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HYDROLOGICAL OBSERVATIONS IN BREGGER GLACIER BASIN, SPITSBERGEN —DISCHARGE, TEMPERATURE AND ELECTRIC CONDUCTIVITY—

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Abstract: The discharge, water temperature and specific electric conductivity (S.E.C.) of the Bayelva River near Ny Ålesund, Spitsbergen, Svalbard were observed from the middle of June to the middle of August 1993. The daily mean of water temperature variation did not show a clear relationship with the discharge rate, whereas that of S.E.C. showed a good correlation with the discharge, showing increasing S.E.C. with decreasing discharge rate, except sometimes when there was a local maximum of discharge due to rainfall runoff. The mean diurnal hodographs of water temperature and S.E.C. to the discharge showed a clockwise hysteretic loop, which could be explained by the combination of the heat and soluble materials added to the stream and the proportion of glacier ice melt water and the base flow.

1. Introduction

The effect of the melting process on the chemical composition in the ice core of temperate glaciers has been investigated. In temperate glaciers, melting affects the chemical compositions of the ice: it sometimes removes the ice, which contains an environmental signal, while at other times meltwater washes away the stored signal, totally changing its chemical composition. In the initial stage of the melting season, the meltwater percolates in the firn and refreezes at the top of the glacier ice, of which the temperature is below 0°C, and the concentrations of chemical constituents in the meltwater are very high, because atmospheric dust stored into the snow cover during winter is dissolved into meltwater while it percolates down through the snow pack. It is anticipated that, from the above process, the concentrations of chemical components in the superimposed ice would be high, however, GOTO-AZUMA *et al.*(1993) have reported that this is not always the case. The high chemical concentrations in the superimposed ice could be homogenized somehow, or dissolved into the meltwater and washed away with the discharge to a river. These chemical processes affect the chemical composition of the river water.

In this paper, hydrological characteristics of a glacier-melt fed river in Spitsbergen are described, especially its temperature and electric conductivity. The investigated watershed consists of a glacier area and a continuous permafrost area. Glacier and permafrost ice meltwater is initially at 0°C, and warms up while running down in streams. The conductivity of the glacier and permafrost ice meltwater is usually low compared to the subsurface water, and it increases, picking up and mixing with soluble materials from the river bed and wall while running down the river (HEWLLET, 1982; GREGORY and WALLING, 1973). This paper reports a preliminary study on the runoff mechanism of the high latitude glacier basin, with the goal of understanding the water and solute cycle in a polar head basin.

2. Observational Site

The investigated river basin is the Bayelva river basin, which originated from the East and West Bregger glacier (Fig. 1). The area of the basin is 31.6 km^2, of which 54% is occupied by the glacier at the end of the ablation season (SKRETTEBERG, 1991). The non-glacier area is permafrost, the thickness of which is roughly estimated as about 150

