alberta, Canada | 22 | 64 | H,HM,S,HC | Binda, 1984; Munro and Young, 1982 |
| Dokriani glacier (Bamak), Himalaya | 23 | 45 | S,HC | Hasnain and Thayyen, 1996 |
| Findelengletscher, Switzerland | 24.9 | 76 | HC,S,H | Collins, 1995 |
| Nigardsbreen, Engabreen, Austre Memurubre, Vesledalsbreen, Norway | Glacier area 40, 39, 9 and 4 | | S | Østrem, 1973 |
| Variegated Glacier, Alaska, USA | 72 | 62.5 | H,S,HC | Humphrey et al., 1986 |
| Gornergletscher, Switzerland | 82 | 83 | HC | Collins, 1979a, 1979b, 1983, 1991 |
| Tsanfienron Glacier, Switzerland | < 100 | < 50 % | HC | Lemmens and Roger, 1978 |
| Oeschinensee Lake, Swizerland | < 100 | 30 | S | Leemann and Niessen, 1994 |
| Batura Glacier, Himalaya | 649 | 56.3 | S | Collins, 1998 |
| Kaskawulsh Glacier, Yukon, Canada | 2456 | 65 | HM | Barnett, 1974; Bryan, 1974a; Johnson, 1991a |

[1] hydrology/subglacial (H), hydrometeorology (HM), sedimentology (S) and hydrochemistry (HC).

Kaskawulsh Glacier, one of the largest valley glaciers in the St. Elias Mountains, Yukon Territory, Canada. Previous research on the Slims River focused on the glacial-fluvial history and annual hydrometeorological regimes (Fahnestock, 1969; Barnett, 1974; Bryan, 1974a, b, c, d; Johnson, 1991a, b). Our objectives are to illustrate the behavior of the suspended sediment, discharge, bulk hydrochemistry, and hydrometeorology of this large glacierized basin on hourly and daily time scales and to place these results within the context of the studies on smaller glacierized basins that dominate the literature.

## STUDY AREA

The Slims River valley is situated in the Kluane National Park Reserve (Fig. 1). The Slims River drainage basin is 2456 $km^2$, of which 55% is glacierized. The glacierized area can be subdivided further into the 2020 $km^2$ Kaskawulsh glacier basin, which is 65% glacierized, and the lower 436 $km^2$ basin, which is only 9% glacierized (Johnson, 1991b). The basin bedrock is heterogeneous (Fig. 1). Mesozoic granitic intrusive bodies within older Paleozoic volcanic rocks are observed near the south end of Kluane Lake (Muller and Christie, 1965; Wheeler et al., 1997). In the lower basin, surrounding the Slims River, Paleozoic slate, greywacke, and conglomerates are common. Mesozoic schist and gneiss surround the main arm of the Kaskawulsh glacier, while Paleozoic carboniferous rocks such as limestone and dolomite underlie most of the upper basin of the Kaskawulsh Glacier, with intermittent intrusive bodies of Mesozoic granodiorite and quartz diorite (Wheeler, 1962; Wheeler et al., 1997).

Meltwater from the Kaskawulsh Glacier forms 70–90% of the Slims River flow, and the remainder is derived from tributary streams (Fig. 2) below the glacier terminus (Bryan, 1974a; Johnson, 1991b). The Kaskawulsh Glacier terminus lies on the hydrological divide between the Alsek River system, of which the Kaskawulsh River is a tributary, and the Yukon River system, of which the Slims River is a tributary (Fig. 2). Kaskawulsh Glacier meltwater may flow predominantly through only one of these river systems in a given year (Barnett, 1974; Bryan, 1974a,b; Johnson, 1991b). Evidence of year-to-year variation in Kaskawulsh Glacier meltwater routing has been observed in Kluane Lake discharge hydrographs (Johnson, 1991b). Kluane Lake discharge hydrographs for 1993 and 1994, however, indicate that Kaskawulsh Glacier meltwaters were channeled via the Slims River into the Yukon River system.

## METHODS

The first field season was from 9 April to 24 June 1993, and the second from 11 May to 5 August 1994. We chose methods and collected data to assess the short-term and seasonal changes in the hydrological, sedimentological, hydrochemical, and hydrometeorological variables.

In both 1993 and 1994, hourly meteorological observations of precipitation and air temperature were collected at the Slims River bridge gauging site and at the Kluane Lake

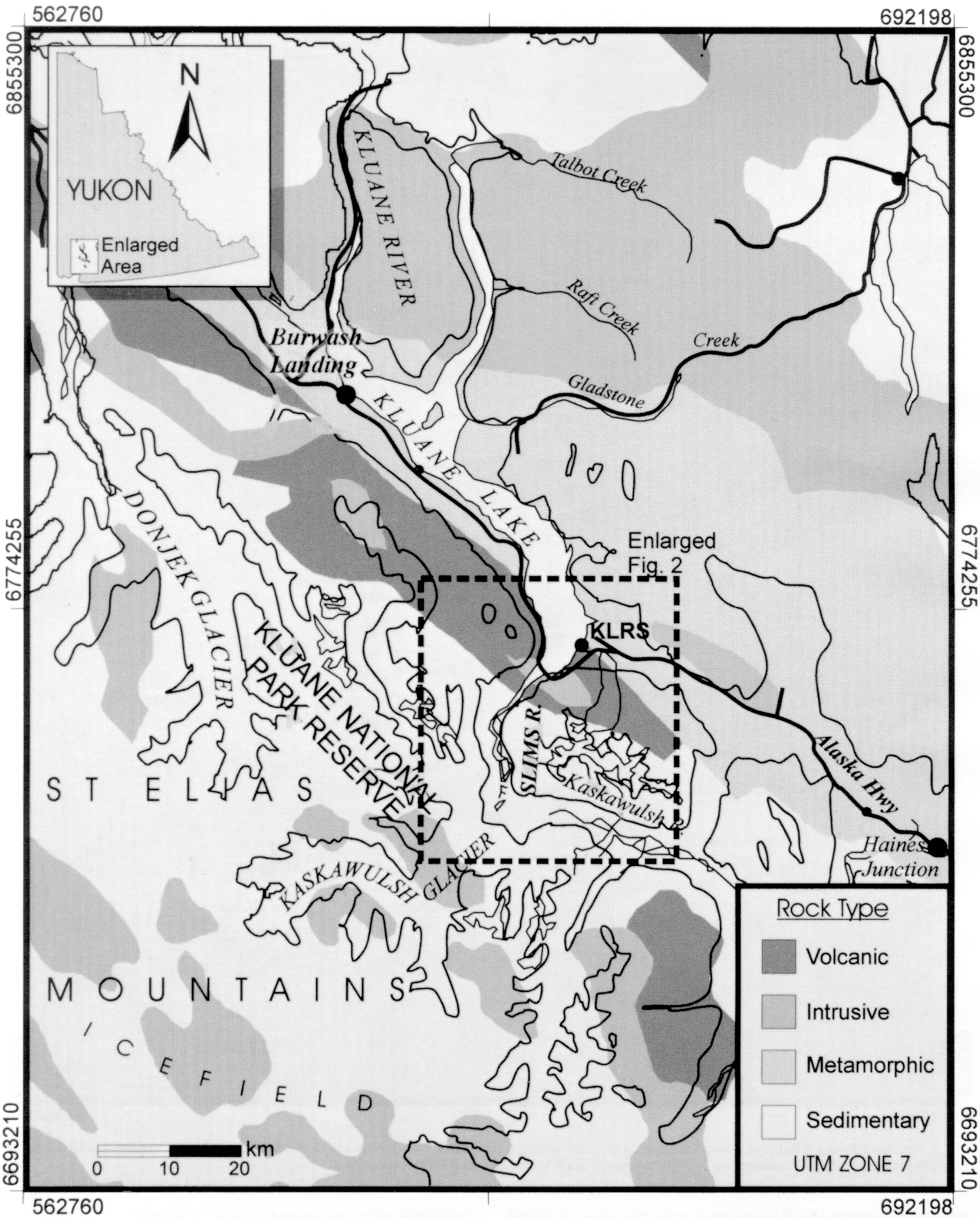


FIG. 1. Regional setting and lithology. Rock types modified from Wheeler et al. (1997). Coordinates are in projected meters under Universal Transverse Mercator Zone 7.

