

Runoff and chemical characteristics of meltwater draining from Koryto Glacier, Kamchatka Peninsula, in 1996 and 1997

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Abstract

From July 9 to 19 in 1996, and from September 9 to 15 in 1997, hydrological and hydrochemical observations were carried out at the proglacial streams of Koryto Glacier, Kamchatka Peninsula, Russia. The discharge of Left Koryto River, one of the two streams draining from the glacier, varied showing a clear diurnal cycle between around $0.1 \text{ m}^3 \text{ s}^{-1}$ and $1.2 \text{ m}^3 \text{ s}^{-1}$ in 1997, whereas in 1996, the discharge increased gradually from $5.5 \text{ m}^3 \text{ s}^{-1}$ to $7.5 \text{ m}^3 \text{ s}^{-1}$. The mean concentration of Na^+ , the dominant cation, was 200 and $63 \mu\text{eq l}^{-1}$ in the observation periods in 1996 and 1997, respectively. The anions were dominated by HCO_3^- , and its concentration was 149 and $63 \mu\text{eq l}^{-1}$ in 1996 and 1997, respectively. Suspended sediment concentration varied linearly correlating with the discharge, from 0 to 0.2 g l^{-1} . The mean value of $\text{non-snowpack SO}_4^{2-} / (\text{non-snowpack SO}_4^{2-} + \text{HCO}_3^-)$ ratio of meltwater in Left Koryto River, which is a index of dominant reaction of chemical weathering in glacier drainage systems, was slightly higher in the 1997 period than in the 1996 period. This may indicate that inflow of surface meltwater affected subglacial drainage system and solute concentration of stream water even in early June in 1996. Using the chemically based mixing model, a separation of the hydrograph from September 12 to 13, 1997 into the two flow components was performed. The quick flow component reached its daily maximum after four hours from the solar noon. It never decreased to zero even in the time when the total discharge reached its minimum. The delayed flow component varied advancing four hours to the total discharge.

1. Introduction

Glacier drainage system and its linkage with glacier dynamics are the ones of the most important and recurrent topics within glacier hydrology. In the last decade, many studies on these topics which were based on laboratory experiments, numerical modelings and integrated observations involving some combination of the field methods have carried out one after another. For example, detailed and realistic image of subglacial chemical weathering (solute acquisition) processes and post-mixing chemical reaction have been provided by means of laboratory experiments (Brown *et al.*, 1994; Brown *et al.*, 1996b), meltwater sampling from boreholes (Sharp *et al.*, 1995; Tranter *et al.*, 1997) and theoretical conceptual model (Tranter *et al.*, 1993). On subglacial drainage system configuration, Nienow *et al.* (1998) suggested on the basis of the results of intensive dye tracing at Haut Glacier d'Arolla, Switzerland, that the sub-

glacial drainage system contains two principal components: a distributed system, that is a series of linked cavities in which flow velocities are of the order of 0.05 m s^{-1} , and a channelized system which consists of arterial channels. During the melt season, the channelized system expands headward at the expense of the distributed system, and this growth of the channels closely follows the upglacier retreat of the transient snowline on the glacier surface. Moreover, according to Tranter *et al.* (1996), solute concentration of bulk meltwater showed considerable change corresponding to the headward expansion of the channelized system at a temperate glacier (Haut Glacier d'Arolla), and also at a polythermal glacier (Austre Brøggerbreen in Norway).

On the other hand, these development in understanding the characteristics of glacier drainage system and chemical weathering processes cast considerable doubt on the chemically based mixing model, which had been widely adopted in studies on glacier

drainage system and used to make quantitative inferences about meltwater fluxes through the different elements of drainage system (e.g. Collins, 1977; Collins, 1979). This model assumes that two types of meltwater, concentrated "subglacial" waters which pass slowly through the system and relatively diluted "englacial" waters which have a rapid transit in supraglacial and/or englacial ice-walled channel. It also assumes that these two waters mix in a region close to the glacier terminus, and produce bulk meltwaters with a chemical composition dependent upon the initial chemistries of the two components and their mixing ratio. Sharp *et al.* (1995) pointed out that three arbitrary assumptions involved in the use of this mixing model, "two drainage components", "unique component chemistries" and "conservative mixing" were not convincing, and thus, argued that the utility of this model as a tool for the investigation of glacier hydrological systems was questionable.

The main research fields of glacier hydrological studies mentioned above have been Alpine glaciers, and we have not enough knowledge on drainage characteristics of glaciers under a maritime condition, though several researches were carried out at South Cascade Glacier in USA (e.g. Fountain, 1992), Middalsbreen in Norway (e.g. Willis *et al.*, 1990) and so on. Kamchatka Peninsula, especially its eastern coast, is a region where many glaciers characterized by intensive mass exchange under a maritime climate (Muravyev, 1999; Dyurgerov and Meier, 1999). At Koryto Glacier in Kronotsky Peninsula on the eastern coast of Kamchatka, glaciological researches were carried out in 1960 and 1971 by Russian scientists (Muravyev *et al.*, 1999) and then, Russo-Japanese Joint Glacier Researches were carried out in the summers of 1996,

1997 and 2000. Short-period observations in 1996 and 1997 were regarded as preliminary researches on the condition of the glacier in early summer and in late summer, respectively. The results of the observation in 2000 which lasted for 45 days during the ablation period will be presented in the near future.

In this paper, we present the results of hydrological observations at Koryto Glacier in the summers of 1996 and 1997, and outline the characteristics of runoff condition, solute and suspended sediment concentrations of streams from the glacier. Then, we discuss on the characteristics of the drainage system of Koryto Glacier.