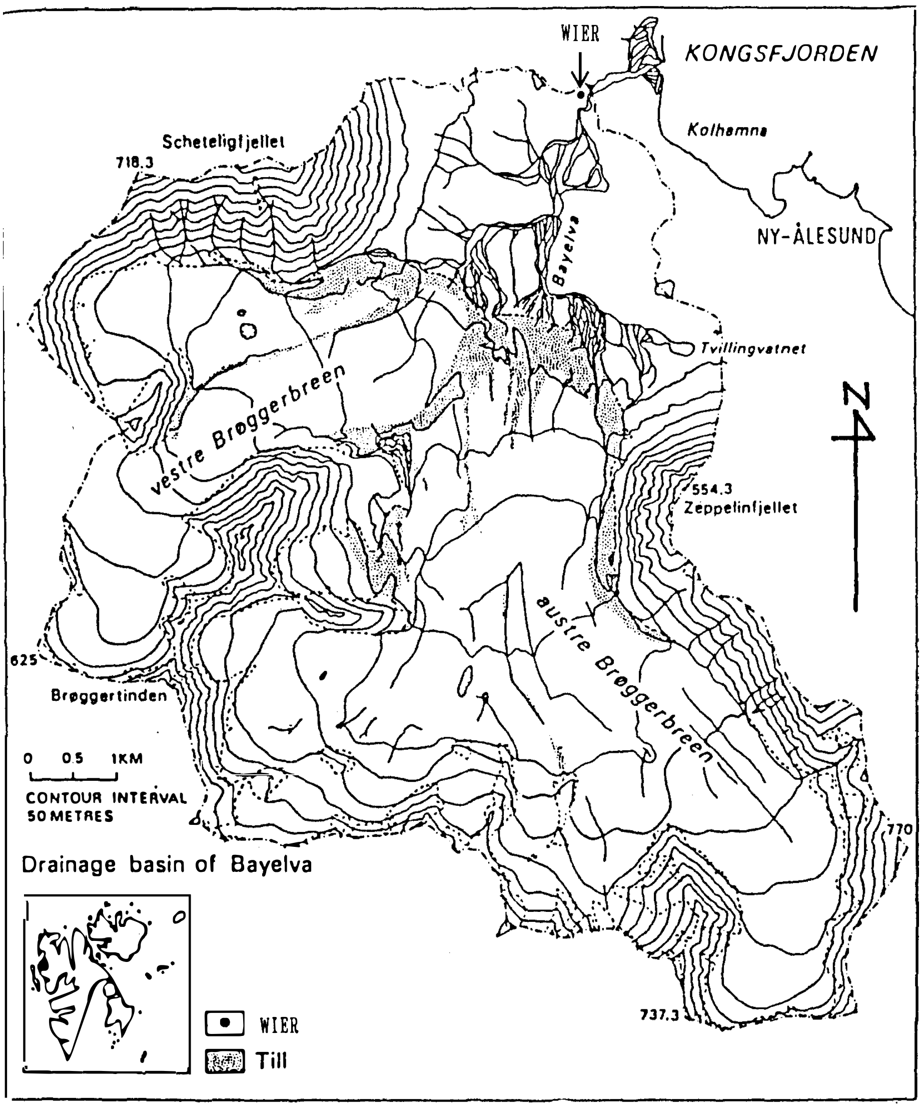

Fig. 1. The Bayelva River drainage basin. The dotted broken line indicates the divide of the basin. The lines crossing the contours indicates streams. From REPP (1988).

m. The thickness of the active layer in summer becomes 0.5 to 1 m. The mean yearly precipitation is 400 to 1000 mm. This high variation is less likely real than a result of observational error: the rain gauge in the town of Ny Ålesund shows 400 mm and the total discharge measured by a weir at the lower part of the Bayelva river 1000 mm. The annual mean temperature is about $-6\,^{\circ}$C, rather high for this high latitude, mainly due to the influence of the Gulf Stream. The mean air temperature in July is $5\,^{\circ}$C. The water flow occurs from May to September. The annual runoff amount for 1989 was about 30 $\times 10^6$ m^3, corresponding to 1000 mm of discharge yield. The highest discharge rate is observed in September 1989, as 32.2 m^{3}s^{-1}. In this basin, the sun is above the horizon all day long from April 18 to August 24 (SKRETTEBERG, 1991).

Data were taken from the middle of June to middle of August at a weir made by the Norwegian Water Resources and Energy Administration (NVE) on the lower part of the Bayelva River (500 m from the mouth of the river, see Fig. 1). Observed quantities are: 1) water levels by a pressure gauge type sensor, 2) water temperature by a thermistor, and 3) specific electric conductivity (S.E.C.) by a conductivity meter. Data from each sensor were recorded on a one channel data logger hourly. The water level was converted to the discharge rate using a formula supplied by the NVE (PETTERSSON, 1991).

3. Observational Results

The discharge, water temperature and S.E.C. from June 30 to August 12, 1993 are shown in Fig. 2. The thick broken line shows the 24 hour running mean for each items.

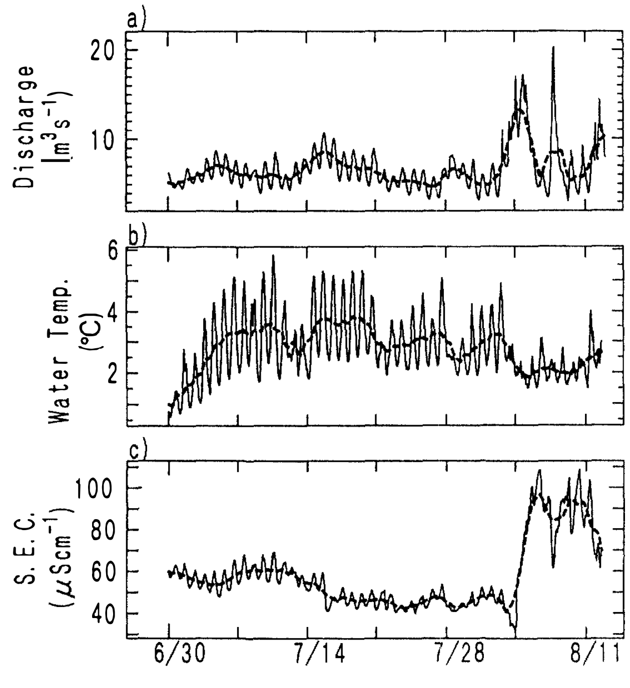

Fig. 2. The discharge, water temperature and S.E.C. from June 30 to August 12, 1993. The thick broken line shows the 24 hour running mean.