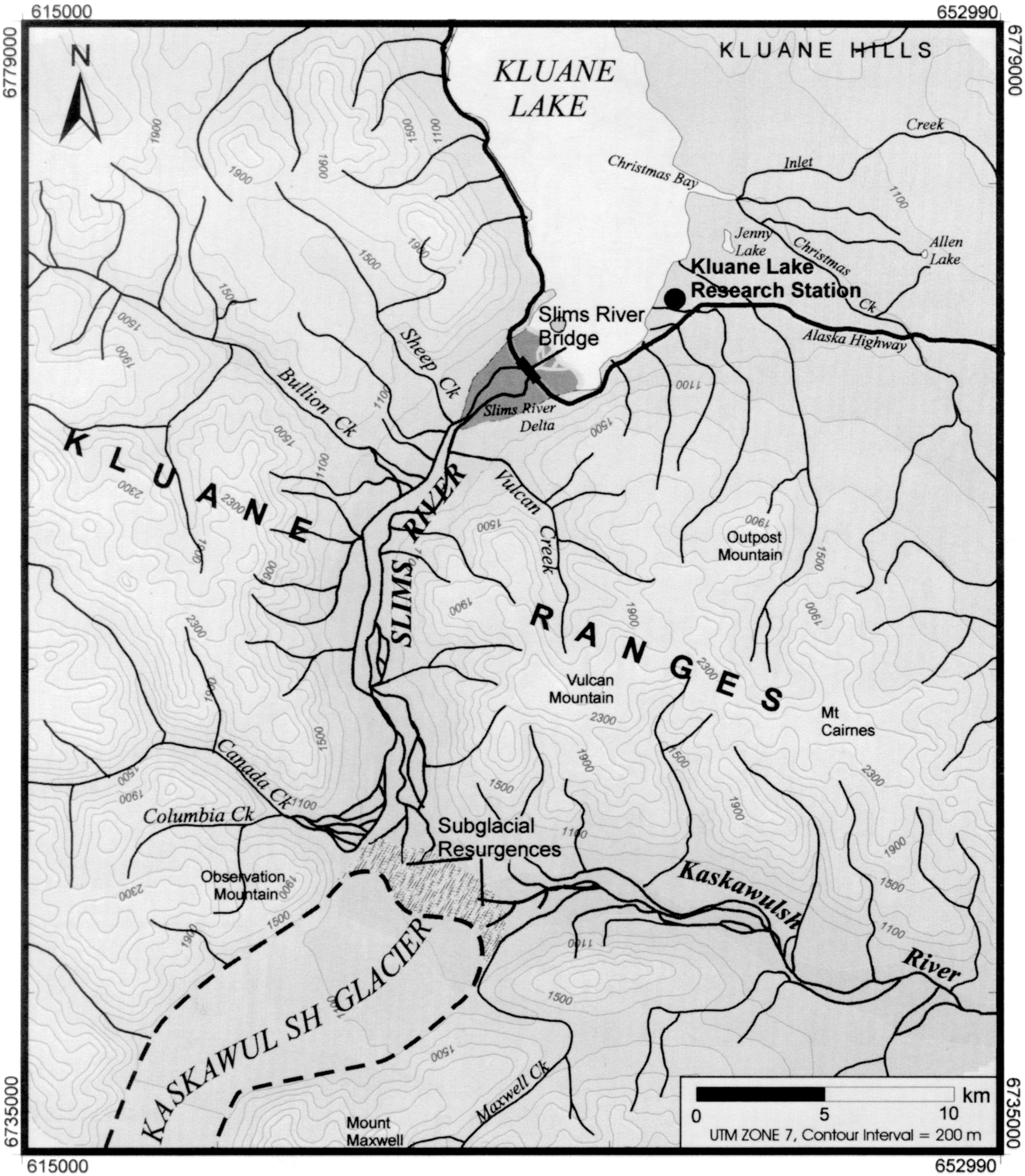


FIG. 2. The Slims River and its major tributaries. Location of sampling station at the Slims River Bridge and meteorological monitoring station at the Kluane Lake Research Station (KLRS). Coordinates are in projected meters under Universal Transverse Mercator Zone 7.

Research Station (KLRS) of the Arctic Institute of North America (Fig. 2), using Meteorological Research Incorporated (MRI) Mechanical Weather Stations. Global solar radiation was measured using a Robitzsch Bimetallic pyranograph. The observations made using this WMO Class 6 shortwave instrument are sensitive to the

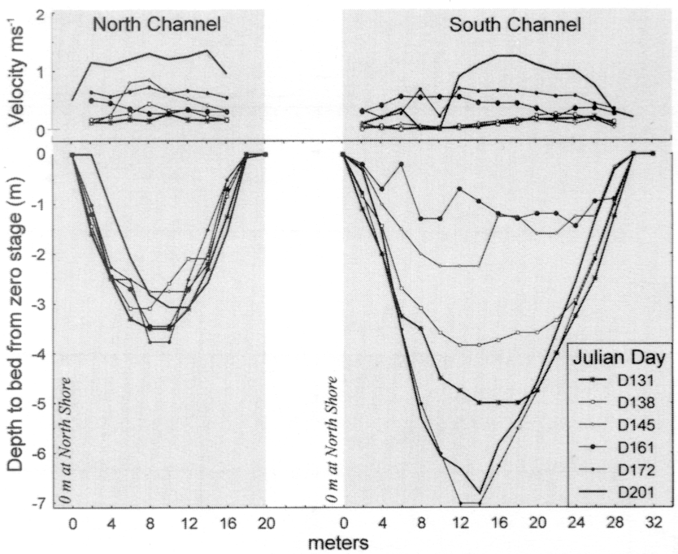


FIG. 3. Representative curves for the 1994 bed level (cross-sectional changes) and velocity in the north and south channel of the Slims River.

temperature of the instrument casing, radiation intensity, elevation, and the azimuth of the sun (Fritschen and Gay, 1979). We present global solar radiation for a given hour as the average incoming and diffuse shortwave radiation (W $m^{-2}$) observed in the previous 60 minutes.

In its delta, the Slims River is constricted into two channels beneath the Slims River bridge before it enters Kluane Lake (Fig. 2), the north channel (20 m wide from shore to shore) and the south channel (32 m wide; Fig. 3). These channels provide a fixed cross-section for continuous monitoring. Instantaneous discharges were determined at the Slims River bridge 23 times in 1993 and 20 times over the sampling season of 1994. To calculate discharges, we measured velocities using an electrostatic current meter every two meters across both channels beneath the Slims River bridge, taking one measurement per vertical at approximately 0.6 times the depth. Representative depth and velocity profiles for the 1994 season are presented in Figure 3. For 1994, the mean seasonal velocities measured in the north channel (0.53 ± 0.32 SD m $s^{-1}$) were somewhat higher than the average measured in the south channel (0.37 ± 0.35 SD m $s^{-1}$). Depth profiles were obtained by using a graduated, weighted cable in 1993 and by Raytheon sonar in 1994. An Ott Type X stage recorder continuously traced relative water stage. Daily water levels were recorded from a fixed staff that allowed stage to be transferred to metric units. In 1994 the equation $Q = 41.35 + 138.62s + 105.18s^2$ ($r = 0.88$; $p < 0.05$) was used to transfer stage ($s$ cm) to discharge ($Q$ in $m^3\,sec^{-1}$), and in 1993 the equation was $Q = 28.64 + 67.95s + 35.34s^2 - 30.55s^3$ ($r = 0.98$; $p < 0.05$). Optimal fits were based on adjusted $r^2$. Separate curves for each season are used for two reasons. First, stream geometric changes due to bed-level changes (Fig. 3) between the two seasons made a combined set less accurate. Second, we changed to bathymetric measurement in 1994. Sources of error in these rating curves are due to channel cross-sectional changes. For example, in 1994, the south channel bed underwent a period of accretion from day 131 to day 161 and was scoured by day 172 but then became relatively constant (Fig. 3). Depth in the north channel remained relatively stable throughout the monitoring season (Fig. 3).

In both monitoring seasons, suspended sediment was collected hourly from the Slims River at the Alaska Highway Bridge using an Alpha Sigma automatic pump-sampler with a hose length of 4 m that was pre- and post-purged. The nozzle intake was adjusted daily so that it remained ~1.5 m from the shore at ~1/3 stream depth ± 10 cm, which is one-half the maximum observed diurnal stage variation due to rising and falling discharges. Because of diurnal stage variation, samples may not be representative of instantaneous sediment concentration but their relative temporal variability should be maintained. In 1993, water samples were filtered through pre-weighed Whatman ashless quantitative 44 filter papers (3 mm retention) using air pressure, dried under three 100-watt light bulbs in a closed reflective box for 24 hours, and then re-weighed. If the filtered water was turbid, the sample was discarded. The suspended sediment in a sample was measured as the difference in weight between the dry, sediment-laden filter and a clean, dry filter. In 1994, evaporation rather than filtration was used to determine suspended sediment concentration, following the methods outlined by Gregory and Walling (1973) and Ward (1984). In both years, no correction for dissolved solids (DS) was required because the suspended sediment weight was always appreciably greater than the average 74 mg $l^{-1}$ DS in the samples (see Ward, 1984 for a discussion).

A Yellow Springs Instruments (YSI) Model 33 Salinity, Conductivity, and Temperature meter measured conductivity hourly in both seasons. In 1994, all conductivity values were calibrated to a reference temperature of 25˚C (Dackombe and Gardiner, 1983). In 1993, however, water temperatures were not taken with conductivity measurements because of malfunctioning equipment, so conductivity calibration was not possible. Consequently, in this paper we present uncalibrated conductivity for both seasons. The uncalibrated conductivities for 1994 have an $r = 0.98$ correlation with the calibrated series and adequately capture the variation in conductivity over the monitoring season.

All statistical analyses used standard procedures designed for the Gaussian distribution. To remove low-order serial dependency prior to cross-correlation analyses, time series were detrended, mean subtracted, and differenced after missing observations were filled by linear interpolation. For bivariate correlations, these operations were not performed. All reported correlation coefficients ($r$) are significant at the $\alpha = 0.05$ level unless otherwise specified. Daily averages (totals in the case of precipitation) were calculated for Julian days 117–174 in 1993 and days 129–216 in 1994, the common time periods in both seasons that had observations for most variables. Missing data was filled in by linear interpolation before averaging.

## RESULTS

### *Site Meteorology*

Burwash Landing and Haines Junction (Fig. 1) are the nearest permanent meteorological monitoring stations. Sporadic meteorological data are available from observations taken by the Icefield Ranges Research Project at KLRS in 1946 and in 1970–71 and by Nickling (1976) during the summer months of 1972–73. Summer data are also available from the present investigation for 1993 and 1994. Data from Burwash Landing and Haines Junction indicate that June, July, and August receive the most precipitation. When compared to the existing records, precipitation and temperatures measured during the present investigation are within the range of variability previously observed.

### *Hydrometeorology*

**Mean Daily and Hourly Precipitation and Discharge**: Effects of total daily precipitation on mean daily discharge were not clearly evident in either year (Figs. 4 and 5). On an hourly time scale, in 1993, no major modification of diurnal discharge amplitudes was associated with precipitation events (Fig. 6). In 1994, immediately after precipitation events on days 163, 168, 181–183, and 209–211, the minimum diurnal discharges were higher than those observed on the preceding or following days (Fig. 7). Consequently, precipitation at those times may have indicated basin-wide events. Increased minimum diurnal discharges were also observed on days 188 and 156, in the absence of recorded precipitation events. These latter increases were associated with decreased global radiation and cool temperatures, which may have indicated precipitation in the Kaskawulsh Glacier basin (Fig. 7).

**Mean Daily Discharge, Global Shortwave Radiation, and Temperature**: In both years, in general, mean daily air temperatures first reached a maximum (or minimum) and were then followed by peaks (or troughs) in mean daily discharge (Figs. 4 and 5). This lag was more pronounced in the later part of the 1994 season and accounts for some of the scatter in the mean daily discharge and air temperature rating plot (Fig. 8A).