2. Site description

Climatic condition of the eastern coast of Kamchatka Peninsula, Russia, is characterized by heavy snowfall in early and late winter season which is strongly affected by activities of Aleutian Low and the intrusion of maritime temperate air masses from southeast (Lydolph, 1977). Accordingly, mass balance and hydrological condition of glaciers in this region are influenced by such climatic condition. Kronotsky Peninsula is located at the eastern coast as a prominent massif intruding into the Pacific Ocean. There are 32 glaciers in this region (Muravyev *et al.*, 1999), the most of which have clean appearance as compared with other glaciers in Kamchatka where the surface of glaciers are usually covered with debris. The glaciers in this region lay at the lowest altitude in Kamchatka, some of which flowing down to the altitude of 250 m.

Hydrological observations were carried out at the terminus of Koryto Glacier (Fig. 1), in the summers of

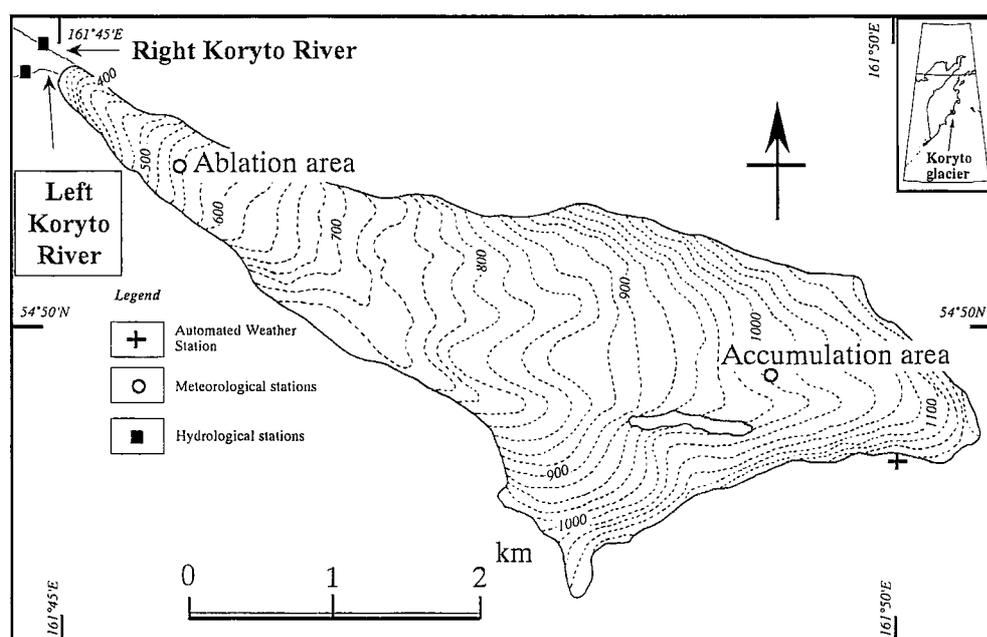


Fig. 1. Topographic map of Koryto Glacier. Locations of the observation points are plotted by symbols.

1996 and 1997. Koryto Glacier is the third largest glacier on the Kronotsky Peninsula, which has the area of 7.78 km² and extends from 1220 m to 320 m a. s.l. towards northwest (Muravyev *et al.*, 1999). The area of Koryto Glacier watershed is 11.9 km². There is a relatively large accumulation area, while the glacier tongue is narrow. The glacier surface is not covered with debris and lacks any icefall or intensive crevasse area. Only little vegetation is found on the steep slopes around the glacier. Koryto Glacier watershed consists of Tertiary volcanic rocks such as tuff and pillow lava.

According to the results of meteorological observations by an automatic weather station from July 1996 to September 1997 (Matsumoto *et al.*, 1997), monthly mean air temperature at the uppermost ridge of the Koryto Glacier (1160 m a.s.l.) varied between -13.6 °C in February and 9.8 °C in August. Daily mean air temperature was higher than 0 °C from early June to mid-October, and this period roughly indicated ablation season at Koryto Glacier. Under such condition, intensive melting of glacier occurs in summertime. In the summer of 1996, Shiraiwa *et al.* (1997) observed an ablation near the terminus which was more than 1 m (in thickness) in the period of 11 days. We have no data of snowfall observation at the glacier yet, whereas Muravyev *et al.* (1999) estimated the mean summer and winter mass balance in recent 60 years to be -4.03 m and 3.41 m w.e., respectively. According to Dyurgerov and Meier (1999), the annual mass balance amplitude of Koryto Glacier as an average of 13-year data is 3.54 m w.e., and is the second largest value among those of 50 glaciers in northern hemisphere (the greatest value, 3.58 m, is that of Kozelsky Glacier in Kamchatka). Due to a large amount of meltwater flux into the bottom of the glacier, the contribution of basal sliding to the surface flow velocity of the glacier is considerably large (Yamaguchi *et al.*, 1997; Yamaguchi *et al.*, 1998).

3. Observations

Hydrological and meteorological observations were carried out at Koryto Glacier from July 9 to 19 in 1996 (the 1996 period), and September 9 to 15 in 1997 (the 1997 period).