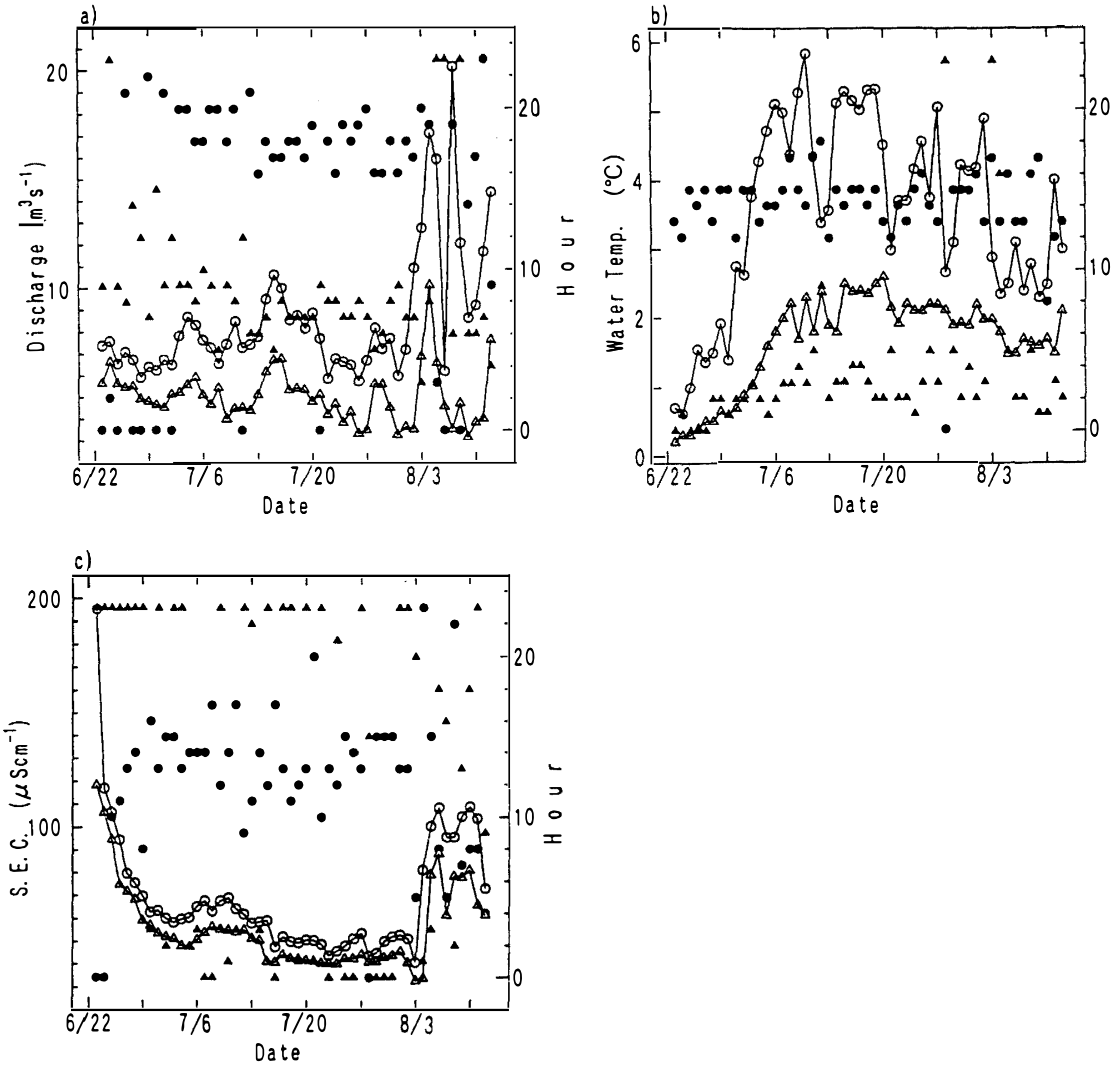

Fig. 3. The daily maxima (hollow circles) and minima (hollow triangles) and their time of occurrence (solid circle for maximum, solid triangle for minimum) in European Summer Time for discharge (a), water temperature (b) and S.E.C. (c) from June 23 to August 12.

