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COMPARISON OF THE WATER DRAINAGE FROM AN ACTIVE NEAR-SLOPE ROCK GLACIER AND A GLACIER, ST. ELIAS MOUNTAINS, YUKON TERRITORY

With 8 figures and 1 table

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Zusammenfassung: Vergleich der Entwässerung eines aktiven Hangfuß-Blockgletschers und eines Gletschers, St. Elias Mountains, Yukon-Territorium

Ein Vergleich der Entwässerung des aktiven Blockgletschers östlich des Slims River mit dem glazialen Abfluß des Slims River läßt erhebliche Unterschiede erkennen. Wassertemperaturen, pH, Abflußregime und Sedimentfracht zeigen markante tages- und jahreszeitliche Schwankungen gegenüber dem Abfluß des aktiven Blockgletschers. Entsprechend den niedrigen Temperaturen des Ursprungsgebietes zeigt der Gletscherabfluß negativere $\delta^{18}O$-Werte. Die elektrische Leitfähigkeit des Wassers aus dem Blockgletscher ist etwa doppelt so hoch wie beim Gletscherabfluß. Die Entwässerung des inaktiven Hilda-Blockgletschers (nach GARDNER u. BAJEWSKY 1987) gleicht mehr dem Gletscherabfluß als dem Abfluß des in dieser Studie untersuchten aktiven Blockgletschers.

Introduction

The water held in solid form in glaciers and active rock glaciers represents a significant water resource (BARSCH 1978; CORTE 1976) that affects the flow regimes and water quality of the streams emanating from their termini. Since the water is used by Man downstream, it is desirable to know more about the modifications this water makes to the rivers into which it flows. This study compares the summer flow regimes and water quality of the contributions of two streams at Kluane, Yukon Territory, one coming from the front of an active rock glacier and the other largely supplied by glacial meltwater.

This will have a more immediate additional use in providing the criteria for distinguishing between active rock glaciers and inactive rock glaciers (JOHNSON 1987). GARDNER and BAJEWSKY (1987) provided some data on the nature of the flow of streams from an inactive rock glacier in the Rocky Mountains of Alberta, and there is considerable, if scattered, literature on the variable water quality and discharge characteristics of glaciers (e. g. KJELDSEN 1983, and the references contained therein for Norway). Unfortunately, data for proven active rock glaciers is lacking. It is impossible to find an active near-slope rock glacier adjacent to a glacier and with similar summer discharge, so differences in scale are inevitable.

The data presented here for the rock glacier was collected during the 1985 field season and the Slims River data was obtained during the next four years. This data allows valuable insights to be gained by comparing the general characteristics of these hydrological regimes on a diurnal and seasonal basis. Specific parameters include water temperature, drainage, pH, salinity, $\delta^{18}O$ and sediment concentration.

If climatic warming occurs, these sources will tend to supply an increasing proportion of the water used by Man in many alpine and arctic areas. This study will also establish whether the outflow from the front of a rock glacier can be used to establish whether it is active or inactive.

Study Sites

The two catchments chosen were the springs at the front of the active rock glacier along the east side of the Slims River Valley (see BLUMSTENGEL 1988; BLUMSTENGEL a. HARRIS 1988) and the Slims River at the Slims River bridge on the Alaska Highway (Fig. 1). At least 80% of the "normal flow" of the Slims River is derived from discharge from the terminus of the Kaskawulsh Glacier, 22 km upstream from the bridge (BRYAN 1972, 1974). The glacier drains 2020 km^2, and probably accounts for a substantially larger proportion of the flow of the Slims River in summer due to the lower flow of the other tributaries, as indicated by extrapolation of asynchronous flow records (Glaciology Divison 1977).

The active lobate rock glacier on the east side of the Slims River is 1.7 km long and 0.6 km wide where it spreads out onto the valley floor (BLUMSTENGEL 1988; BLUMSTENGEL a. HARRIS 1988). It is developed in a diamicton with greenstone clasts up to 20 cm long that originate at about 1230 m elevation below a cliff on the valley side. The valley was deglaciated about 12,500 ± 200 years B. P. (Y-1386, DENTON a. STUIVER 1966). The lower portion of the rock glacier is forested with a spruce-lichen woodland and has a thin loess cover over the rocks forming the rock glacier. This loess is added to by saline silt blown from the nearby