For both years, no significant correlation exists between mean daily shortwave radiation and mean daily discharge. Mean daily discharge and mean daily air temperature, however, are strongly correlated ($r$ = 0.72 for 1993; $r$ = 0.60 for 1994). Moreover, for 1994, in the same time period common to 1993 (days 129–174), the relation between mean daily discharge and mean daily air temperature is $r$ = 0.80. After day 174 in 1994, the correlation between mean daily discharge and air temperature drops to $r$ = 0.34 ($r$ = 0.29 for the hourly series until day 174, and $r$ = 0.01 for the hourly series for day 175 and after; Fig. 8A). This weak correlation after day 174 suggests that

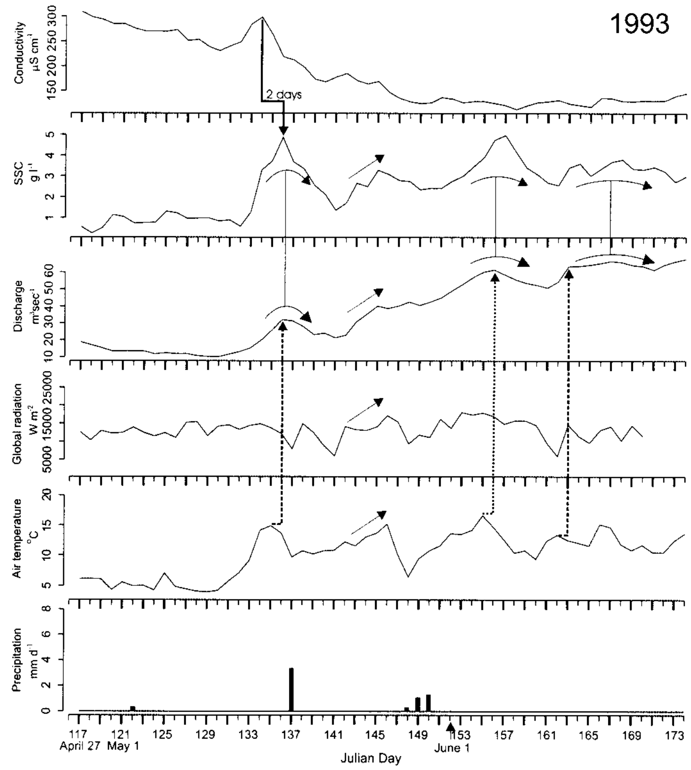


FIG. 4. Mean daily time series for 1993. Solid arrow indicates a conductivity peak preceding an SSC peak. Dotted arrows illustrate temperature peaks that precede discharge peaks. Curved arrows illustrate times of synchronicity between SSC and discharge. Note the difference in discharge scales between this figure and Figure 5.

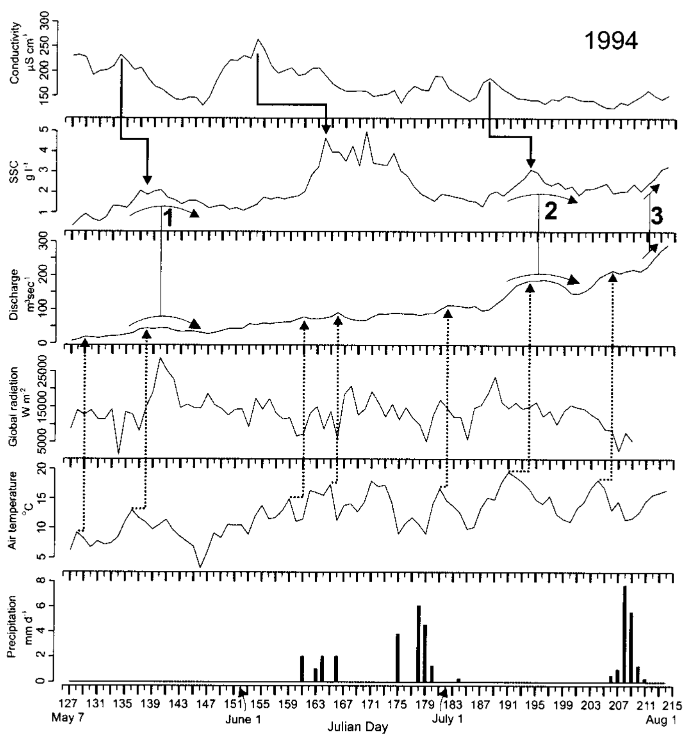


FIG. 5. Mean daily time series for 1994. Solid arrows indicate conductivity peaks preceding SSC peaks. Dotted arrows illustrate temperature peaks that precede discharge peaks. Curved arrows illustrate times of synchronicity between SSC and discharge. Note the difference in discharge scales between this figure and Figure 4.

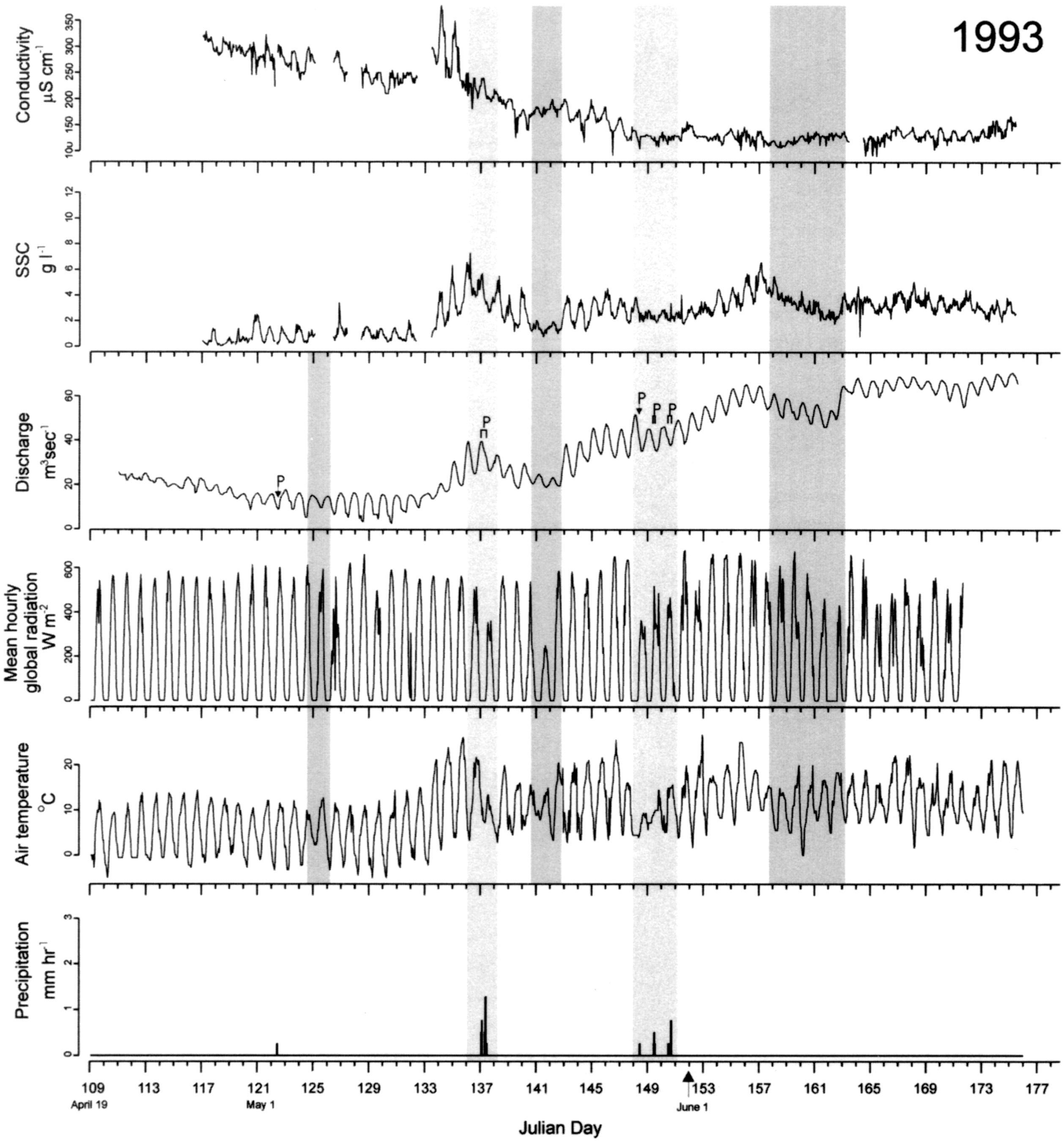


FIG. 6. 1993 hourly time series. The symbol P indicates the location of single or clustered precipitation events. The light gray vertical bands indicate periods of decreased global shortwave radiation and air temperature accompanying precipitation. The darker gray bands indicate periods when discharge, SSC, and conductivity decreased during periods of reduced global radiation or temperature, in the absence of precipitation. Note the difference in discharge scales between this figure and Figure 7.

mean daily discharge becomes less responsive to changes in mean daily air temperature. Thus, in 1994, mean daily temperature becomes a poorer index of discharge during sustained ablation. We believe that this change in correlation after day 174 is a basis for separating the 1994 time-series into two different periods: a snowmelt-dominated regime before day 175 and a glacier melt regime for day 175 and later. Other measured variables that also exhibit changes around this time are explored in the following sections.

**Hourly Global Shortwave Radiation, Air Temperature and Discharge**: Cross-correlation analysis indicates that hourly discharge and global shortwave radiation are most strongly correlated when hourly global shortwave radiation is shifted 11 hours forward in 1993 and 13 hours forward in 1994. Because of the phase shift, the non-lagged shortwave series has a weak negative correlation with discharge ($r$ = -0.09 in 1993; $r$ = -0.15 in 1994). Incorporating the lags into the correlation analyses produces positive correlations of $r = 0.15$ in 1993 and $r = 0.05$