Two proglacial streams flow down from the terminus of Koryto Glacier. Although two outlets of subglacial channels found in the summer of 2000, we could not observe the configuration of the outlets at the terminus in detail. However, we supposed that meltwater draining from the glacier once mixed in front of the terminus, and then branched off into two streams, called Left Koryto River and Right Koryto River (these are the same streams as "Stream A" and "Stream B" named by Kodama *et al.* (1997)). Ratio of discharge of two streams could be affected by the

distribution of seasonal snowpack and/or topography near the terminus. The greater part of meltwater from the glacier flowed through Left Koryto River in the 1996 period, but oppositely, the most of meltwater flowed through Right Koryto River in the 1997 period. Both in 1996 and 1997, hydrological data were mainly collected at Left Koryto River (250m a.s.l.) about 100 m downstream from the terminus. Water level, water temperature and specific electric conductivity of Left Koryto River were measured and recorded at 10-minute interval in the 1996 period. During the 1997 period, water level was measured only and recorded at 10-minute interval. The stage-discharge curves (H-Q curves) were obtained in each year and the 2-hour running mean was taken. The main reason why we had kept measuring Left Koryto River in the 1997 period was that we wanted to compare chemical characteristics of the same proglacial stream.

Stream water samples were taken for chemical analysis in the intensive observation periods (IOPs) in both years: July 10 - 11 and 15 - 16 in 1996; September 11 - 13 in 1997. The water samples were collected with polyethylene bottles, and then, were filtered. The concentration of the major ions (Na⁺, K⁺, Mg²⁺, Ca²⁺, Cl⁻, NO₃⁻ and SO₄²⁻) of these samples were determined by an ion chromatograph (Dionex 2020i/SP or Dionex DX500). Bicarbonate (HCO₃⁻) as expressed by alkalinity was determined only for the samples in 1996 by titration with sulfuric acid. It took several months before starting the analysis due to the delay in the transportation of the samples to laboratory in Japan. The samples are kept refrigerated until the analysis.

To measure suspended sediment concentration, stream water was sampled temporally and filtered at the camp using a handy vacuum pump and glass fiber filters (pore size = 0.6 μm). Suspended sediment concentration was obtained by measuring dry weights of those filter papers in laboratory.

Meteorological observations on Koryto Glacier were carried out at the ablation area station (545 m a. s.l.) and the accumulation area station (1005 m a.s.l.) in 1996 and 1997. The meteorological elements measured at two sites in 1997 are: air temperature (height from the ground: 1.5 m), relative humidity (1.5 m), global radiation (1.0 m; only at the ablation area station), wind speed (3.5 m), wind direction (3.5 m), atmospheric pressure (0.5 m) and precipitation (0.5 m). All the data were measured and recorded at 1-hour interval. Detailed information of meteorological condition and heat balance, and brief characteristics of runoff variation in the 1996 period were already reported by Kodama *et al.* (1997). Results of meteorological observations in the 1997 period were also presented by Nishimura *et al.* (1999).

4. Results

4.1. Variation in discharge of Left Koryto River

Discharge of Left Koryto River and principal meteorological elements (air temperature, global radiation and precipitation) in the 1996 and the 1997 periods are shown in Figs. 2 and 3, respectively. According to the results of Shiraiwa *et al.* (1997), mean ablation rate in the 1996 period along the transverse lines including the ablation area station and the accumulation area station were 39.1 and 38.4 mm w.e. d^{-1} , respectively. During the 1997 period, mean ablation rate at the ablation area station was 42.9 mm w.e. d^{-1} .

In the 1996 period, the discharge of Left Koryto River increased gradually from $5.5 \text{ m}^3 \text{ s}^{-1}$ to $7.5 \text{ m}^3 \text{ s}^{-1}$, and the daily maximum discharge occurred around 14:00 to 18:00 in local time (Fig. 2). The discharge of Left Koryto River in the 1997 period was much less than that in the 1996 period and varied between around 0.1

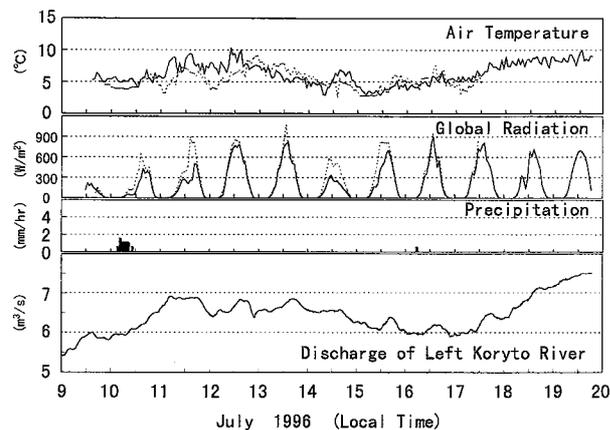


Fig. 2. Meteorological and hydrological elements observed at Koryto Glacier in July 1996. Air temperature and global radiation at the ablation area are indicated by solid lines. These in the accumulation area are indicated by broken lines.

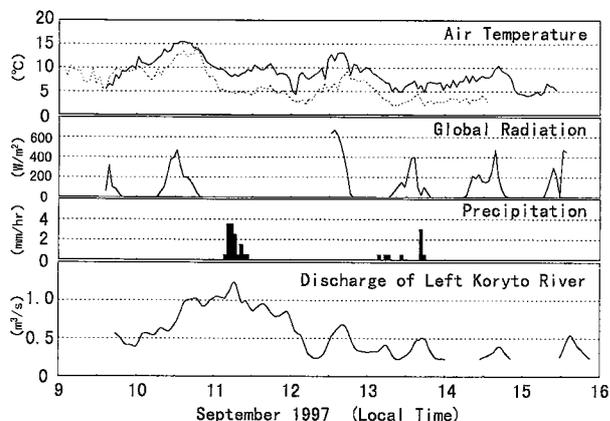


Fig. 3. Meteorological and hydrological elements observed at Koryto Glacier in September 1997. Air temperature at the ablation area and the accumulation area are indicated by solid line and broken line, respectively.