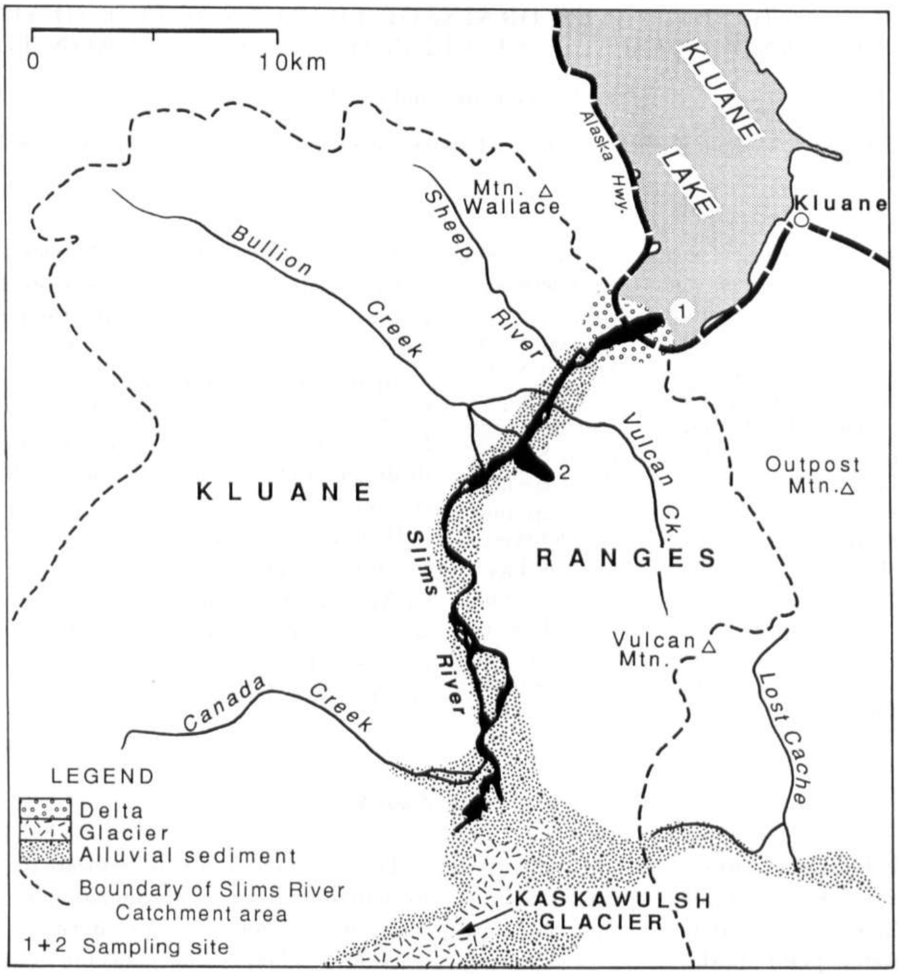

Fig. 1: Drainage of the Slims River valley above Kluane Lake and location of the study sites. Site 1 is the Slims River Bridge and site 2 is at the toe of the East Slims rock glacier

Entwässerung im Slims River-Tal oberhalb des Kluane Lake und Lage der Untersuchungsstellen. Stelle 1 ist die Slims River-Brücke und Stelle 2 liegt am unteren Ende des East Slims-Blockgletschers

Slims River delta by northerly winds each winter. The rock glacier has ploughed into alluvial silts of the Kaskawulsh flood-plain so that a silty push-lobe is present along the rock glacier front. From this front several streams emanate (Fig. 2).

The Kaskawulsh glacier is one of a number of large outlet glaciers flowing northwards from the major icefields of the St. Elias range, and its meltwater feeds two rivers: the Kaskawulsh River flowing east to join the Alsek drainage, and the Slims River, which flows north into Kluane Lake.

The discharge of the Slims River is augmented by four major tributary streams: Vulcan Creek on the east side and Canada, Bullion and Sheep Creeks on the west, with a combined area of 436 km^2 (Fig. 1). FAHNESTOCK (1969) carried out a study of the flow regime of the Slims River, showing that its discharge varied from 318 m^3/sec (11 250 cfs) in late summer to 0.2 m^3/sec (8 cfs) in winter. He postulated that peak flows could reach 566 m^3/sec (20 000 cfs). FAHNESTOCK also observed large variations in channel patterns and sediment transport, while the Glaciology Division (1977) emphasizes the evidence for periodic sudden outflows of water resulting from the release of water ponded in one of the 35 glacier-dammed lakes along the Kaskawulsh glacier.

Methods Used

All water temperatures were measured using a mercury in glass thermometer (to ± 0.5 °C). In the case of the spring water below the rock glacier, the thermometer was placed in the centre of flow, not