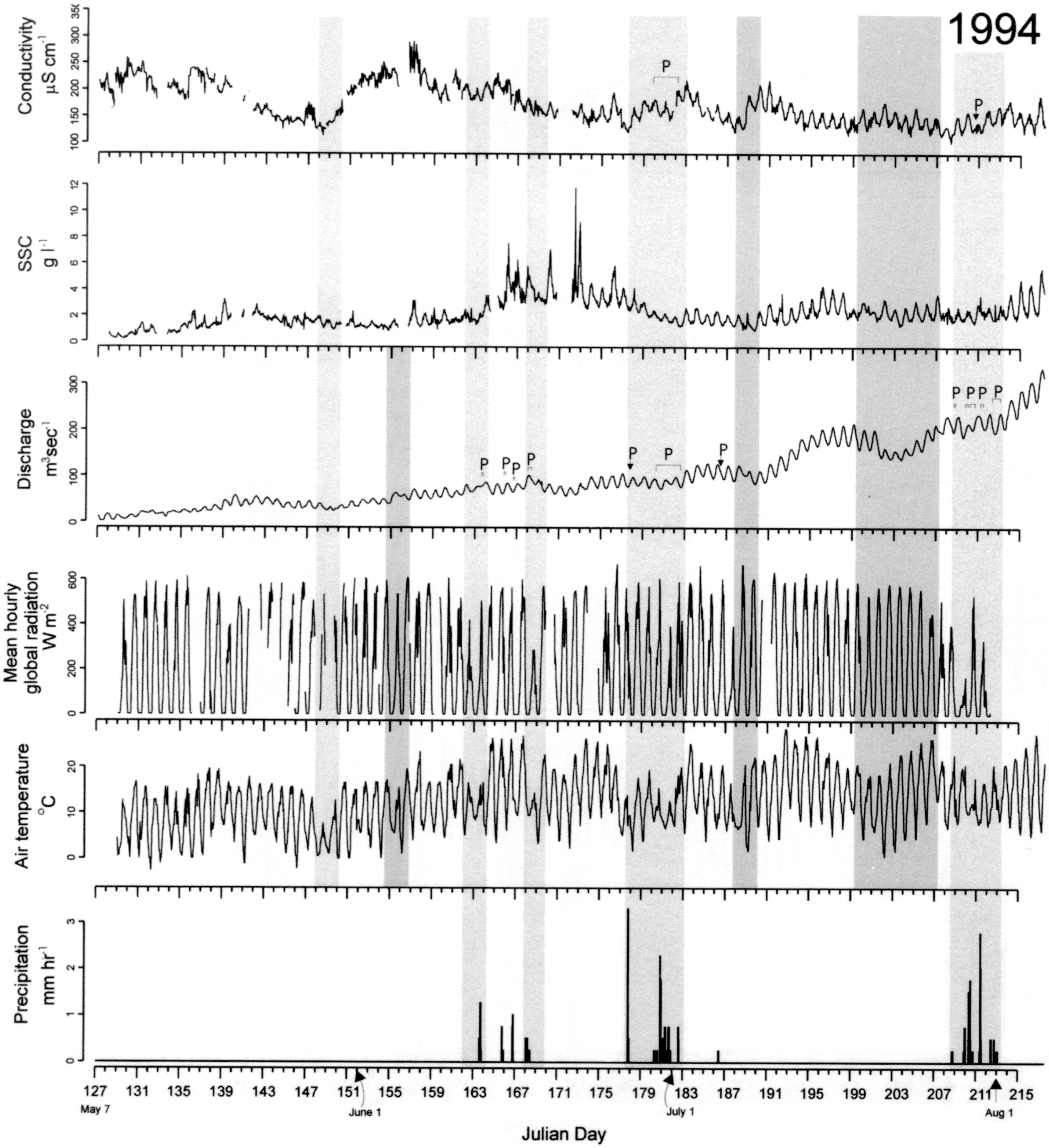


FIG. 7. 1994 hourly time series. The symbol P indicates the location of single or clustered precipitation events. The light gray vertical bands indicate periods of decreased global shortwave radiation and air temperature accompanying precipitation. The darker gray bands indicate periods when discharge, SSC, and conductivity decreased during periods of reduced global radiation or temperature, in the absence of precipitation. Note the difference in discharge scales between this figure and Figure 6.

in 1994. Hourly global shortwave radiation is positively correlated with air temperature for both years ($r = 0.61$ in 1993; $r = 0.64$ in 1994).

In the absence of precipitation, extended periods of cloud cover, or cool temperatures, diurnal discharge is strongly periodic and, like shortwave radiation, it is out of phase with diurnal temperature variations for both years (Figs. 6 and 7). Cross-correlation analysis indicates that a 10-hour forward lag of hourly temperature in 1993 and an 11-hour forward lag in 1994 produce the strongest correlation with hourly discharge. This pronounced phase-shift leads to weak positive correlation between non-lagged temperature and discharge ($r = 0.37$ in 1993 and $r = 0.25$ in 1994). Incorporating the lags into the correlation analyses produces positive correlations of $r = 0.55$ for 1993 and $r = 0.44$ for 1994.

When hourly air temperature in 1994 is shifted forward by 11 hours, assuming that the two variables should be in phase for a basin of this size, then a given hourly air temperature becomes associated with progressively

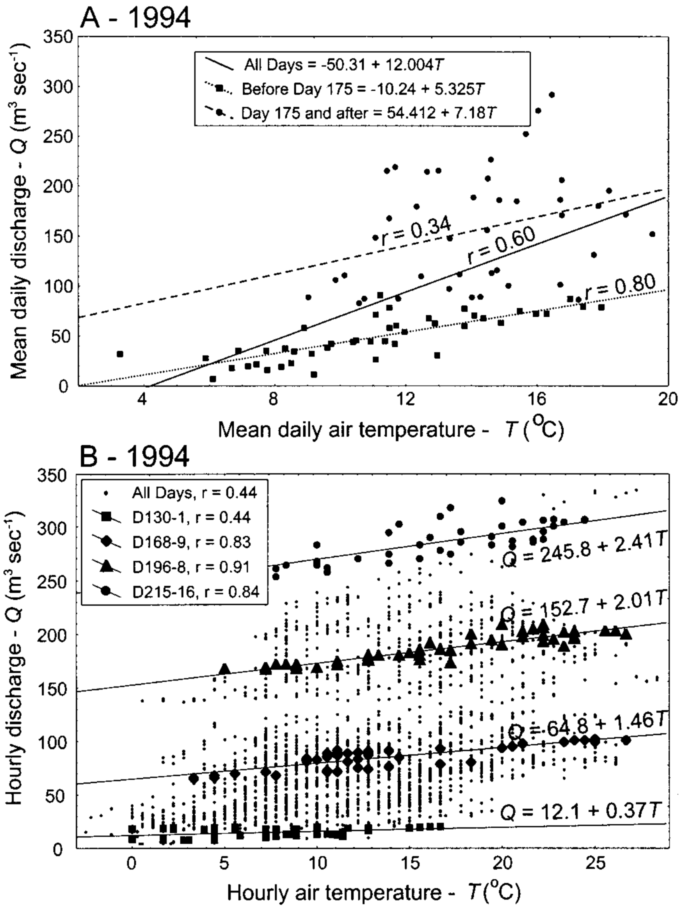


FIG. 8. A) 1994 relation between mean daily air temperature and mean daily discharge before and after day 175 in 1994; B) 1994 air temperature and discharge, illustrating the range of discharges associated with a given temperature and the strong relation between the two variables for different time periods over the season. Temperature is lagged 11 hours forward with respect to discharge.

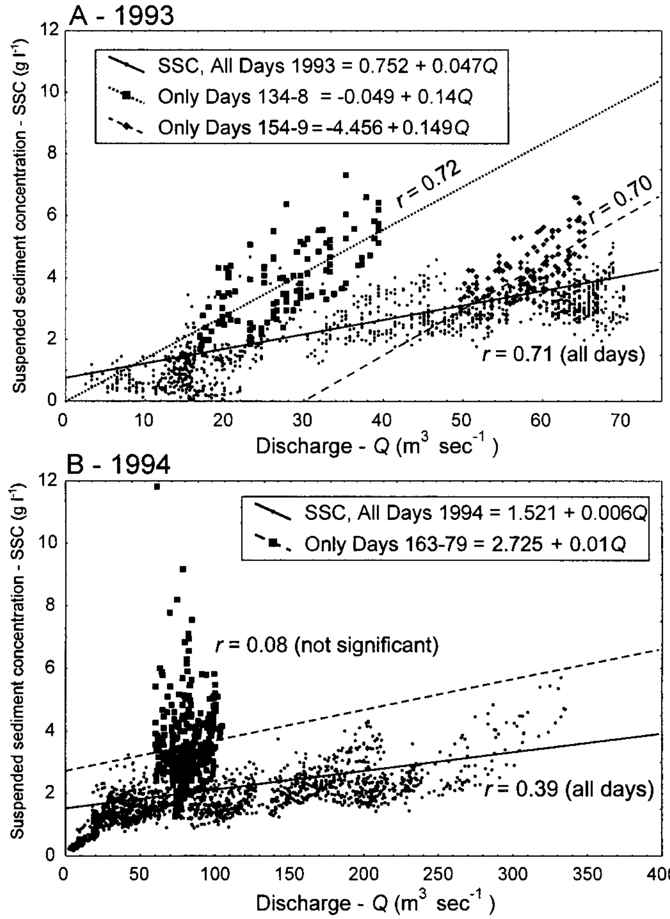


FIG. 9. A) 1993 relation between hourly suspended sediment concentration (SSC) and hourly discharge, illustrating the two large peaks in SSC in Figures 4 and 6; B) 1994 relation between SSC and discharge, illustrating the seasonal peak in SSC (Figs. 5 and 7) as a seasonal outlier. Note different discharge scales.

higher discharges through the season (Fig. 8B). This effect produces significant scatter and makes any bivariate relation inappropriate when using hourly values on a seasonal time scale. An identical relation is found when global shortwave radiation is lagged forward and correlated with discharge on a seasonal scale.

The slopes of the rating curves in Figure 8B increase as the melt season progresses, suggesting that a given rate of change in temperature is associated with greater increases in discharge. For example, a substantial discharge event took place in 1994 between day 201 and day 205, when daily discharge amplitude (Fig. 7) decreased commensurate with mean daily discharge (Fig. 5) in response to a preceding temperature trough. Similar temperature troughs early in the season did not produce such drastic reductions in diurnal and mean daily discharge. This event is consistent with the observation that a given change in temperature is associated with larger changes in discharge as the melt season progresses. Seasonally increasing diurnal discharge amplitude provides further evidence for an increasing discharge response to similar energy inputs through the 1994 melt season ($Amplitude = 9.634e^{0.019(d-126)}$, where $d$ is the Julian day within the interval $126 \le d \le 216$).

### *Suspended Sediment Transport*

**Mean Daily Suspended Sediment Concentration (SSC) and Discharge**: A visual comparison of data for 1993 and 1994 shows that mean daily suspended sediment concentration (SSC) follows trends in the mean daily discharge (Figs. 4 and 5). In comparison with the hourly correlation (discussed below), however, the mean daily series of SSC and discharge are only slightly better correlated ($r = 0.72$ in 1993; $r = 0.38$ in 1994), the latter showing no improvement over the correlation of the hourly time series (below).

**Hourly Suspended Sediment Concentration and Discharge**: On an hourly time scale, 1993 data show a strong positive relation between SSC and instantaneous discharge, with $r = 0.71$ (Fig. 9A). Two seasonal maximum SSC events in 1993 (on days 134–138 and 154–159) are both positively related to discharge (Fig. 9A) but contribute to the overall seasonal residual variance in SSC. Removing these two events from the hourly record produces a slightly stronger correlation ($r = 0.84$) between SSC and discharge.