The seasonal snow cover over the non-glacier area was melted completely and the diurnal variation of the three items was not seen before June 30. The discharge fluctuates between 3 and 10 m^3s^{-1} until August 2, and then it varies substantially due to rain storms, reaching this season's maximum value of larger than 20 m^3s^{-1}. The water temperature shows diurnal fluctuation clearly. The higher the daily mean temperatures, the larger the daily ranges. In the period of rain storms from August 3 to 12, the diurnal range of water temperature was rather small. The S.E.C. also shows a clear diurnal fluctuation before the rain storms.

Figures 3a–c show the daily maximum and minimum and their times of occurrence (in European Summer Time) for discharge, water temperature and S.E.C. from June 23 to August 12. The tangential line of the daily minimum of discharge (hollow circles in Fig. 3a) is falling till the end of July before the rain storm period, with occasional increases probably due to glacier-melt fluctuations and rainfall. The maximum discharge occurred around 2100 to midnight at the end of June, and then it gradually shifted from 1600 to 2000 by the end of July. The same tendency is seen for the occurrence time of minimum discharge, which is about 1000 on an average at the end of June, shifting to about 0700 as an average by the end of July.

The minimum water temperature (Fig. 3b) increased until the middle of July and gradually decreased afterward. The occurrence times of daily maximum and minimum water temperature were on average around 1400 and 0200, respectively. The time of daily maximum water temperature coincided with that of the daily maximum air temperature.

The daily minimum of S.E.C. (Fig. 3c) decreased until July 5, indicating the influence of melting of seasonal snow cover. It gradually decreased until August 2, recording the local minimum of 34 μScm^{-1}. In the rain storm period from August 2, the values of S.E.C. returned to the values of the seasonal snow melting period. The occurrence time of the maximum fluctuated from 0800 to midnight, having a mean of 1300. The minimum values mostly occurred at 2300 or midnight.

Figures 4a and b show the relationships of daily mean S.E.C. and water temperature to that of discharge from June 30 to August 12. The dependence of water temperature on discharge has two modes. The water temperature (Fig. 4b) decreased when the discharge increased substantially, but for a small increase of discharge it increased. The increasing tendency of the water temperature with a small increase of discharge occurs when the discharge is relatively small. The S.E.C. fluctuation against discharge (Fig. 4a) is grouped in 3 stages, divided by the local maximum of discharge probably due to rainfall. In each stage, the S.E.C. almost always decreased as the discharge increased except when the discharge changed toward/from its local maximum.

Figures 5a and b show the mean diurnal hodograph of the hourly values of water temperature and S.E.C. and that of discharge rate for the periods from July 5 to 8 (Fig.

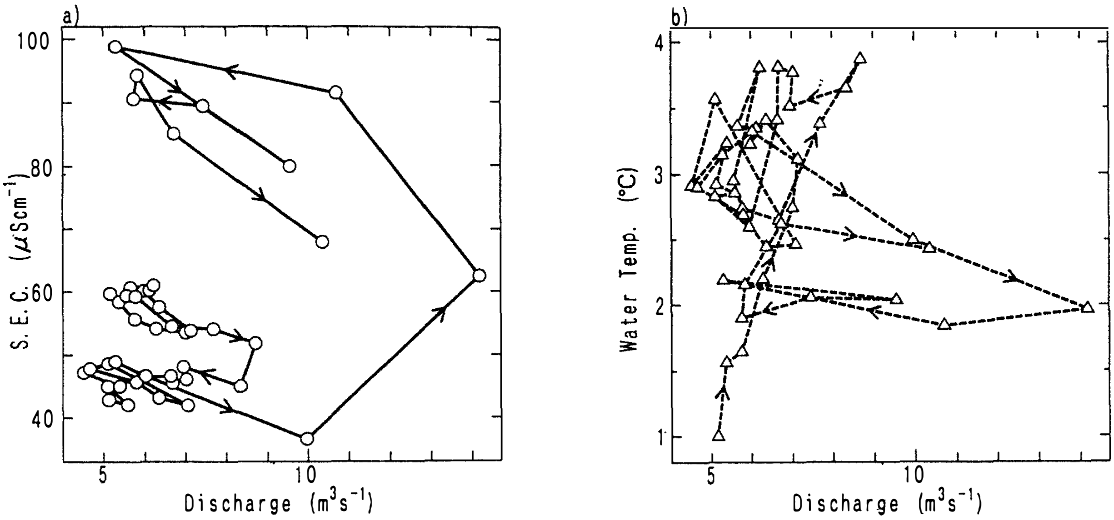

Fig. 4. The relationships of daily mean of S.E.C. (a) and water temperature (b) to that of discharge from June 30 to August 12.