$\text{m}^3 \text{ s}^{-1}$ and $1.2 \text{ m}^3 \text{ s}^{-1}$ (Fig. 3). One of the reasons of such small discharge of Left Koryto River was that main portion of the meltwater from the glacier flowed through Right Koryto River. Discharge of Right Koryto River could not be measured in the period, and was visually estimated about five times larger than that of Left Koryto River. The discharge was large and remained more than $0.5 \text{ m}^3 \text{ s}^{-1}$ on 10 and 11 September, and then, decreased to less than $0.5 \text{ m}^3 \text{ s}^{-1}$ in the last half of the period. This pattern of variation corresponded well to that of air temperatures on the glacier. The lag-time between the variations of discharge and air temperatures seems to be around half a day in Fig. 3. In the mornings of September 14 and 15, water level got lower than the depth at which water level sensor was installed. As compared with the 1996 period, diurnal cycle of discharge was clearly found in the last half of the 1997 period. Diurnal cycle was not found from 10 to 11 September, because rainstorm with precipitation of 13 mm and severe wind sustained at that period. Excluding the period of the rainstorm, the daily maximum discharge occurred around 14:50 to 16:50 in local time.

4.2. Solute concentrations

The temporal variations of the chemical solute concentration of the stream water from Koryto Glacier during the IOPs in 1996 and 1997 are shown in Figs. 4 and 5, respectively. In Table 1, mean values of solute concentrations in Left Koryto River, Right Koryto River, supraglacial streams, snowpack on the glacier, glacier ice and rain are shown as references. Meltwater in Left Koryto River and supraglacial streams in the 1996 period have higher solute concentrations than those in the 1997 period. During the 1996 period, solute concentrations of the most constituents in Left Koryto River were higher than those in Right Koryto River.

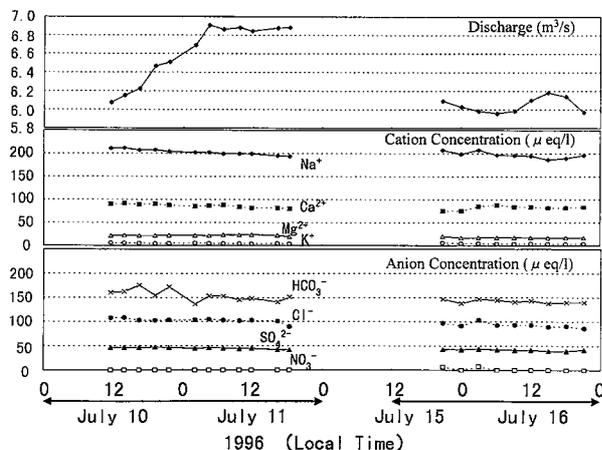


Fig. 4. Variations in discharge and solute concentrations of Left Koryto River in June, 1996.

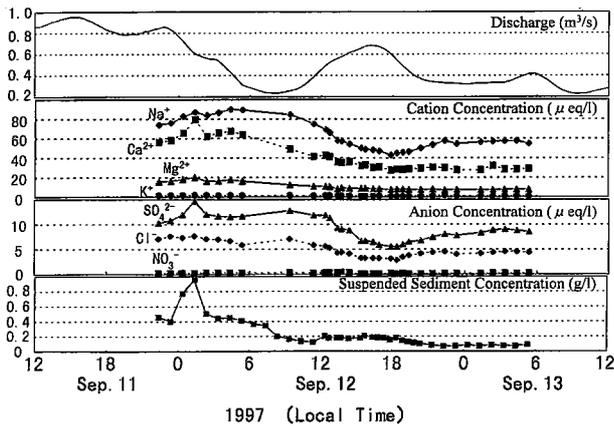


Fig. 5. Variations in discharge, solute and suspended sediment concentrations of Left Koryto River in September 1997.

The cations in Left Koryto River are dominated by Na^+ and Ca^{2+} in both years, whereas the concentrations of four constituents in the 1997 period decreased to half of those in the 1996 period. The anions are dominated by HCO_3^- in the 1996 period, and Cl^- and SO_4^{2-} had the second and the third highest concentrations, respectively. HCO_3^- concentrations in the 1997 period are not shown in Fig. 5 and Table 1, because these were not measured directly. But, HCO_3^- concentrations in the 1997 period was estimated as the charge-balance residuals, which are expressed in units of equivalents as follows:

$$(\text{HCO}_3^-)^* = (\text{Na}^+ + \text{K}^+ + \text{Mg}^{2+} + \text{Ca}^{2+}) - (\text{Cl}^- + \text{NO}_3^- + \text{SO}_4^{2-}). \quad (1)$$

Because specific electric conductivity (SEC) of each sample in the 1996 period which was calculated from the concentrations of these eight constituents was very close to measured SEC (the ratio of calculated SEC to measured SEC dispersed between 0.99 and 1.04), we assumed that other constituents such as H^+ are negligible. Then, the calculation of $(\text{HCO}_3^-)^*$ could be checked by comparing estimated against measured values of the samples. The best-fit regression equation was:

$$(\text{HCO}_3^-) = 1.285 (\text{HCO}_3^-)^* - 64.9. \quad (r^2 = 0.36) \quad (2)$$

The standard deviation of the differences between measured HCO_3^- and HCO_3^- obtained from equations (1) and (2) was $8.85 \mu\text{eq l}^{-1}$.