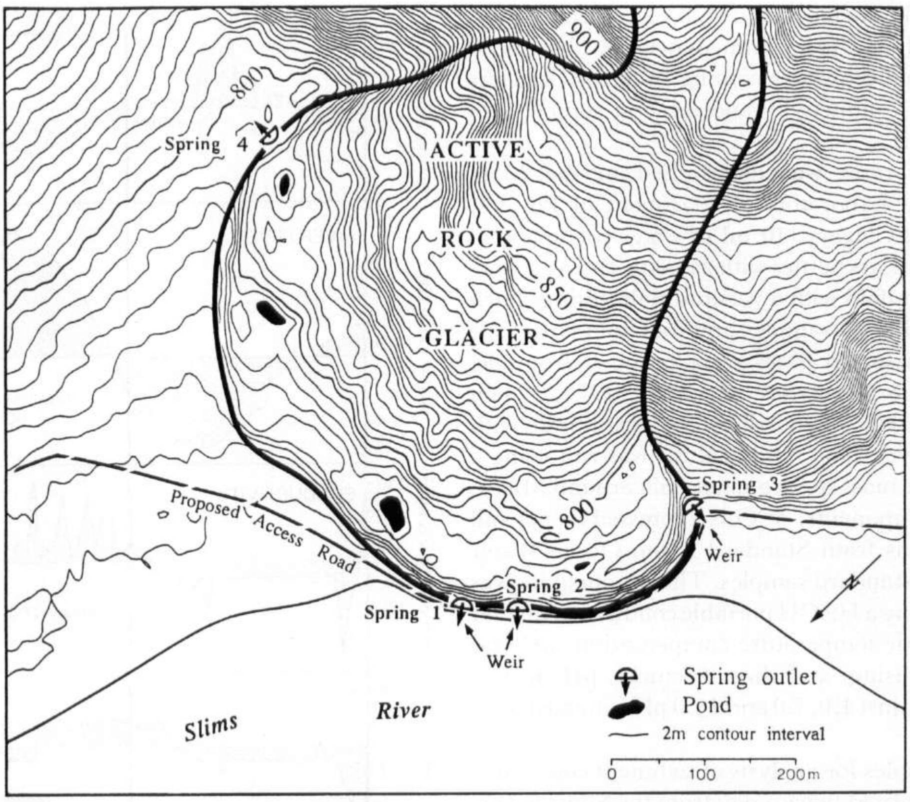

Fig. 2: Location of the springs on the terminus of the rock glacier
Lage der Quellaustritte am Fuß des Blockgletschers

more than 1 m from where the spring issued from the rock glacier front. The temperature data for the Slims River was obtained under the bridge at the Alaska Highway. A wooden platform located under the bridge allowed the water temperature to be measured 2 m from the bank of the river. Air temperature readings were provided by a Lambrecht recording hygrothermograph located at the snout of the rock glacier, and were checked by a YSI thermistor. Precipitation was measured during the 1985 summer season at the rock glacier site using a Forester 8″ rain gauge which was read to ±0.01″ once each day, and totalled 127 mm for June, July and August.

Plywood (either 90° or 60°) V-notched weirs were installed on the springs at the front of the rock glacier, depending on the flow. A gauging staff was emplaced in each one for measuring stream stage. Discharge was then determined following the methods outlined in BS 3680 (1965) using the equations:

60° V-notch $D = 2451.650 \times H^{2.5}$

90° V-notch $D = 4267.487 \times H^{2.5}$

where D is discharge in litres/min^{-1}; H is head of water (feet) flowing over the weir.

On the Slims River, a gauging staff was fixed to the bridge pier at the Alaska Highway. No discharge estimates were made using the stage data for the Slims River due to inadequate knowledge of channel geometry.

At both sites, visual readings of stage were made once or twice a day, from May to August 1984 and 1987, to determine the general pattern of variation during the summer. Diurnal variations were studied at both sites by carrying out visual readings of stage at 1/2 hour (Slims River site) and 1 hour (rock glacier site) intervals over a continuous 30-hour period in mid-summer.

At the same time, water samples were collected in clean 30 ml plastic Nalgene bottles that were dipped in the water and rinsed several times before the actual sample was collected. Spring water from the rock glacier was collected from the centre of stream flow, less than 1 m from where the spring emanated from the front of the rock glacier. The Slims River water samples were collected beneath the bridge at the Alaska Highway. Samples for stable isotope analysis were stored frozen, whereas those for pH and conductivity were taken to the Kluane Lake Research Station (AINA) and analyzed immediately. It has been postulated that the water coming from rock glaciers has a higher conductivity and mineral content (see Corte 1978).

The $\delta^{18}O$ ratio was determined in the Mass Spectrometry Laboratory, Department of Physics, University of Calgary. 10 ml of water was pipetted into standard glass bottles with 24 bottles being screwed onto a manifold with a vacuum-tight fitting. Each run consisted of 20 samples and four standards. Air and other dissolved gases were pumped from the water through capillaries (Roether 1970). Then CO_2 was introduced and allowed to equilibrate with the sample overnight. The analysis was run using a 90° Neir-type mass spectrometer built around Micromass 903 components. $\delta^{18}O$ is expressed as per mil (‰) deviations from Standard Mean Ocean Water based on the standard samples. The conductivity was measured using a HACH portable conductivity meter with automatic temperature compensation. pH was determined using a Fisher Accumet pH meter, calibrated against 4.0, 7.0 and 10.0 pH standard solutions.

Water samples for analysis of sediment concentration were collected twice a day from the Slims River. Analyses were performed by the Field Laboratory of the Department of Indian Affairs and Northern Development in Whitehorse. Turbidity was measured by attenuation of a light beam passing through the sample using a Hellige turbidity meter. Suspended solids (including settleable solids) were measured gravimetrically by filtering a well-mixed sample through a weighed standard glass-fibre filter and drying in an oven to constant weight at 103–105 °C (see method 209C, Greenberg et al. 1985, pp. 96–97).