For 1994, a positive but weak relation exists between hourly SSC and discharge, with $r = 0.39$ (Fig. 9B). Three minor sediment concentration crests (1, 2, and 3 in Fig. 5)

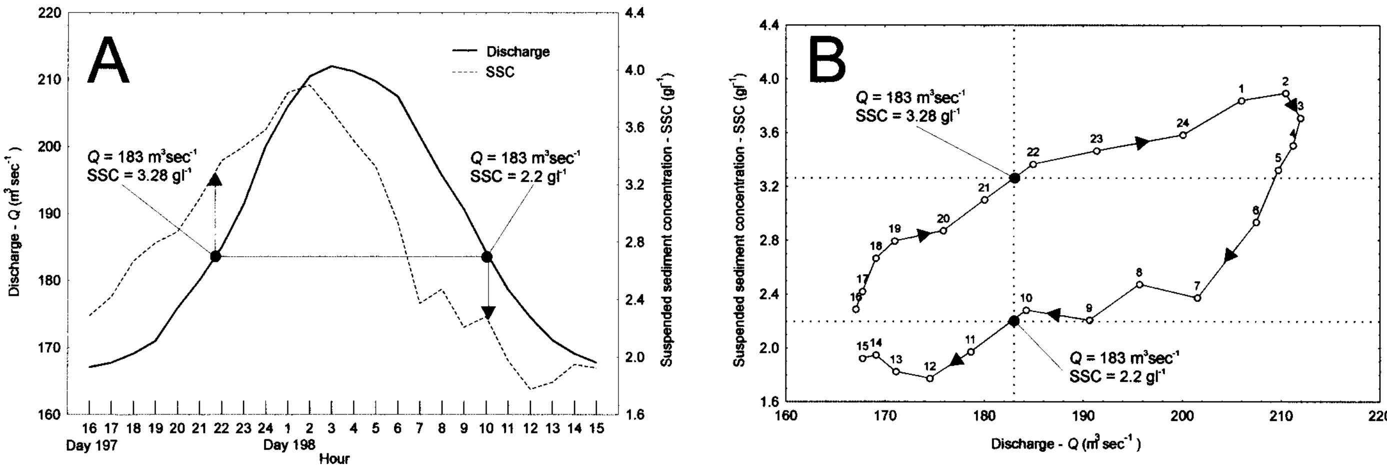


FIG. 10. A) Representative diurnal cycle from days 187–188 in 1994, showing higher suspended sediment concentrations (arrows) on the rising hydrograph limb for equal discharges (black circles). B) Q-C-T plot illustrating clockwise hysteresis loop as a result of higher suspended sediment concentrations on the rising diurnal hydrograph limb. Labels are hours from x-axis of Figure 10A.

TABLE 2. Percentage occurrence of diurnal hysteresis between suspended sediment concentration and discharge for the 1993 and 1994 monitoring seasons, classified by type of hysteresis. The 1994 record is further broken down into the periods before and after the proposed time at which glacier melt dominates the Slims River hydrological regime.

| Type of Hysteresis | 1993 | 1994 | Before Day 178 in 1994 | After Day 178 in 1994 |
|---|---|---|---|---|
| Non-Hysteretic | 48 | 15 | 27 | 0 |
| Clockwise | 37 | 69 | 59 | 91 |
| Counter-Clockwise | 10 | 9 | 0 | 9 |
| Missing Days | 5 | 9 | 14 | 0 |

exhibit a positive relation with discharge variation. However, the seasonal peak period on days 163–179, with SSCs up to 11.9 $gl^{-1}$ (Fig. 7), is an outlier in the seasonal scatter plot and has no statistically significant correlation with discharge ($r$ = 0.08; Fig. 9B). Removing this event from the record provides a correlation of $r = 0.75$, which is similar to the 1993 seasonal correlation. After the peak seasonal event, SSCs show a moderate rising trend, but discharge increases; this provides some evidence that the stream is operating under capacity in late 1994. As further evidence, in 1993 discharges between approximately 25 $m^3sec^{-1}$ and 70 $m^3sec^{-1}$ produced SSCs as much as 2.5 to 3 times greater than those of identical discharges in 1994 (Fig. 9A, B).

**Diurnal Hysteresis between SSC and Discharge**: Suspended sediment concentration was strongly diurnal in both years, with a repeating period of 24 hours following discharge variations (Figs. 6 and 7). During times of reduced temperatures and global shortwave radiation, the diurnal SSC amplitudes decreased notably (Figs. 6 and 7). Furthermore, in both years there was a phase shift between SSC and discharge on a diurnal basis: SSC lagged behind discharge by an average of 1–2 hours (Fig. 10A).

In both years, this phase shift produced frequent diurnal clockwise hysteresis (Fig. 10B; Table 2); this lessens the variance in SSC that can be explained by discharge. In 1993, clockwise hysteresis was less frequent (Table 2), and the consequent similarity between SSCs on the rising and falling limbs of the diurnal hydrograph contributes to the stronger linear relation with discharge. In 1994, however, clockwise hysteresis was most frequent later in the season, during glacier melt (Table 2). If we exclude the SSC event of days 163–179 in 1994, the considerable scatter in the SSC-discharge relation (Fig. 9B) is primarily due to successive clockwise hysteresis loops. The early part of the 1994 season, before day 178, shows less frequent hysteresis.

Stratifying the SSC according to its occurrence on the rising or falling diurnal hydrograph limb does not substantially reduce the residual variance in SSC. Over the 1994 season, the relation between discharge and SSC is $r = 0.44$ for the rising hydrograph limbs and $r = 0.34$ for the falling limbs. Stratification of the 1993 data did not change the correlation.

*Dissolved Solids*

**Mean Daily Conductivity**: In 1993, mean daily discharge and conductivity were inversely related over the season ($r$ = -0.85). A decreasing trend in conductivity began at over 300 $\mu S\ cm^{-1}$ with a local maximum between days 131 and 136, followed by a decrease to less than 130 $\mu S\ cm^{-1}$ by the end of the monitoring period (Fig. 4). The local maximum conductivity crest preceded a maximum in suspended sediment concentration on days 134–138 (Fig. 4).

In 1994, mean daily discharge and conductivity were inversely related over the season ($r$ = -0.62). The two major peaks in the 1994 conductivity record are shown in Figure 5. The first peak occurred at the start of the record: in spring, conductivity was high, up to 250 $\mu S\ cm^{-1}$; it then decreased to approximately 120 $\mu S\ cm^{-1}$ by day 148. The second peak occurred from day 148 to day 157, when conductivity rose to over 280 µS $cm^{-1}$; it then decreased until the end of the monitoring period, with minor local maxima and minima (Fig. 5). Both of these peak conductivities preceded peaks or crests in suspended sediment concentration by several days (Fig. 5).

**Hourly Conductivity**: In both years, the maximum observed hourly conductivity values were up to 200 µS $cm^{-1}$ greater (and minimum values were as much as 40 µS $cm^{-1}$ greater) than those of most small glacier-fed streams (e.g., Collins, 1979b). The ratio of maximum to minimum conductivity was 4.3 in 1993 and 2.58 in 1994. As an indication of the seasonal ranges of variation in solute concentration, these ratios are consistent with those of other glacierized basins (e.g., Collins 1979b).

On an hourly time scale, both monitoring seasons exhibit inverse relations between hourly conductivity and discharge ($r$ = -0.82 for 1993; $r$ = -0.58 for 1994; Fig. 11A, B). The inverse relation in both years is curvilinear. However, it is poorly explained by standard rating equations of the form $C = aQ^{-b}$, where $C$ is conductivity, $Q$ is discharge and $a$ and $b$ are intercept and slope parameters, respectively, estimated by linear regression of $\log_{10}C$ vs. $\log_{10}Q$ (Fig. 11A, B). This simple mixing model does not adequately explain the variation in the conductivity values associated with a given discharge, a finding consistent with data from smaller glacierized basins (e.g., Collins, 1979b).

Conductivity undergoes repeated periodic diurnal fluctuations out of phase with discharge. Cross-correlation analysis of the discharge and conductivity series indicates that conductivity peaked approximately 2 hours before discharge in 1993 and 5 hours before discharge in 1994. This phase shift produced clockwise hysteresis for 63% of the diurnal cycles in 1993 and for 72% in 1994.

**Conductivity and Hydrometeorological Conditions**: Periods of decreased diurnal conductivity amplitude in 1993 and 1994 were generally associated with precipitation or lower temperatures (or both) and reduced global shortwave radiation (Figs. 6 and 7). In 1994, these decreases in conductivity amplitude were more evident in the early season and on day 211. Furthermore, diurnal conductivity amplitudes in 1994 were best defined during the later season (e.g., after day 175) when meteorological conditions favor sustained ablation (Fig. 7). The same pattern is not clearly evident for 1993.

**Major Cations**: In 1993, the cations with highest concentrations were $Ca^{2+}$, $Mg^{2+}$, $K^+$ and $Na^+$, in that order (Table 3). Six samples analyzed in 1994 indicate that the same order was maintained. Over the 1993 monitoring period, $Ca^{2+}$ showed the least proportional variation, as measured by the coefficient of variation, and $Na^+$ had maximum variation (Table 3). When compared to some smaller glacier streams, the Slims River shows less proportional variation, as measured by the percentage ranges for all cations (Table 4). Generally, over both monitoring periods, cations followed the general trend of conductivity: concentrations decreased in response to dilution from increasing discharge.

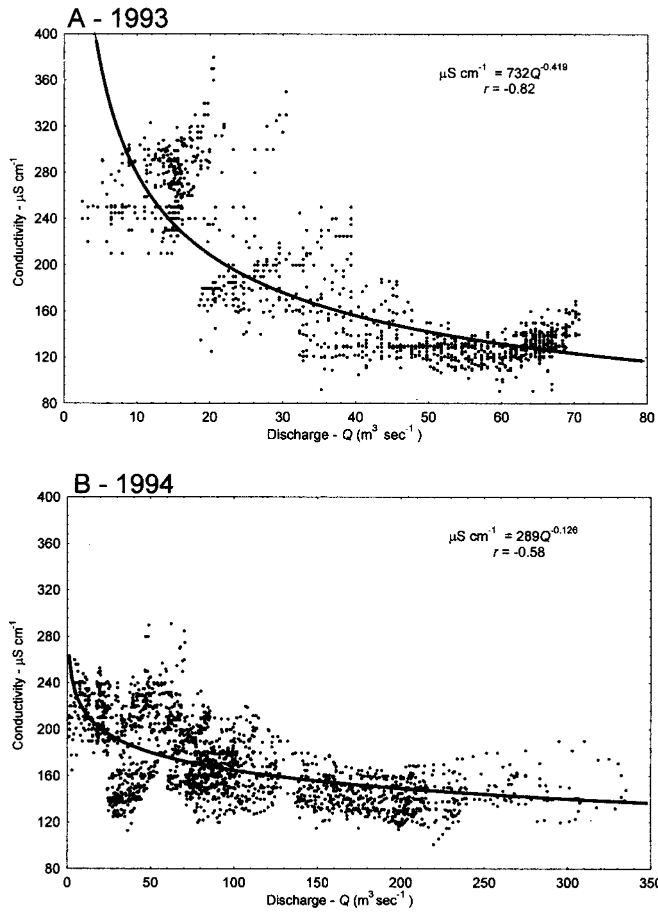


FIG. 11. A) 1993 relation between hourly conductivity and discharge, illustrating an inverse curvilinear relation; B) 1994 relation between hourly conductivity and discharge, illustrating an inverse curvilinear relation. Note different discharge scales.