The mean value of estimated HCO_3^- in the 1997 period was $62.7 \mu\text{eq l}^{-1}$, therefore, HCO_3^- was also the most dominant anion constituent in the 1997 period. The concentration of Cl^- fell into the third highest constituent and its concentrations were less than a tenth of those in the 1996 period.

In both years, solute concentrations were decreasing with the increase of the discharge. But, as shown in Fig. 5, occurrence time of the daily maximum and minimum concentrations were not the same as the time of the minimum and the maximum discharges. According to Kodama *et al.* (1997), SEC of meltwater which was manually measured at arbitrary interval in the 1996 period was decreasing with the increase of discharge.

The relationship between the discharge and the seven solute (Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , NO_3^- , SO_4^{2-} and

Table 1. The mean solute concentrations and their ranges of variations of water ice and snow samples collected at Koryto Glacier.

1996	Left Koryto River		Right Koryto River		Supraglacial Channel	Glacier Ice	Snowpack
	(mean)	(range)	(mean)	(range)		(mean)	(mean)
Na^+	200.1	211.4-186.6	122.2	126.6-114.8	8.3	7.1	10.0
K^+	4.5	6.1- 3.3	3.4	3.8- 2.8	1.5	2.0	2.2
Mg^{2+}	20.0	23.8- 16.4	21.1	22.2- 19.7	2.5	2.5	4.1
Ca^{2+}	84.4	91.3- 74.9	66.9	69.4- 64.9	13.5	17.8	25.2
Cl^-	98.3	108.0- 86.0	36.5	37.5- 34.1	1.7	0.9	4.2
NO_3^-	0.7	7.4- 0.0	0.0	0.0- 0.0	0.0	0.0	0.0
SO_4^{2-}	43.7	47.4- 39.3	19.3	21.0- 19.9	2.3	3.1	3.9
HCO_3^-	148.8	175.6-136.3	149.8	176.8-144.0	38.1	—	—
No. of Samples	21		10		1	3	2

1997	Left Koryto River		Supraglacial Channel	Glacier Ice	Snowpack	Rainwater
	(mean)	(range)	(mean)		(mean)	(mean)
Na^+	62.5	90.0- 43.0	1.2	139.5	6.5	36.5
K^+	0.9	1.6- 0.5	0.2	30.5	0.6	2.8
Mg^{2+}	10.3	20.1- 6.7	0.9	1.7	0.7	9.4
Ca^{2+}	40.0	79.6- 26.4	2.0	5.7	2.8	41.9
Cl^-	4.9	7.6- 2.8	0.5	7.7	4.7	23.8
NO_3^-	0.2	0.4- 0.1	0.1	0.2	0.1	0.1
SO_4^{2-}	9.3	15.1- 5.5	0.2	1.0	1.6	22.6
HCO_3^-	—	—	—	—	—	—
No. of Samples	35		2	1	2	2

estimated HCO_3^- concentrations in the IOP in 1997 are shown in Fig. 6. The sampling period can be divided into two falling limb stages and two rising limb stages of the hydrograph. In the first falling limb stage (F1), the solute concentrations first increased, then decreased. During other three stages (R1, F2 and R2), especially after 10:20 on September 12, every solute concentrations fluctuated with different pattern from that of the first period, F1. Mg^{2+} , Ca^{2+} and HCO_3^- were almost stable in their falling and rising limbs, but decreased around the maximum discharge. In contrast, Na^+ , Cl^- and SO_4^{2-} and fluctuated like a hysteretic loop. When the discharge was increasing, the solute concentrations reached to the daily maximum and then decreased before the discharge reached its maximum. Further, they reached their minimum before the discharge reached its minimum. Constituents with low concentration, especially NO_3^- , did not show a clear relationship with the discharge. The reason why the relationship between the discharge and the solute concentrations in the first falling limb stage was different from those in other three stages is that rainwater was supplied into meltwater by storm event in September 11 (Fig. 5). The rainwater, which has different chemical composition, must have been quickly flushed away and mixed with the meltwater. Here, we assume that mixing of the rainwater with the meltwater had finished at 10:20 on September 12. With this consideration, an attempt of hydrograph separation in this period is discussed in Chapter 5.