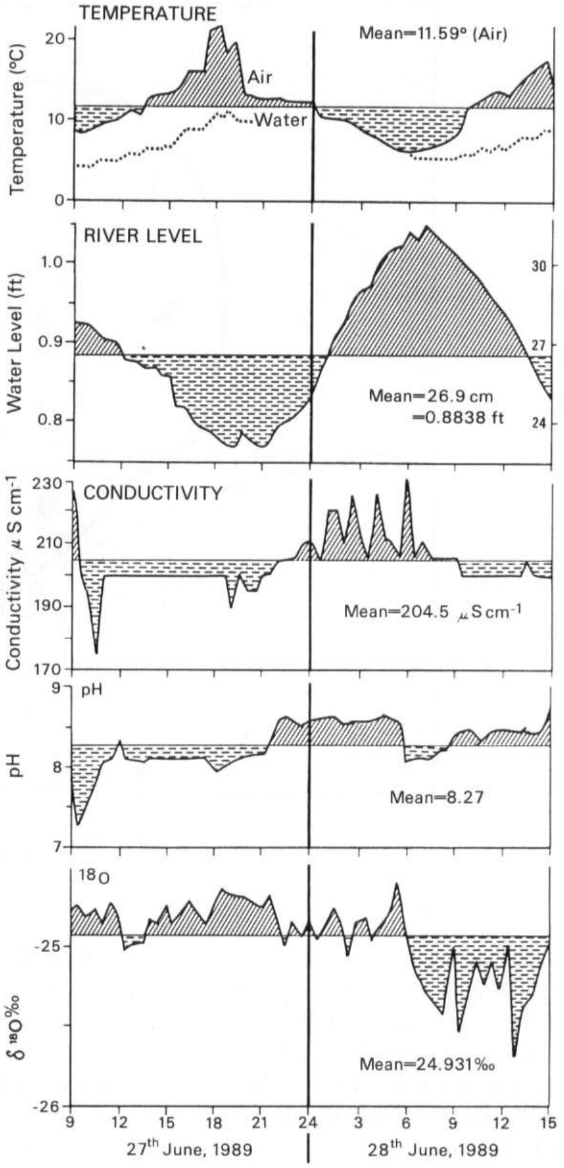

Fig. 3: Diurnal variations in the properties of the Slims River water based on sampling at 30 minute intervals on June 27–28, 1989

Tagesschwankungen der Wassereigenschaften des Slims River, gestützt auf halbstündliche Messungen am 27.–28. Juni 1989

Results

For convenience, these will be divided into specific parameters:

1. Temperature

Water temperature of the spring water from the rock glacier showed negligible diurnal variations, and maintained temperatures between 1 °C and 2 °C for two entire summer seasons (1984 and 1985). This was in marked contrast to the water temperature in the Slims River which showed substantial variations both diurnally (Fig. 3) and seasonally (Fig. 4). The variations in the water temperature in the river closely followed those of the air temperature for most of the summer, which is to be expected along a shallow braided river.

2. Diurnal Flow Regimes

The flow regime of the rock glacier springs (Fig. 5) was essentially constant when measured at 1 hour

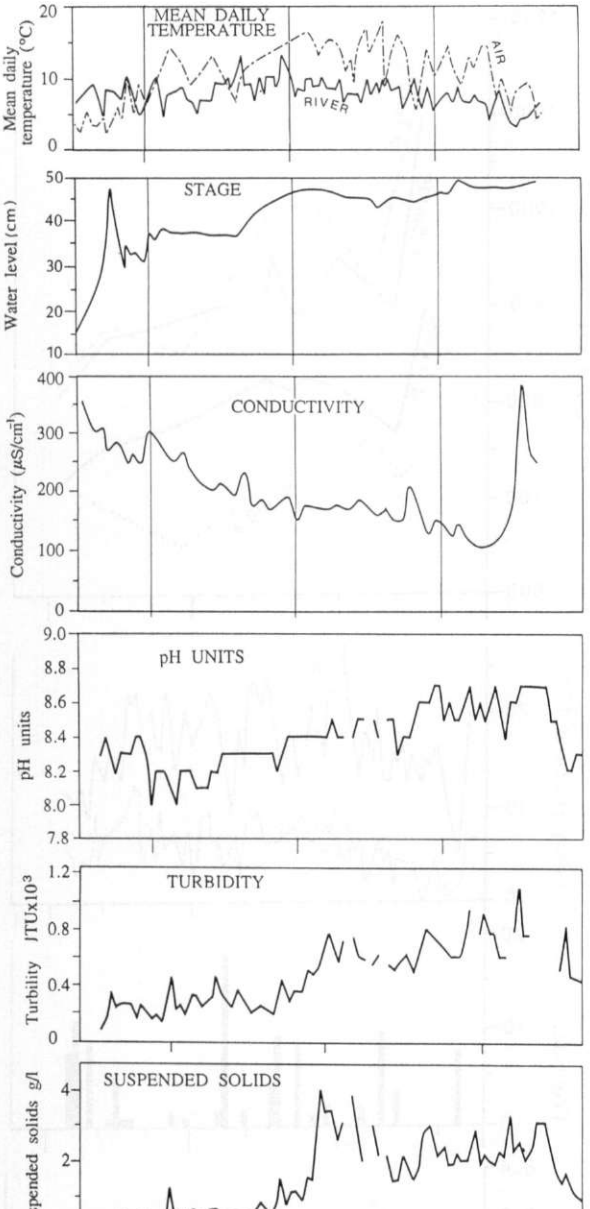

Fig. 4: Seasonal variations in the properties of the Slims River water during the summer of 1987

Saisonale Schwankungen der Wassereigenschaften des Slims River im Sommer 1987

intervals for 29 hours in 1985, and this was found to be typical of all these streams. Measurements taken in 1984 using a Leupold and Steven's Type Chart Recorder over several 3-day periods during the summer also showed no diurnal variations (BLUMSTENGEL 1988). However, in the Slims River (Fig. 3), the flow regime showed a marked diurnal variation which was offset from the peaks of air temperature by approximately 9–10 hours due to the distance from the snout of the glacier.