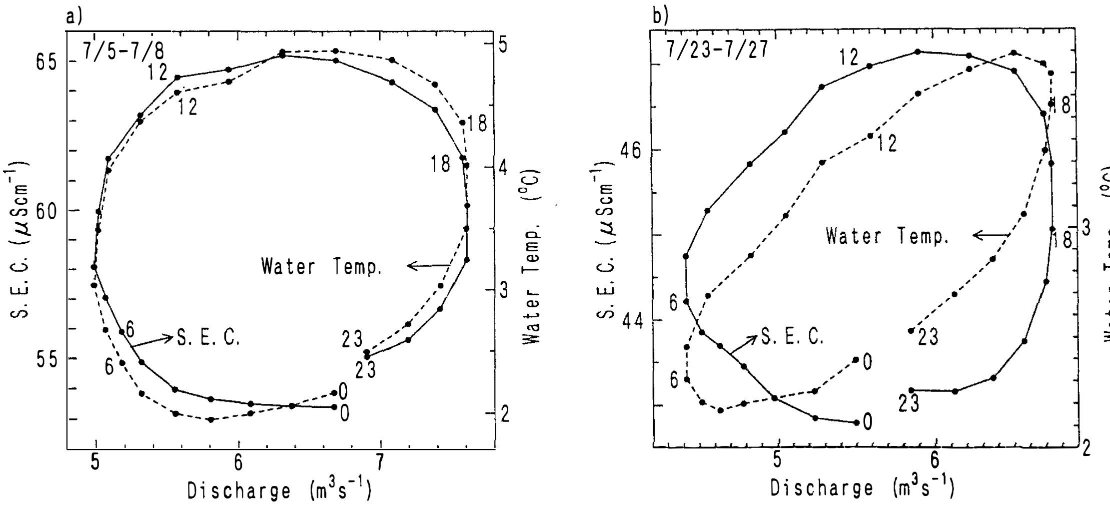

Fig. 5. The mean diurnal hodograph of the hourly values of water temperature (broken line) and S.E.C. (solid line) and that of discharge rate for the periods from July 5 to 8 (a) and from July 23 to 27 (b). The numbers by the line indicate the hour in European Summer Time.

5a) and from July 23 to 27 (Fig. 5b). There was no rainfall in either period. In these periods, the relationships of daily mean water temperature and S.E.C. against the discharge (Fig. 4) show an increasing tendency as the discharge decreases. However, the hourly courses of the temperature and S.E.C. fluctuations show an increasing tendency as the discharge increases.

The hourly changes of both water temperature and S.E.C. against discharge show clockwise hysteretic loops. When the discharge is increasing, both the water temperature and S.E.C. reach to the daily maximum and then decrease before the discharge reaches its maximum. Further, they reach their minimum before the discharge reaches its minimum.

This is very different from the snowmelt runoff observed in a no-glacier watershed. Generally, the water temperature and S.E.C. in the non-glacier watershed reach their minimum when the dicharge reaches its maximum, indicating that the source of the low temperature and low electric conductivity is the snowmelt water (KOBAYASHI, 1985, 1986). However, in this glacier fed watershed, the low temperature source is the glacier melting water, and it is somehow heated up before reaching the weir. For the S.E.C., the low S.E.C. of the glacier melt water is somehow influenced by the large mass of S.E.C. material, which might be dissolved into the stream water. In the next section, these relationships are discussed.

4. Discussion

4.1. Diurnal variation of water temperature

The daily mean of water temperature (Fig. 4b) showed two clear relationships with the discharge: one is that the temperature increases with increasing discharge, when the discharge is relatively small; and the other is that the temperature decreases with increasing discharge, when the change of discharge from the previous day's value is

Table 1. Occurrence time (in European Summer Time) of extreme events for discharge rate, water temperature and specific electric conductivity.

	Discharge		Water temperature		Electric conductivity	
	Max.	Min.	Max.	Min.	Max.	Min.
July 5–8	19	08	15	03	14	00
July 23–27	18	06	15	04	13	00

relatively large. This relationship is provably affected by the combination of the amount of glacier-melt water and the heat absorbed by the stream between the glacier terminus and the weir.