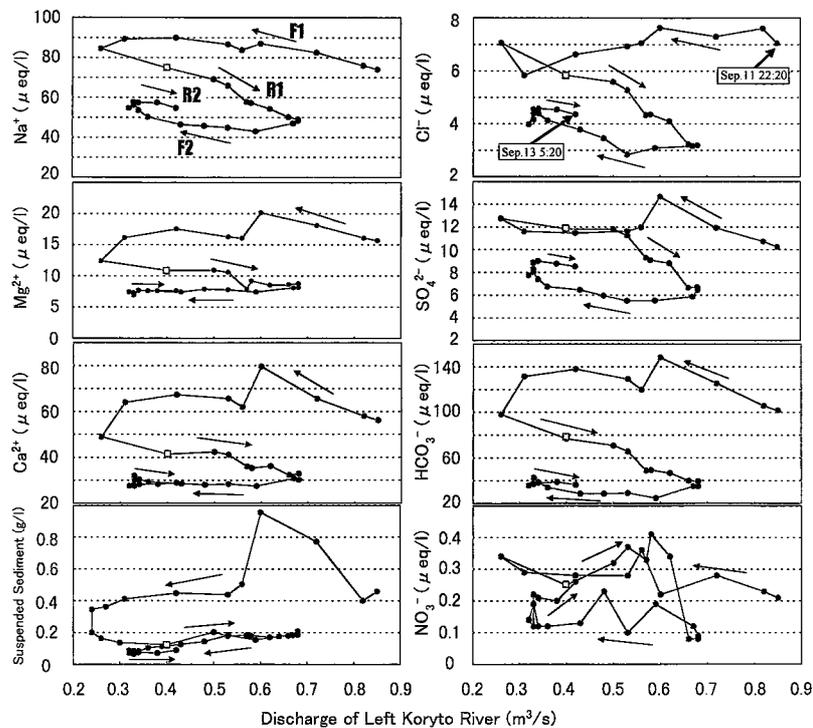


Fig. 6. Relationship between discharge and solute or suspended sediment concentrations in Left Koryto River in September 1997. Open square indicates the sample of 11:20, September 12.

The ratio of the cation concentrations of Left Koryto River is compared with those of other water sources using triangular diagram (Fig. 7). The points of Left Koryto River in the 1996 period and in the 1997 period distribute in close area in the triangular diagram. In the 1997 period, the points distribute linearly connecting the ratio at the maximum discharge (22:20 on September 11; indicated by open triangle) and that at the minimum discharge (8:10 on September 14; open square) which is almost same as the ratio in the 1996 period. The relationship between the discharge and the ratio of concentrations is following: As the discharge increases, percentage of $(\text{Na}^+ + \text{K}^+)$ becomes remarkably lower and that of Ca^{2+} gets higher. During the 1996 period, the percentage of $(\text{Na}^+ + \text{K}^+)$ in Right Koryto River was lower, but the percentage of Ca^{2+} was higher than that in Left Koryto River. The difference can be explained that the source of water in Right Koryto River was mainly the meltwater of the seasonal snow accumulated on the steep slope around the glacier (Kodama *et al.*, 1997). However, we have no data to explain the reason of high Ca^{2+} concentration in snowpack and glacier ice in the 1996 period. And it is questionable that whether the solute concentrations of these samples represent the solute concen-

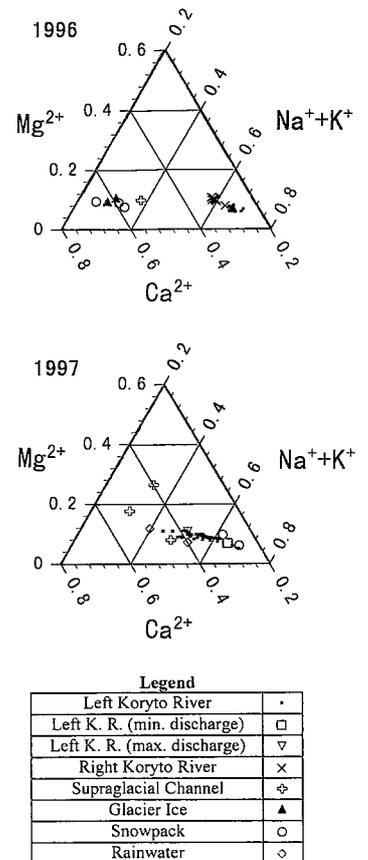


Fig. 7. Triangular diagrams of the ratio of major cation concentrations of water, ice and snow samples collected at Koryto Glacier.

trations of snowpack and ice on the entire glacier in the early ablation season.

4.3. Suspended sediment concentrations

Variation of suspended sediment concentrations (SSC) in Left Koryto River during the IOP in 1997 is shown in the bottom of Fig. 5. SSC in Left Koryto River increased strikingly at 23:20 on September 11, then, reached its maximum (0.95 g l^{-1}) at 1:20 on September 12. After that, SSC decreased gradually, and varied between 0 and 0.2 g l^{-1} in the afternoon and on September 13.

It is well known that SSC in stream water usually fluctuates correlating positively with the discharge (e. g. Gurnell, 1987). The relationship between SSC and the discharge in Left Koryto River during the IOP in 1997 is shown in Fig. 6. Like the solute concentrations already discussed in 4.2, two periods also can be found according to the patterns of relationship. In the first falling limb stage, amplitude of SSC variation was as large as 0.5 g l^{-1} . During the later three stages, especially after 10:20 on September 12, SSC varied linearly correlating with the discharge, but the amplitude was so much small (about 0.1 g l^{-1}). The reason why the SSC in the first falling limb stage is so much higher than that in the latter stages at the times of almost same discharge is not clear now.

5. Discussions

5.1. Condition of drainage system as revealed by anion concentrations of the stream water

According to Tranter *et al.* (1996), the growth of the channelized system at the expense of the distributed system produces a systematic variation in the chemistry of the bulk meltwaters at Haut Glacier d'Arolla and at Austre Brøggerbreen. It is believed that carbonation reactions are dominant in the channelized system and that sulphide oxidation and carbonate dissolution are important chemical weathering reactions in the distributed system (Tranter *et al.*, 1993). Therefore, meltwater in the distributed system contains high SO_4^{2-} concentration and higher $\text{SO}_4^{2-} / (\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio than that of surface meltwater, and thus, water draining from the distributed system into the channelized system impart a high $\text{SO}_4^{2-} / (\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio to the bulk discharge (Tranter *et al.*, 1996). In the case of Haut Glacier d'Arolla in 1989, $\text{SO}_4^{2-} / (\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio of the bulk meltwater was higher than 0.35 when the bulk discharge was less than $1 \text{ m}^3 \text{ s}^{-1}$ early in the ablation

season. Then, SO_4^{2-} concentration remarkably decreased whereas the bulk discharge and its fluctuation increased in June, and $\text{SO}_4^{2-} / (\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio diminished to around 0.2 (Brown *et al.*, 1996a).