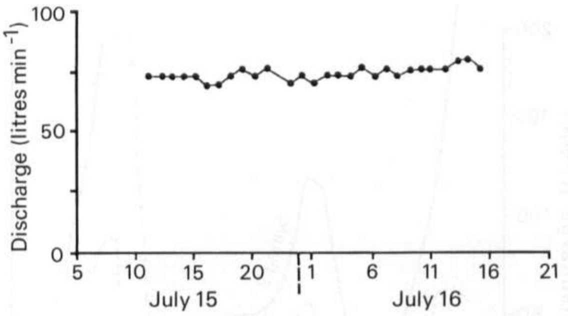

Fig. 5: Diurnal flow regime of spring no. 3, measured once every hour on July 15–16, 1985

Tageszeitliches Abflußregime der Quelle Nr. 3; stündliche Messungen am 15. und 16. Juli 1985

3. Seasonal Flow Regimes

The seasonal flow regime of the rock glacier springs (Fig. 6) showed a recession in the spring (220 litres/min or .0037 m^3/sec) at Spring 2 at the time of the snow-melt, followed by a fairly flat base flow. Very heavy or prolonged rains caused a peak with a delay time of 10–14 days, suggesting that the precipitation entered the active layer and flowed laterally down slope above the thawing front to feed the stream at the front of the rock glacier. The base flow was slightly higher in late July and early August when the air temperatures were at a maximum, and the discharge peaks were higher for a given rainfall event when the air temperatures at the time of the precipitation were over 15 °C, indicating more heat input into the upper layer of permafrost, resulting in greater melting of ground ice.

The stage of the Slims River is low until the spring thaw, when there is a rapid increase due to melting of the snow pack. This is followed by a slow rise through to mid-August (Fig. 4). Although no data were collected after the middle of August, a visual assessment of flow was made early in September, indicating a substantial decrease in flow. This correlates with lower maximum and minimum daily air temperatures and far shorter daylight hours.

4. Sediment Load

There were no visible sediments in any of the spring waters from the active rock glacier, even at the

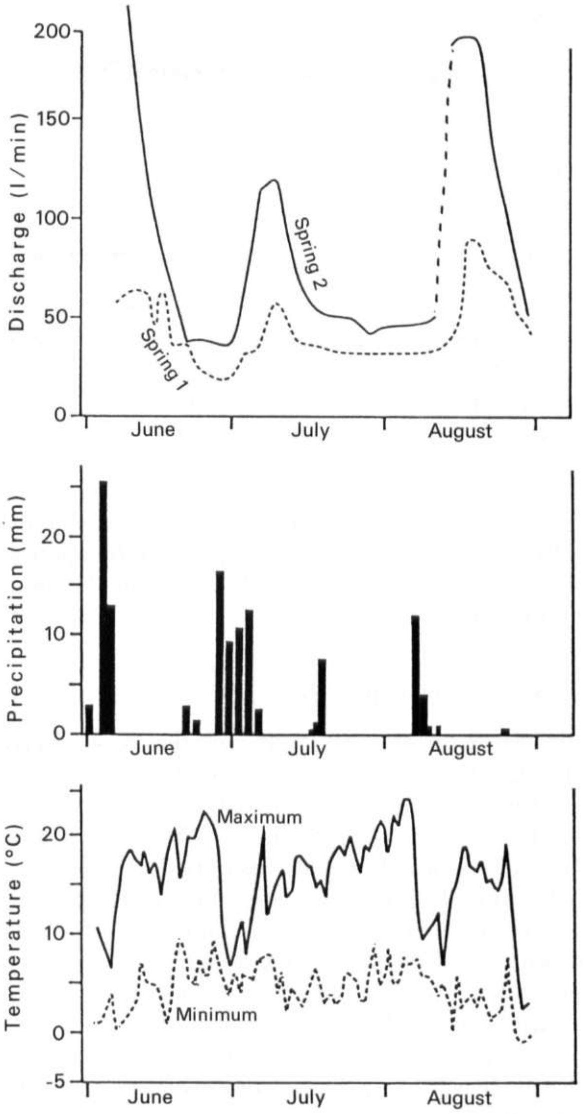

Fig. 6: Seasonal discharge of springs no. 1 and no. 2 with air temperature and precipitation for 1984 (from Blumstengel a. Harris, 1988, Fig., 7, p. 692)

Saisonale Entwässerung der Quellen Nr. 1 und 2 mit Lufttemperaturen und Niederschlag für 1984

time of snow melt. However, the turbidity of the Slims River water (Fig. 4) increases during the summer until peak flow is achieved in early August. The sediment load of the Slims River has been shown to be derived primarily from ablation of the Kaskawulsh glacier and the release of its sediment load (Johnson, personal communication, 1989). Settleable and suspended solids are low until the end of June when there is a large increase in ablation from the Kaskawulsh glacier. At that time, there was a change in the weather from predominantly cloudy days to clear,