The mean diurnal variation of water temperature against discharge (Fig. 5) goes through 4 phases: I —from the minimum discharge to the water temperature maximum; II —from the water temperature maximum to the discharge maximum; III —from the discharge maximum to the water temperature minimum; IV—from the water temperature minimum to the discharge minimum. The occurrence times for the extreme values are shown in Table 1. In phase I, when the discharge increased moderately due to melting of the glacier and permafrost ice, the stream water as well is heated up by radiation and the atmospheric sensible heat exchange, consequently reaching the maximum water temperature at the end in the period I. In phase II, the discharge from the melting glacier and permafrost, which are basically at temperature 0°C, is increased, reducing the otherwise heated stream water temperature. In phase III, the amount of discharge decreased due to the reduction of melting, and the negative heat balance at the surface of the stream water reduced the water temperature further. In phase IV, the discharge further decreased and the water temperature increased because to that the stream water is heated mainly by positive heat input to the stream.

For a small head basin in temperate climate with no permafrost or glacier area, the water temperature of snowmelt runoff shows its minimum at high discharge because the contribution of the snowmelt water at 0°C is largest at the maximum discharge (KOBAYASHI, 1985). This is true if the basin is small enough or the distance between the terminus of the glacier and the weir is short enough so that the heat added to the stream water is negligible. It seems that, for this basin, the distance from the terminus of the glacier to the weir is long enough to alter the stream temperature.

4.2. Diurnal variation of specific electric conductivity

The mean diurnal hodograph of S.E.C. against the discharge rate (Fig. 5) goes through 4 different phases as does the water temperature. During the first phase, discharge increases rapidly but S.E.C. increases moderately, as a result of the flushing of readily soluble material (which shows high electric conductance) from the bed and wall of the stream, which reverses the expected dilution effect of the glacier and permafrost ice melt runoff. In the second phase, discharge increases and the dilution effect works to decrease the S.E.C. due to the 'fresh' character of the glacier and permafrost ice melt runoff. In the third stage, after reaching the maximum discharge, discharge begins to recede and the S.E.C. falls rapidly showing the 'fresh' character reducing due to decrease in melting of glacier and permafrost ice and the high stream stages which prevent ground water seepage from entering the stream. The fourth phase representing the recession limb is marked by gradually increasing S.E.C., as a result of a reduction in the proportion of ice melt runoff and increase in base flow (GREGORY and WALLING, 1973). The subsurface flow in this basin is rather complicated (LAURITZEN, 1991) and is believed to have only a small effect on the runoff because the thickness of the active layer could be as deep as 1.5 m.

This is very different from the snowmelt runoff observed in a non-glacier watershed. Generally, S.E.C. in the non-glacier watershed reaches its minimum when the discharge reaches its maximum, indicating that the source of the low electric conductivity is the snowmelt water (KOBAYASHI, 1986). However, in this glacier-fed watershed the pattern is different. For the S.E.C., the low S.E.C. of the glacier melt water is somehow influenced by the large S.E.C. material, which might be dissolved into the stream water and the base flow.

5. Summary

The discharge, water temperature and specific electric conductivity of the Bayelva River near Ny Ålesund, Spitsbergen, Svalbard were observed from the middle of June to the middle of August 1993. The data in the period from June 30 to August 3 are mainly used because they show clear diurnal variations. The data before that period were not used because they showed the receding part of seasonal snow melt runoff. The data after that period were discarded because a rainstorm affected the discharge.

The daily mean of water temperature variation showed two modes of relationship with the discharge, probably because it is affected by the combination of the amount of glacier-melt water and the heat absorbed by the stream between the glacier terminus and the weir, where the temperature was measured. The mean diurnal hodograph of water temperature as a function of the discharge showed clockwise hysteretic loops, which could also be explained by the combination of the heat added to the stream and the proportion of glacier ice melt.

The daily mean of S.E.C. showed a good correlation with the discharge, showing increasing S.E.C. with decreasing discharge rate. The relationship is sometimes broken due to the local maximum of discharge due to rainfall runoff. The mean diurnal hodograph of the S.E.C. to the discharge showed a clockwise hysteretic loop, which is probably due to the combination of amount of soluble material and the proportion of the glacier ice melt water to the base flow.

The quantitative discussion of the glacier melt runoff could be done by a separation method using water temperature or the electric conductivity if the amount of heat added to the stream or the amount of soluble material and its conductivity are known.

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