At Koryto Glacier, the transient snowline which indicates the boundary of two drainage systems lay around 480 m a.s.l., on the area very close to the terminus during the 1996 period, whereas it lay around 600 m a.s.l. in the 1997 period. Thus, we suspect that the distributed system developed in much smaller area beneath Koryto Glacier during the 1996 period than in the 1997 period. Here, we compare $\text{SO}_4^{2-} / (\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio in bulk meltwater of Left Koryto River to estimate the conditions of drainage systems in two periods. Owing to a small number of water samples, the mean anion concentrations throughout each period are used for this analysis.

We first need to separate atmospheric SO_4^{2-} , and to obtain SO_4^{2-} acquired from chemical weathering (oxidation of sulphides). Assuming that the average ratio of SO_4^{2-} to Cl^- in snowpack on the glacier during ablation season is 0.340 in units of equivalents which is obtained from the samples in the 1997 period, we calculate the non-snowpack SO_4^{2-} , ${}_{\text{nsp}}\text{SO}_4^{2-}$, as follows:

$${}_{\text{nsp}}\text{SO}_4^{2-} = {}_{\text{total}}\text{SO}_4^{2-} - (0.340 \text{ Cl}^-), \quad (3)$$

where ${}_{\text{total}}\text{SO}_4^{2-}$ denotes the SO_4^{2-} concentration measured in the bulk meltwater.

Table 2 shows the mean concentrations of SO_4^{2-} , ${}_{\text{nsp}}\text{SO}_4^{2-}$, HCO_3^- , Cl^- and the mean ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio in the 1996 period and the 1997 period. HCO_3^- concentration in the 1997 period is estimated by the equations (1) and (2). The mean ${}_{\text{nsp}}\text{SO}_4^{2-}$ concentration in the 1996 period was higher than that in the 1997 period. However, the ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio was slightly higher in the 1997 period, in contrast with the results of Tranter *et al.* (1996) which shows very high ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio in the beginning of ablation season. This may indicate that a large amount of surface meltwater had already flowed into the channelized system which lay near the terminus. And it may also indicate that the period which is characterized by small discharge and anion concentrations greatly predominated by water in the distributed system had already pass away when we started the observations in 1996. However, if we assume that snowpack in early ablation season (e.g. the 1996 period) contained less atmospheric SO_4^{2-} and the ratio of SO_4^{2-} to Cl^- in snowpack was close to the ratio in seawater (0.103),

Table 2. The mean concentration of SO_4^{2-} , ${}_{\text{nsp}}\text{SO}_4^{2-}$, HCO_3^- , Cl^- and ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio in Left Koryto River.

	SO_4^{2-}	${}_{\text{nsp}}\text{SO}_4^{2-}$	HCO_3^-	Cl^-	${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$
1996 (Jul.)	43.7	10.3	148.8	98.3	0.06
1997 (Sep.)	9.3	7.6	(62.7)	4.9	0.11

the difference between the mean ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio in the 1996 period and in the 1997 period must be nearly equivalent to the seasonal range of the mean ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$ ratio at Austre Brøggerbreen in 1991 and 1992 (Tranter *et al.*, 1996).

5.2. Hydrograph separation by the chemically based mixing model

In order to clarify the drainage system of Koryto Glacier, hydrograph separation using the chemically based mixing model was carried out. For this analysis, the period from 11:20 in September 12 to 5:20 in September 13 in 1997 was chosen. There was no rainfall in the period. As we have already introduced in Chapter 1, the mixing model usually assumes that the two drainage components of which chemical compositions are constant: diluted "englacial" and concentrated "subglacial" components mix in a region close to the terminus. And it also assumes that the mass of solutes transported by these two flow components remains unchanged after they mix (Collins, 1977; Collins, 1979). Sharp *et al.* (1995) pointed out on the basis of recent development in glacier hydrology and hydrochemistry that these assumptions are unlike to be convincing. Indeed, we also disapprove extensive application of this model in a research on glacier drainage system. But we believe, under a restricted condition, it must be still a helpful method for a rough estimation on the contribution of the rapidly flowing dilute water which is derived largely from the ablation area and then flow through the channelized system.

Thus, we adapt the model for hydrograph separation in our analyzed period, dealing with the assumptions involved in the use of the model as the following. No valid evidence has been obtained to prove that the total meltwater drainage from Koryto Glacier consists of two primary components, because we have never tried intensive dye-tracing or borehole-based studies of which Sharp *et al.* (1995) suggested necessity for applications of the mixing model. But, as already shown in 4.2, temporal variation in the ratio of cation concentrations in Left Koryto River distributes linearly in the triangular diagram (Fig. 7), connecting the ratio at the maximum discharge and that at the minimum discharge. It may indicate that water in Left Koryto River consists of two primary components whose chemical composition distributes on the two ends of the line. Therefore, we applied the assumption "two drainage components" in this study. According to Sharp *et al.* (1995), here we use the terms "delayed flow" and "quick flow" instead of misleading terms such as "subglacial" and "englacial", respectively. On the assumption "unique component chemistries", we would have less problem. Because the analyzed period is so short and variation of measured SSC in the period is small (Fig. 6), seasonal variation of chemical composition of meltwater can be disregarded, and

temporal variation of those may be small.