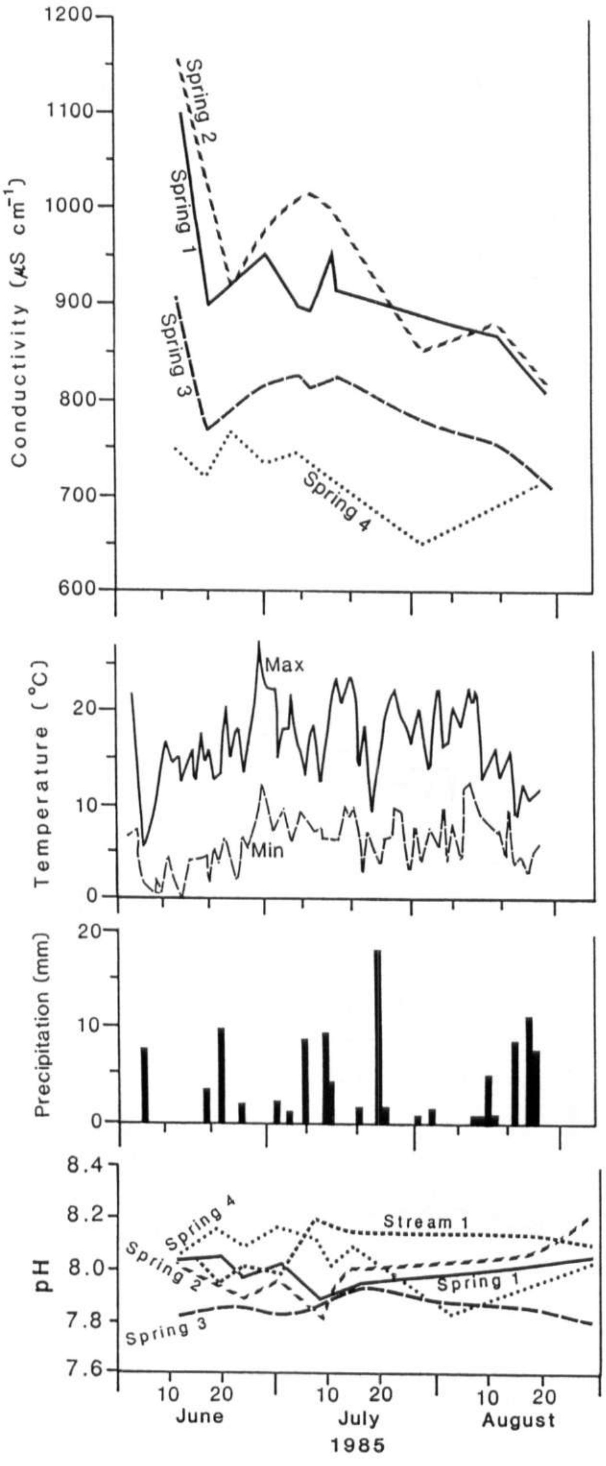

Fig. 7: Seasonal variations in conductivity of the springs in front of the rock glacier in 1985

Saisonale Schwankungen der Leitfähigkeit der Quellen am Fuß des Blockgletschers 1985