TABLE 3. Ionic concentrations and proportional variation in Slims River meltwaters from April to June 1993.

| Statistic | Ionic Concentration (ppm) $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | % x of ($Ca^{2+}$+$Mg^{2+}$+$K^+$+$Na^+$) per sample $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ |
|---|---|---|---|---|---|---|---|---|
| Mean | 41.4 | 11.4 | 3.0 | 2.5 | 71.6 | 18.9 | 5.6 | 3.9 |
| Max | 76.9 | 26.3 | 5.5 | 6.6 | 76.3 | 23.8 | 8.7 | 6.3 |
| Min | 26.2 | 6.4 | 0.5 | 1.1 | 66.4 | 16.6 | 0.5 | 2.9 |
| SD | 16.7 | 6.3 | 1.0 | 1.8 | 2.5 | 1.9 | 1.3 | 1 |
| CV | 40.3 | 54.6 | 32.5 | 72.2 | 3.5 | 10.2 | 23.9 | 25.8 |

## DISCUSSION

### *Hydrometeorology*

**Precipitation**: Periods of precipitation combined with decreases in global radiation and air temperature were generally associated with decreases in diurnal suspended sediment concentration and conductivity amplitude. However, because precipitation had little direct effect on the strongly diurnal discharge record in either monitoring season, it is difficult to explain why SSC and conductivity amplitudes should have decreased substantially at these

TABLE 4. Summary of proportional cationic percentage ranges of meltwaters from the Slims River and other glacier-fed streams.

| Glacier / River | Sample Period | No. Samples | Range of % as % of ($Ca^{2+}$ + $Mg^{2+}$ + $K^{+}$ + $Na^{+}$) $Ca^{2+}$ | $Mg^{2+}$ | $K^{+}$ | $Na^{+}$ | Source |
|---|---|---|---|---|---|---|---|
| Slims River, Yukon | April – June 1993 | 56 | 66.4–76.3 | 16.6–23.8 | 0.5–8.7 | 2.9–6.3 | This study |
| Castner Glacier, Alaska | July – August 1968 | 11 | 67.2 | 17.6 | 4.2 | 10.9 | Collins (1979b) |
| Gornera, Switzerland | July – August 1974 | 69 | 45.0–90.5 | 5.2–23.3 | 1.8–22.0 | 1.3–17.4 | Collins (1979b) |
| Moiry Glacier, Switzerland | Summer 1971 | 15 | 68.7–90.1 | 3.7–14.4 | 1.7–13.3 | 1.4–6.9 | Lorrain and Souchez (1972)[1] |

[1] Calculated using data on dissolved constituents presented in Table 1 of Lorrain and Souchez (1972).

times. A possible explanation is that extended periods of cool temperatures and decreased solar radiation result in decreasing or steady diurnal discharges that may not tap new sediment sources. Consequently, diurnal SSCs could have decreased because of supply exhaustion. A similar argument may be made for decreased conductivity amplitudes; in addition, diurnal meltwater may have been diluted by precipitation with low concentrations of dissolved solids.

The lack of response of discharge to precipitation during the snowmelt period in 1993 and 1994 could be due to a snowpack that slowed throughflow, whereas lack of response during sustained ablation could be due to precipitation not registered at KLRS or precipitation falling as snow in the upper basin. Meltwater flow (or precipitation) through snow would be slower than that over bare ice (Fountain, 1996) and would increase meltwater concentration time at the Slims River bridge. During ablation, however, less snow in the contributing area and more exposed glacier ice should allow for more effective precipitation runoff (Smith, 1985). In effect, some increases in minimum diurnal discharges were associated with precipitation events in 1994, but such increases also took place when no precipitation was measured. Unfortunately, because the basin is large, precipitation measurements at KLRS do not accurately represent basin-wide precipitation timings and magnitudes. Moreover, the effects of precipitation alone on discharge, conductivity, or SSC are difficult to discern because the discharge record surrounding precipitation events also reflects the associated meteorological conditions of decreased temperatures and global solar radiation and their effects on ablation and snowmelt.

**Shortwave Radiation, Temperature and Discharge**: In general, the energy available for icemelt in a glacierized basin is derived primarily from net radiation and secondarily from sensible heat transfer (Munro and Young, 1982). Micrometeorological measurements may exhibit weak statistical relations with discharge in glacierized basins because of variations in surface cover, slope and aspect (Munro and Young, 1982).

In this study we found variations in air temperature rather than variations in global shortwave radiation (an approximation to net radiation) to be more strongly correlated with discharge in both years. Neither variable, however, is strongly correlated with discharge on a seasonal time scale. But on an hourly time scale, over periods of two to four days, both global shortwave radiation and air temperature show strong positive relations to discharge and are associated with increasing discharges as the melt seasons progress. The gradual melting of snow and exposure of more glacier ice should cause an amplified melt response to similar temperatures and radiative inputs during progressive ablation. Snowpack recession and an increasing contributing area composed of exposed glacier ice (which has lower albedo than snow-covered ice) are primary contributors to the increased meltwater production in smaller glacierized basins during ablation (Collins, 1998; Hodson et al., 1998). This amplified meltwater response contributes to the poor correlation of temperature and shortwave radiation with discharge on a seasonal scale.

Extrapolation of temperature and global shortwave radiation variations from the low-altitude monitoring site at KLRS to the upper valley and mountains weakens their relation to discharge as a melt season progresses. The 1993 season captured mainly the spring melt period, and for this same time period in 1994, the correlation between air temperature and discharge is similar. This fact suggests that the low-altitude air temperature and radiation series measured in this study are a reasonable index of low-altitude snowmelt response. In a high-albedo snowpack, sensible heat may be more effective in meltwater production. Discharges occurring late in the 1994 season may not have been controlled by the trends and magnitudes of low-altitude temperatures, in which case a spurious correlation has been introduced for late 1994 that weakens the overall seasonal correlation of the hourly and daily temperature and discharge series, particularly after day 175. Consequently, air temperature becomes a progressively poorer index of melt response as snow cover in the basin lessens.

Finally, our statistical analyses do not reveal that global shortwave radiation is an effective index of meltwater response in either season. Considering the basin size, and as demonstrated by Munro and Young (1982), our single meteorological monitoring site is likely unrepresentative of the entire basin because of variations in surface cover, exposure, slope, and cloud cover that moderate radiation exchange at the ice surface where melt is produced. Moreover, the basic statistical procedures that we used, like regression and correlation, cannot recognize that meltwater response is different (nonlinear) for similar temperatures or shortwave radiation values as the season progresses.

*Suspended Sediment*

In 1994, discharge increased substantially after the peak SSC event, while concentrations remained comparable to those measured early in the season. These observations suggest that the stream was operating under capacity in 1994. A stream operating under capacity suggests that the Kaskawulsh glacier's ability to supply sediment is limited over the long term. The Slims River is a large, braided stream with numerous migrating braid bars, indicative of a stream operating at or over its capacity to transport the imposed sediment load. The seasonal changes in the hydraulic geometry along the course of the Slims River and the properties of the subglacial resurgences that supply the stream with sediment are largely unknown. Consequently, conclusions on competence or capacity are strictly applicable only to the monitoring reach.

The peak suspended sediment concentration event in 1994, which lasted for approximately 16 days (days 163–179), exhibits no statistical correlation with discharge. Studies on smaller glacier-fed streams suggest that large suspended sediment concentration events not strongly correlated with discharge (Gurnell and Warburton, 1990; Collins, 1991) could be caused by adjustment or reorganization of the subglacial hydrological system during periods of enhanced glacier motion (Humphrey et al., 1986; Willis et al., 1996) or by the yearly establishment of the subglacial system, which is accompanied by expulsion of sediments accumulated during the non-ablation season (Johnson, 1991a,b). The timing and magnitude of the 1994 concentration peak is similar to that observed in the Slims River in 1983 (Johnson, 1991b). We suggest that the subglacial drainage system was becoming established at this time and that glacier icemelt discharge dominated the Slims River regime after approximately day 175. None of the 1993 SSC peaks (max. SSC 7.32 $gl^{-1}$, Fig. 6) were comparable in magnitude to the 1994 SSC peak (max. SSC 11.83 $gl^{-1}$, Fig. 7). Because of the shorter duration, early seasonal occurrence, and strong positive relation to discharge variations of SSC peaks in 1993, we believe that it would be premature to attribute those peaks to opening of the glacier hydrological system. Consequently, snowmelt discharge and valley-train sediment supply likely controlled the suspended sediment regime in 1993.

The 1–2 hour phase shift between SSC and discharge produced frequent clockwise hysteresis, which contributed to the residual variance in SSC, particularly in 1994. Diurnal clockwise hysteresis, in which suspended sediment concentrations for a given discharge are greater on the rising hydrograph limb, is quite common in smaller glacierized basins (Østrem, 1973; Collins, 1979A; Bogen, 1980; Gurnell and Warburton, 1990; Johnson, 1991a; Hasnain and Thayyen, 1996; Willis et al., 1996; Hodgkins, 1999). Clockwise hysteresis was less frequent for the whole of 1993 and in the early season of 1994, leading to stronger linear relations between SSC and discharge during snowmelt.

Remobilization of fine sediments deposited during low flow has been proposed as one reason for clockwise hysteresis (e.g., Bogen, 1980; Willis et al., 1996). Sediment deposited in the proglacial or subglacial system because of loss of competence during falling limb discharges and low-flow conditions at night is entrained, exhausted, and added to the sediment transported during the next day's rising discharge. Hence, SSCs are higher on the rising hydrograph limb. Applying this explanation to the Slims River is problematic because particle size analysis of daily suspended sediment samples indicates that sediments were progressively dominated by fine silt as the 1994 melt season progressed (Sawada, 1996). Furthermore, in the later season of 1994 the stream was operating under capacity; with greater velocities, the stream had greater competence during this time (e.g., Fig. 3). Thus the suspended sediment in late 1994 was easily transported, and deposition on the falling hydrograph limbs should not have taken place through loss of competence.

Alternatively, given an equivalent time-varying supply of sediment to the rising and falling hydrograph limbs, dilution of sediment by larger flow volumes on the falling hydrograph limb (because of hydrograph asymmetry) is capable of producing hysteresis. For example, after day 175 in 1994, clockwise hysteresis occurred during 80% of the diurnal cycles that exhibited greater flow volumes under the falling diurnal hydrograph limb (Sawada, 1996).