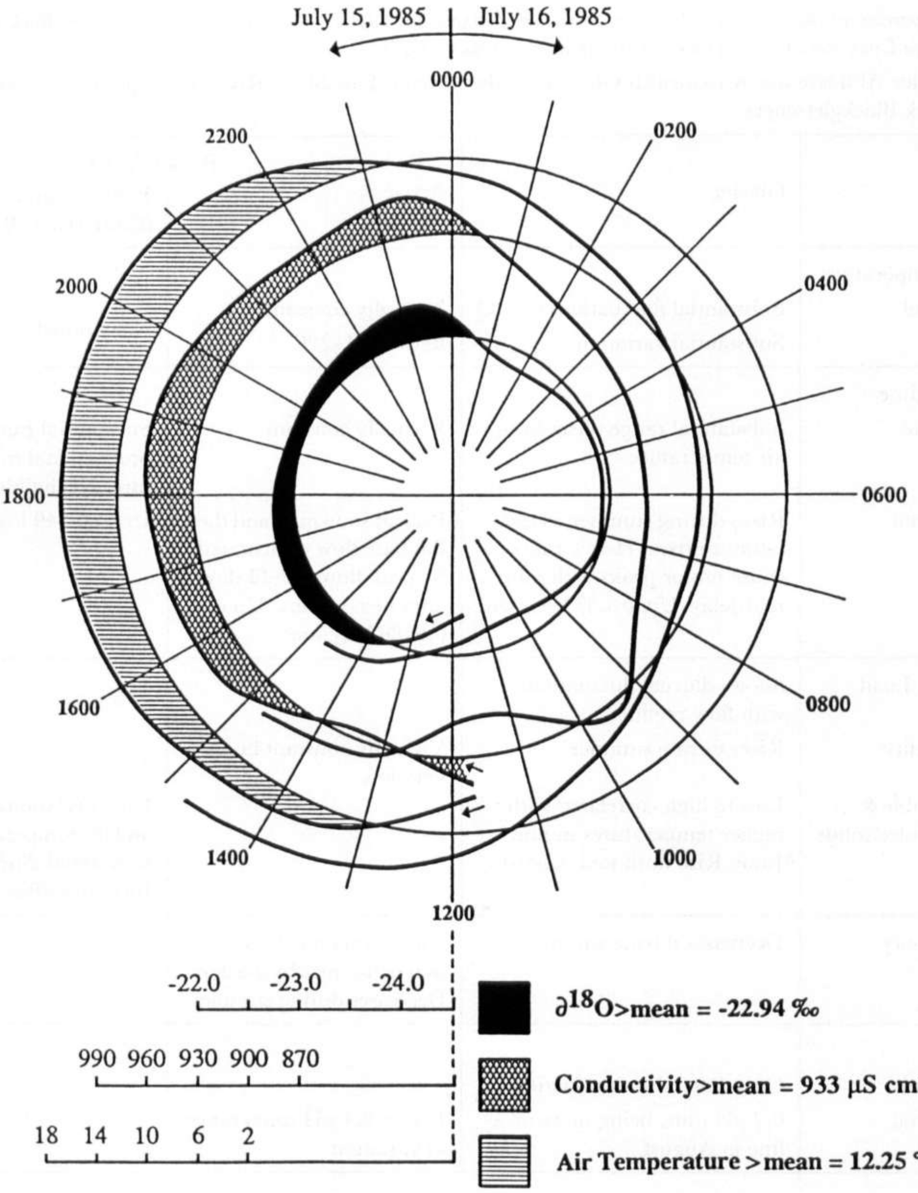

Fig. 8: Diurnal variations in water chemistry for spring no. 1 based on one hour samples on July 15–16, 1985
Tagesschwankungen wasserchemischer Kennwerte für Quelle Nr. 1 nach stündlichen Probenahmen am 15. und 16. Juli 1985

hotter weather. Suspended solids decrease with decreasing flow in mid-August. Apparently there is more limited erosion in the area during the snow-melt in the spring and the bulk of the sediment comes from the glacier.

There are minor peaks of low and high settleable and suspended solids that are not correlated with weather. These peaks may reflect debris flow occurrences within the basin (GUSTAFSON 1986; HARRIS a. GUSTAFSON 1988) or may be related to variable discharge from the glacier itself (FAHNESTOCK 1969). The variability in sediment yield and flow of the Slims River seen early in the season, which is not directly related to new precipitation, may be due to runoff connected with melting of the snow pack.

5. pH

The pH of the springs in front of the rock glacier showed fairly constant pH values (Fig. 7). Individual

Table 1: Comparison of the hydrology of streams below the Kaskawulsh Glacier, the active East Slims River Rock Glacier, and the inactive Hilda Creek Rock Glacier (from GARDNER a. BAJEWSKY 1987)

Vergleich der Abflüsse des Kaskawulsh Gletschers, des aktiven East Slims River Blockgletschers und des inaktiven Hilda Creek Blockgletschers

		Rock Glacier	
Property	Glacier	Active	Predominantly inactive (GARDNER a. BAJEWSKY 1987)
(1) Water temperature			
a. Diurnal	Substantial fluctuations c. 7 °C Substantial variation	Virtually constant Between 1–2 °C	Not studied
(2) Flow Regime			
a. Diurnal	Substantial range offset from air temperature.	Virtually constant	Substantial range directly proportional to air temperature. Negligible offset.
b. Seasonal	Rises during summer as temperature rises. Heavy rains cause minor peaks with minimal delay. Up to 3.33 l/sec/km^2	Peak at snowmelt and then flat base flow punctuated by peak flows 10–14 days after heavy rains. Up to 0.0286 l/sec/km^2	Up to 0.349 l/sec/km^2
(3) Sediment Load	Shows diurnal fluctuations with flow regime		
a. Turbidity	Rises during summer.	Virtually constant but very low.	
b. Settleable & suspended solids	Low to high correlated with higher temperatures in mid June. Rise until mid August.		Direct relationship to flow and air temperature with substantial diurnal variability. Increases after rains.
(4) Conductivity	Decreases during summer.	Approximately 2 times that below nearby glaciers. Decreases during summer.	
(5) pH			
a. Diurnal	Over 1.0 pH unit variation.		
b. Seasonal	0.7 pH unit, being more alkaline in August.	Under 0.4 pH units range of variation.	
(6) $\delta^{18}0$			
Diurnal	Related to air temperature. Mean −24.93‰ ~ −2‰ lower than mean local precipitation.	Related to air temperature. Mean −22.94‰ = local precipitation.	

springs showed slightly different patterns, and the maximum range recorded in a spring during the summer was 0.4 pH units. The mean varied between 7.9 and 8.1 for the four streams.

The river water showed much greater variability in pH than the springs in front of the rock glacier. The pH of the Slims River water (Fig. 4) slowly rose from around 8.0 in May to about 8.7 in early August and then declined. There was also a diurnal fluctuation of over 1 pH unit (Fig. 3).

6. Conductivity

Both the water in the springs emanating from the rock glacier (Fig. 7) and the conductivity of the Slims River water (Fig. 4) decreased during the summer.