*Dissolved Solids*

The relative proportions of cations follow the same order as in other glacier-fed streams underlain by igneous and metamorphic rocks, despite differences in percentage glacierization, the large size of the current basin, and the extensive sedimentary rocks present. However, when compared to smaller glacierized basins, the Slims River shows less proportional variation as measured by the percentage ranges for all cations. Small proportional variation may be attributable to a number of factors:

1. Equilibrium may be encouraged by longer contact time between water and suspended sediments. Because dissolved solids in glacierized streams are acquired by ion exchange at the interface between meltwater and bedrock or meltwater and suspended sediment (Lorrain and Souchez, 1972; Lemmens and Roger, 1978; Collins, 1995; Brown et al., 1996), contact time between water and suspended sediments may be longer during subglacial and proglacial transport. In smaller glacierized basins, solutes are most often measured from samples taken very near the glacier portal, so there is less time for proglacial and subglacial cation exchange than in a basin the size of the Kaskawulsh.

2. The extensive carboniferous sedimentary bedrock in the Kaskawulsh basin may provide a relatively uniform solute source.

3. All suspended sediment may be of similar provenance.

The variation in relative concentrations, although small, alludes to solute acquisition from different lithologies along the watercourse or changes in drainage pathways over the season, or both.

In 1993, the low proportional variation (Table 3) was reflected in good correlation between the four major cations as the season progressed. Lemmens and Roger (1978) suggest that good correlation can indicate that the cation sources remain relatively constant over a melt season. This would be consistent with the low proportional variation observed in this study. In the present case, the stability of the relative proportional cation variation is a likely indicator of the general lithological influences of the basin. Dolomite ($CaMg[CO_3]_2$) and Calcite ($CaCO_3$) are found in the Kaskawulsh glacier basin in significant quantities and may contribute to cationic stability, as well as to the high relative proportions of $Ca^{2+}$ and $Mg^{2+}$. In general, because there are ranges in percentage composition, conductivity cannot be used as an absolute measure of individual ion activity (Collins, 1979b) in the Slims River.

Both years exhibit higher conductivity values than are found in streams emanating from smaller glaciers. The concentration of dissolved solids should be positively associated with factors that increase contact time between meltwater and sediment, such as greater percentage of glacierization (Collins, 1979b, 1983) or larger basin size. Our observations are consistent with this hypothesis. Higher concentrations of dissolved solids observed in this study may be due to these factors:

1. The size of the glacier. A larger glacier will increase the residence time of meltwater and lead to ion enrichment because of longer contact with sediment or bedrock in the subglacial system or proglacial system.

2. The source of the Slims River flow is primarily subglacial resurgences (Fig. 2) that are highly enriched with fine glacially eroded materials and dissolved solids.

3. The suspended sediment is dominated by washload-sized materials (average modal class is 8 – 4 microns in Slims River samples; Sawada, 1996) that cause a large surface area-to-volume ratio that encourages cation exchange. Concentrations of dissolved solids can increase as a function of increasing surface area to volume ratio, given favorable mineralogy (Zeman and Slaymaker, 1975), and sufficient contact time (Collins 1979b, 1995) in the glacial and proglacial hydrological system.

High conductivity values in 1993 and during the same time period in 1994 suggest that the contribution of dissolved solids in the early season is derived from ion enrichment of snow meltwater that flows through colluvium and alluvium in the lower basin tributaries. Water flowing through these deposits would have greater concentrations of dissolved solids than ice or snow meltwaters (Lemmens and Roger, 1978).

Diurnal hysteresis between conductivity and discharge is consistent with observations in smaller glacier-fed streams (e.g., Collins, 1979b) and is most pronounced during well-defined diurnal discharge fluctuations in the latter half of the 1994 season. Two situations can cause phase shifts between conductivity and discharge.

1. Dilute meltwaters, initiated by daily ablation on the glacier surface, are first routed supraglacially and englacially. These dilute meltwaters may be delayed in reaching the ion-rich subglacial meltwater system or glacier portal, which leads to higher dissolved solids concentrations on the rising hydrograph limb.

2. Water from tributaries travels more quickly to the monitoring site than water from the glacier. Thus tributary waters with high concentrations of dissolved solids will arrive before the greater discharge from the glacier, producing clockwise hysteresis.

Collins (1979b) suggests that restoration of surface ablation in the morning provides an increase in discharge at the glacier portal that is paralleled by a drop in conductivity as nighttime low flow is diluted. Conductivity rises as discharge declines and the proportion of flow derived from subglacial storage/routing increases. Similar mechanisms may act in the early season, except that high-conductivity low flows become diluted by daily snowmelt.

The second seasonal peak in conductivity of 1994 was not associated with precipitation events, major increases in temperature, or rapid fluctuations in discharge and may indicate the expulsion of ion-enriched subglacial waters. Proximal to the glacier, higher concentrations are expected when the subglacial hydrological system opens, releasing enriched water that was in contact with basal materials (Collins, 1979b, 1983; Binda, 1984; Brown and Tranter, 1990). Furthermore, this second conductivity peak preceded the 1994 seasonal peak in SSC, which we believe reflected the opening of the glacier hydrological system. In 1994, as icemelt increased, it acted to dilute groundwater and subglacial sources of dissolved solids and caused decreases in conductivity over the melt season.

## CONCLUSIONS

Precipitation was infrequent and ineffective in modifying discharge on hourly and daily time scales in both years. Precipitation events and their associated meteorological conditions were associated with decreases in diurnal suspended sediment concentration and conductivity amplitudes. The equivocal relation between discharge and precipitation is primarily due to questions of what effective magnitude and spatial extent of precipitation are required to produce clear discharge responses in a basin of this size. We cannot properly address these questions with data from a single micrometeorological site in the lower basin.

Statistical correlation is insufficient to describe the relation of discharge to air temperature and global shortwave radiation during a melt season. Correlation does not take into account increasing meltwater responses to similar energy inputs as snowmelt gives way to icemelt in the basin. Hourly and mean daily discharge and air temperature are most correlated during snowmelt, when sensible heat transfer is more effective in meltwater production within a high-albedo snowpack. After snowmelt has ended, air temperature becomes a poor index of meltwater production. This conclusion is consistent with those of studies in smaller glacierized basins.

We believe that the peak seasonal suspended sediment concentration in 1994 represents the late springtime establishment of the subglacial hydrological system of the Kaskawulsh glacier and the tapping of sediment sources accumulated by glacial erosion during the fall, winter, and early spring. This theory is consistent with observations on SSC variations in smaller glacierized basins at times of enhanced subglacial activity.

As in smaller glacierized basins, frequent diurnal hysteresis and less frequent extreme suspended sediment concentration events unrelated to discharge leave little of the variance of suspended sediment concentration to be explained by discharge on an hourly time scale. Application of standard least-squares rating curves in the presence of frequent hysteresis leaves autocorrelated residuals and poor explanation of variance in SSC by discharge (Willis et al., 1996; Hodgkins, 1999). Models based on autoregressive or similar procedures have better success in modelling the variance of SSC using discharge (e.g., Gurnell and Fenn, 1984; Willis et al., 1996). Although hysteresis occurs often in fluvial systems, the frequency of hysteresis found in the present investigation has not been explicitly documented on a diurnal scale in such a large glacierized basin and warrants further study of the causal mechanisms.

As in smaller glacierized basins, conductivity exhibits an inverse relation with discharge over both seasons, and simple mixing models do not sufficiently characterize the relation. In both years, major conductivity peaks preceded peaks in SSC, and in particular the second peak in 1994 was consistent with the emergence of ion-enriched meltwaters during an establishing subglacial drainage system. Clockwise hysteresis dominates the diurnal relation between conductivity and discharge and is consistent with smaller glacierized basins that exhibit diurnal dilution of nighttime-enriched subglacial water by meltwaters generated during daytime ablation of clean glacier ice or snow. The large conductivity values observed in the Slims River support the hypothesis that absolute solute concentrations increase as the proportion of glacierization and basin size increase. This hypothesis requires further testing using data for a range of basin sizes. The high absolute concentrations and low proportional variance in major cations throughout 1993 reflects the influence of basin size and lithology. The larger proportions of $Ca^{2+}$ and $Mg^{2+}$ are due first to the abundance of dolomite and calcite in the basin and second to the large basin size and consequent increase in time that meltwaters were in contact with sediments or bedrock.

Despite the large basin size, our results illustrate that the daily and hourly variability of the Slims River are generally consistent with those of smaller glacierized basins. However, the size of the Kaskawulsh glacier basin makes the hydrometeorological relations complex, and our statistics are unable to capture non-linear relations. More extensive sampling that covers the entire area over an entire ablation season in the Kaskawulsh or other large glacierized basins could better assess scale influences within the hydrological regime.

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## REFERENCES

BARNETT, A.P. 1974. Hydrological studies of the Slims River, Yukon, June-August 1970. In: Bushnell, V.C., and Marcus, M.G., eds. Icefield Ranges Research Project, Scientific Results Vol. 4. New York: American Geographical Society and Montreal: Arctic Institute of North America. 143–150.

BINDA, G.G. 1984. Fluvioglacial sediment and hydrochemical dynamics, Peyto Glacier, Alberta. M.A. Thesis, Department of Geography, University of Ottawa, Ottawa, Ontario, Canada. 85 p.

BOGEN, J. 1980. The hysteresis effect of sediment transport systems. Norsk Geografisk Tidsskrift 34:45–54.

BROWN, G.H., and TRANTER, M. 1990. Hydrograph and chemograph separation of bulk meltwaters draining the upper Arolla glacier, Valais, Switzerland. In: Lang, H., Musy, A., Sinniger, R.O., and Monbaron, M., eds. Hydrology in mountainous regions I: Proceedings of two international symposia that were part of the international conference on water resources in mountainous regions held 27 August–1 September 1990 at Lausanne, Switzerland. International Association of Hydrological Sciences (IAHS) Publication 193. 429–437.

BROWN, G.H., TRANTER, M., and SHARP, M.J. 1996. Experimental investigations of the weathering of suspended sediment by alpine glacial meltwater. Hydrological Processes 10(4):579–597.

BRYAN, M.L. 1974a. Variations in quality and quantity of Slims River water, Yukon Territory. In: Bushnell, V.C., and Marcus, M.G., eds. Icefield Ranges Research Project, Scientific Results Vol. 4. New York: American Geographical Society and Montreal: Arctic Institute of North America. 155–161.

———. 1974b. Sublacustrine morphology and deposition, Kluane Lake, Yukon Territory. In: Bushnell, V.C., and Marcus, M.G., eds. Icefield Ranges Research Project, Scientific Results Vol. 4. New York: American Geographical Society and Montreal: Arctic Institute of North America. 171–187.

———. 1974c. Sedimentation in Kluane Lake. In: Bushnell, V.C., and Marcus, M.G., eds. Icefield Ranges Research Project, Scientific Results Vol. 4. New York: American Geographical Society and Montreal: Arctic Institute of North America. 151–154.

———. 1974d. Water masses in southern Kluane Lake. In: Bushnell, V.C., and Marcus, M.G., eds. Icefield Ranges Research Project, Scientific Results Vol. 4. New York: American Geographical Society and Montreal: Arctic Institute of North America. 163–169.

BUTZ, D. 1989. The agricultural use of meltwater in Hopar settlement, Pakistan. Annals of Glaciology 13:35–39.

COLLINS, D.N. 1979a. Sediment concentration in melt waters as an indicator of erosion processes beneath an alpine glacier. Journal of Glaciology 23(89):247–257.

———. 1979b. Hydrochemistry of meltwaters draining from an alpine glacier. Arctic and Alpine Research 11(3):307–324.

———. 1983. Solute yield from a glacierized high mountain basin. In: Webb, B.W., ed. Dissolved loads of rivers and surface water quantity/quality relationships: Proceedings of a symposium held during the 18th general assembly of the International Union of Geodesy and Geophysics, 15–27 August 1983, Hamburg, Germany. International Association of Hydrological Sciences (IAHS) Publication 141. 41–49.

———. 1991. Climatic and glaciological influences on suspended sediment transport from an alpine glacier. In: Peters, N.E., and Walling, D.E., eds. Sediment and stream water quality in a changing environment: Trends and explanation: Proceedings of a symposium held during the 20th general assembly of the International Union of Geodesy and Geophysics, 11–24 August 1991, Vienna, Austria. International Association of Hydrological Sciences (IAHS) Publication 203. 3–12.

———. 1995. Dissolution kinetics, transit times through subglacial hydrological pathways and diurnal variations of solute content of meltwaters draining from an alpine glacier. Hydrological Processes 9(8):897–910.

———. 1998. Suspended sediment flux in meltwaters draining from Batura Glacier as an indicator of the rate of glacial erosion in the Karakoram Mountains. Quaternary Proceedings No. 6:1–10.

DACKOMBE, R.V., and GARDINER, V. 1983. Geomorphological field manual. London: Allen and Unwin.

DAVIDOVICH, N.V., and ANANICHEVA, M.D. 1996. Prediction of possible changes in glacio-hydrological characteristics under global warming, southeastern Alaska, USA. Journal of Glaciology 42(142):407–412.

FAHNESTOCK, R.K. 1969. Morphology of the Slims River. In: Bushnell, V.C., and Ragle, R.H., eds. Icefield Ranges Research Project, Scientific Results Vol. 1. New York: American Geographical Society and Montreal: Arctic Institute of North America. 161–172.

FOUNTAIN, A.G. 1996. Effect of snow and firn hydrology on the physical and chemical characteristics of glacial runoff. Hydrological Processes 10(4):509–521.

FOUNTAIN, A.G., and TANGBORN, W.V. 1985. The effect of glaciers on streamflow variations. Water Resources Research 21(4):579–586.

FRITSCHEN, L.J., and GAY, L.W. 1979. Environmental instrumentation. New York: Springer-Verlag.

GREGORY, K.J., and WALLING, D.E. 1973. Drainage basin form and process: A geomorphological approach. New York: Wiley.

GURNELL, A.M. 1982. The dynamics of suspended sediment concentration in an alpine pro-glacial stream network. In: Glen, J.W., ed. Hydrological aspects of alpine and high mountain areas: Proceedings of a symposium held during the first scientific general assembly of the International Association of Hydrological Sciences (IAHS), 19–30 July 1982, Exeter, UK. International Association of Hydrological Sciences (IAHS) Publication 138. 319–330.

GURNELL, A.M., and FENN, C.R. 1984. Box-Jenkins transfer function models applied to suspended sediment concentration-discharge relationships in a proglacial stream. Arctic and Alpine Research 16:93–106.

GURNELL, A.M., and WARBURTON, J. 1990. The significance of suspended sediment pulses for estimating suspended sediment load and identifying suspended sediment sources in alpine glacier basins. In: Lang, H., Musy, A., Sinniger, R.O., and Monbaron, M., eds. Hydrology in mountainous regions I: Proceedings of two international symposia that were part of the international conference on water resources in mountainous regions, 27 August–1 September 1990, Lausanne, Switzerland. International Association of Hydrological Sciences (IAHS) Publication 193. 463–470.

GURNELL, A.M., WARBURTON, J., and CLARK, M.J. 1988. A comparison of the sediment transport and yield characteristics of two adjacent glacier basins, Val d' Hérens, Switzerland. In: Bordas, M.P., and Walling, D.E., eds. Sediment Budgets: Proceedings of the symposium held 11–15 December 1988 at Porto Alegre, Brazil. International Association of Hydrological Sciences (IAHS) Publication 174. 431–441.

HASNAIN, S.I., and THAYYEN, R.J. 1996. Sediment transport and solute variation in the meltwaters of Dokriani Glacier (Bamak), Garhwal Himalaya. Journal of the Geological Society of India 47(6):731–739.

HODGKINS, R. 1999. Controls on suspended-sediment transfer at a High-Arctic glacier, determined from statistical modelling. Earth Surface Processes and Landforms 24(1):1–21.

HODSON, A.J., GURNELL, A.M., WASHINGTON, R., TRANTER, M., CLARK, M.J., and HAGEN, J.O. 1998. Meteorological and runoff time-series characteristics in a small, High-Arctic glaciated basin, Svalbard. Hydrological Processes 12(3):509–526.

HOOKE, R.LeB., WOLD, B., and HAGEN, J.O. 1985. Subglacial hydrology and sediment transport at Bondhusbreen, southwest Norway. Geological Society of America Bulletin 96:388–397.

HUMPHREY, N., RAYMOND, C., and HARRISON, W. 1986. Discharges of turbid water during mini-surges of Variegated Glacier, Alaska. Journal of Glaciology 32(111):195–207.

JOHNSON, P.G. 1991a. Pulses in glacier discharge: Indicators of the internal drainage system of glaciers. In: Prowse, T.D., and Ommanney, C.S.L., eds. Northern hydrology selected perspectives: Proceedings of the northern hydrology symposium held 10–12 July 1990 at Saskatoon, Saskatchewan, Canada. National Hydrology Research Institute (NHRI) Symposium 6. 165–176.

———. 1991b. Discharge regimes of a glacierized basin, Slims River Yukon. In: Prowse, T.D., and Ommanney, C.S.L., eds. Northern hydrology selected perspectives: Proceedings of the northern hydrology symposium held 10–12 July 1990 at Saskatoon, Saskatchewan, Canada. National Hydrology Research Institute (NHRI) Symposium 6. 151–164.

LEEMANN, A., and NIESSEN, F. 1994. Varve formation and the climatic record in an alpine proglacial lake: Calibrating annually-laminated sediments against hydrological and meteorological data. The Holocene 4(1):1–8.

LEMMENS, M., and ROGER, M. 1978. Influence of ion exchange on dissolved load of alpine meltwaters. Earth Surface Processes 3:179–187.

LORRAIN, R.D., and SOUCHEZ, R.A. 1972. Sorption as a factor in the transport of major cations by meltwaters from an alpine glacier. Quaternary Research 2:253–256.

McGOWAN, H.A., and STURMAN, A.P. 1996. A hydro-meteorological approach to the forecasting of inflows to alpine lakes. Physical Geography 17(6):513–533.

MELACK, J.M., DOZIER, J., GOLDMAN, C.R., GREENLAND, D., MILNER, A.M., and NAIMAN, R.J. 1997. Effects of climate change on inland waters of the Pacific Coastal Mountains and western Great Basin of North America. Hydrological Processes 11(8):971–992.

MULLER, J.E., and CHRISTIE, R.L. 1965. Geology, Kluane Lake, Yukon Territory. Geological Survey of Canada, Map 1177A.

MUNRO, D.S., and YOUNG, G.J. 1982. An operational net shortwave radiation model for glacier basins. Water Resources Research 18(2):220–230.

NICKLING, W.G. 1976. Eolian sediment transport, Slims River valley, Yukon Territory. Ph.D. thesis, Department of Geography, University of Ottawa, Ottawa, Ontario, Canada.

ØSTREM, G. 1973. Sediment transport in glacial meltwater streams. In: Jopling, A.V., and Mcdonald, B.C., eds. Glaciofluvial and glaciolacustrine sedimentation. Publication 23. Tulsa, Oklahoma: Society of Economic Paleontology and Mineralogy. 101–118.

SAWADA, M.C. 1996. Seasonal and short-term periodic suspended sediment concentration and bulk hydrochemical variations, Slims River 1993 and 1994, Yukon Territory, Canada. M.A. Thesis, Department of Geography, University of Ottawa, Ottawa, Ontario, Canada.

SINGH, P., and KUMAR, N. 1997. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. Journal of Hydrology 193 (1–4):316–350.

SMITH, N.D. 1985. Proglacial fluvial environment. In: Ashley, G.M., Shaw, J., and Smith, N.D., eds. Glacial sedimentary environments. Tulsa, Oklahoma: Society of Palaeontologists and Mineralogists. 85–127.

WARD, P.R.B. 1984. Measurement of sediment yields. In: Hadley, R.F., and Walling, D.E., eds. Erosion and sediment yield: Some methods of measurement and modelling. Norwich, England: Geo Books. 37–70.

WHEELER, J.O. 1962. Geology, Kaskawulsh (Mount St. Elias, East Half) Yukon Territory. Geological Survey of Canada, Map 1134A.

WHEELER, J.O., HOFFMAN, P.F., CARD, K.D., DAVIDSON, A., SANFORD, B.V., OKULITCH, A.V., and ROEST, W.R. 1997. Geological Map of Canada. Geological Survey of Canada, Map D1860A.

WILLIS, I.C., RICHARDS, K.S., and SHARP, M.J. 1996. Links between proglacial stream suspended sediment dynamics, glacier hydrology, and glacier motion at Midtdalsbreen, Norway. Hydrological Processes 10(4):629–648.

ZEMAN, L.J., and SLAYMAKER, H.O. 1975. Hydrochemical analysis to discriminate variable runoff source areas in an alpine basin. Arctic and Alpine Research 7(4):341–351.