This is probably due to leaching of salts during snowmelt from the saline, windblown silts that tend to be blown up-valley from the delta during winter onto the rock glacier and the lower salt content of the meltwater derived from both glacier ice and ground ice.

There was a noticeable inverse relationship between air temperature and conductivity in the Slims River (Fig. 4), but a direct relationship between these variables in the case of the rock glacier (Fig. 7). The latter results are not due to using the temperature compensation, since the measurements were made under constant temperature conditions (GURNELL a. CLARKE 1987).

7. $\delta^{18}O$

This was measured in the samples collected at regular intervals (30 or 60 minutes) during 30-hour studies at both locations (Figs. 3 a. 8); variations in the $\delta^{18}O$ of the water were quite small. In the case of the water from the rock glacier, the $\delta^{18}O$ was closely related to air temperature, but the mean values were 2‰ more negative for the river water, reflecting the colder environment on the icefields where the ice was formed (see MACPHERSON a. KROUSE 1967; WEST a. KROUSE 1972). However, this is a trend observed over a short period and the overall cycle of $\delta^{18}O$ values has not been determined.

Discussion and Conclusions

Only limited studies have been carried out on the hydrology of the streams below rock glaciers. Most of these were cases where the rock glacier was probably inactive, and this would appear to be true for the study of the Hilda rock glacier (see LUCKMAN a. CROCKETT 1978) by GARDNER a. BAJEWSKY (1987), which represents the most thorough study reported in the literature. Thus we can summarize and compare their results with those reported above in Table 1.

Table 1 indicates that there are important differences between the outflows of active rock glaciers and glaciers. The springs in front of a rock glacier exhibit a steady flow with clear water, whereas the diurnal flow of glacial meltwater varies considerably and is turbid. The water from the rock glacier has about twice the electrical conductivity of the glacial meltwater, showing the effect of the longer residence time. In addition, when the runoff is calculated for the two catchments (discharge/area), the average summer runoff for the glacier using the measurements of FAHNESTOCK (1969) is three orders of magnitude greater than the runoff calculated from the springs in front of the rock glacier (0.0286 litre/sec/km^2).

The present results confirm and amplify those of most other authors, e. g. runoff and greater overall variability (CORTE 1978; JACKSON a. MACDONALD 1980; JOHNSON 1981; EVIN a. ASSIER 1983a, 1983b, 1984; HAEBERLI 1985). The substantial difference in scale between the two catchments used in the present study does not appear to affect the results.

When the results noted by GARDNER a. BAJEWSKY (1987) are compared with the data presented in this study, it becomes apparent that their data are very different from that for the active rock glacier along the east side of the Slims River. Instead, the stream below the Hilda rock glacier showed a variation more like meltwater below a glacier or a spring below a talus slope. Its runoff is also much higher. An anonymous reviewer commented that "their rock glacier overlies the Stephen-Eldon contact which is a major spring line in this part of the Rockies. In other words, their 'rock glacier' spring is actually a groundwater spring mantled by the rock glacier". Thus, more work will be needed to establish what are the characteristics of inactive rock glaciers so as to complete this examination of the prediction by JOHNSON (1981).

Both glaciers and rock glaciers represent an important storehouse of water in the form of ice in the mountains. Glaciers consist of about 97–99% pure ice, but in rock glaciers, ice makes up only 40–60% of the landform (e. g. BARSCH 1978). Meltwater from these landforms modifies the flow regimes of the streams down-valley.

If climatic warming occurs, the active rock glaciers are likely to increase their output of melted ice. The discharge will probably remain relatively small and consistent in volume. Dissolved salts will be relatively high but the outflow will carry little suspended sediment from the landform. Complete melting will take a long time. Glacial discharge will undoubtedly increase in volume and variability, with higher diurnal and seasonal peak flows ranging down to the usual minuscule flows in winter. In this case, the water will carry large quantities of sediment but comparatively low amounts of dissolved solids. The rate of response to the warming will also tend to be more rapid in the case of glaciers than in rock glaciers.

Climatic change involving a reduction of precipitation but without a change in temperature would result in retreat of the glaciers, but increased moisture storage in rock glaciers due to the decreased winter snow cover. However, if the mean annual precipitation is less than about 350 mm, there is too little moisture stored in the permafrost to allow for rock glacier movement, whereas glaciers may still occur in places where sufficient snow accumulates each year. For example, the Karakorum Range and in Tibet (HARRIS, in press).

Conversely, an increase in precipitation without warming would result in increased moisture storage in glaciers and more melting of the interstitial ice in rock glaciers. The characteristics of the run-off from each source would not change as long as the rock glacier contains ice. HAEBERLI (1978, Fig. 2) has predicted that there will be a value of precipitation at which the equilibrium line on glaciers descends below the lower limit of rock glaciers. Where higher precipitation occurs, active rock glaciers could not form nor persist. He later suggested that this critical amount of annual precipitation is slightly greater than 2500 mm in the Alps (HAEBERLI 1983).

Finally, if there were a reduction in mean annual temperature without a change in precipitation regime, both rock glaciers and glaciers would enlarge and store more moisture. Thus it is essential to know the nature of any climatic change before the response of the two kinds of landforms can be predicted. Conversely, if the response of both rock glaciers and glaciers is known, the nature of the climatic change can be inferred.

Acknowledgements

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