Here, the conservative mixing of two drainage components can be expressed as follows:

$$Q_t C_t^i = Q_q C_q^i + Q_d C_d^i \quad (4)$$

where, Q represents the stream discharge and C is the concentration of ion constituent i . Subscripts t , q and d denote the total, quick flow and delayed flow components, respectively. Continuity of flow implies:

$$Q_t = Q_q + Q_d \quad (5)$$

Combining Equations (4) and (5) gives the following expression:

$$Q_q = Q_t (C_d^i - C_t^i) / (C_d^i - C_q^i) \quad (6)$$

Equation (6) indicates that four parameters must be determined to perform a hydrograph separation. Q_t and C_t^i are measured routinely in our observation. On the assumption "conservative mixing", Sharp *et al.* (1995) suggested that better estimates are likely to be obtained if separations are based upon measurements of the concentration of conservative constituent such as Mg^{2+} , Cl^- , NO_3^- and especially SO_4^{2-} . Tranter and Raiswell (1991) also concluded that SO_4^{2-} might be the best constituent to use for mixing-model calculations. In addition, difference of C_q^i to C_d^i is the largest in SO_4^{2-} among all measured constituents (Table 1). Therefore, we used ${}_{\text{nsp}}\text{SO}_4^{2-}$ for the marker constituent i in this study. C_q^i is obtained by using the mean ${}_{\text{nsp}}\text{SO}_4^{2-}$ concentrations sampled from supraglacial stream (Table 1), and C_d^i is estimated using the maximum ${}_{\text{nsp}}\text{SO}_4^{2-}$ concentration in meltwater of Left Koryto River, which was recorded in 8:10 on September 14. Because C_d^i is obtained by such indirect way, note that value of C_d^i should be regarded as a *minimum* estimate of the actual solute concentration of the delayed flow component.

Figure 8 shows the result of hydrograph separation under the conditions mentioned above. Q_d varied in diurnal cycle in advance of the total stream discharge (Q_t), whereas the pattern of variation in Q_q looks almost the same as that in Q_t . The maximum discharge in Q_q occurring at 16:50 was $0.43 \text{ m}^3 \text{ s}^{-1}$, and the minimum discharge at 11:20 was $0.10 \text{ m}^3 \text{ s}^{-1}$. By contrast, the maximum discharge in Q_d at 12:40 was $0.38 \text{ m}^3 \text{ s}^{-1}$, and the minimum discharge at 20:20 was $0.15 \text{ m}^3 \text{ s}^{-1}$. The range of discharge variation in Q_q is larger than that in Q_t . Surface melting reaches its maximum around solar noon (13:00 in local time), therefore, residence time of Q_q from generating to draining out from the glacier is about 4 hours. Now we compare this residence time with the lagtime between the peak rainfall and the peak discharge caused by the rainfall. The event which shows a clear relationship between rainfall and corresponding increase of total discharge occurred in the morning of September 13 (Fig. 3). At that event, the lagtime

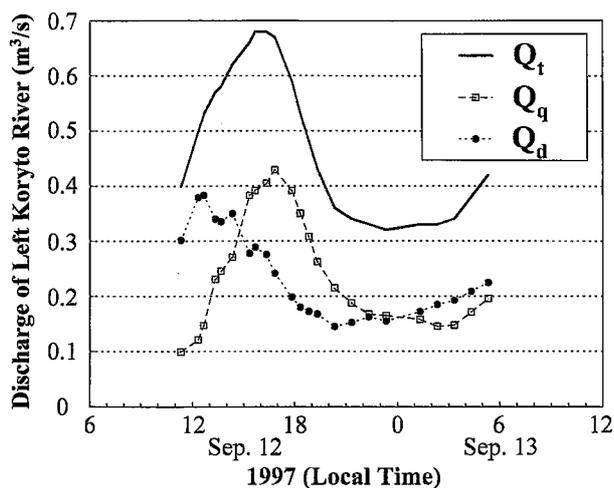


Fig. 8. Result of hydrograph separation of total discharge of Left Koryto River in September 1997. Total discharge, quick flow component and delayed flow component are indicated by solid line, open square and solid triangle, respectively.

between the peak rainfall and the peak discharge was about 2 or 3 hours, therefore, it shows good consistency with the residence time of Q_q .

The proportion of Q_q to Q_t varied between 66 % and 24 %. If C_d^i in here is smaller than the actual solute concentration of the delayed flow component, Q_q must be larger than 24 % of Q_t . Anyway, the quick flow component never decreased to zero even in the time when the total stream discharge reaches its minimum.

6. Concluding remarks

Hydrological and hydrochemical observations were carried out at the terminus of Koryto Glacier in 1996 and 1997. The discharge of Left Koryto River in the 1997 period was much less than that in the 1996 period and varied showing a clear diurnal cycle between around $0.1 \text{ m}^3 \text{ s}^{-1}$ and $1.2 \text{ m}^3 \text{ s}^{-1}$, whereas in the 1996 period, the discharge of Left Koryto River increased gradually from $5.5 \text{ m}^3 \text{ s}^{-1}$ to $7.5 \text{ m}^3 \text{ s}^{-1}$. The cations in left Koryto River were dominated by Na^+ and Ca^{2+} in both years. The anions were dominated by HCO_3^- in both years, whereas HCO_3^- was estimated as charge-balance residuals in the 1997 period. The constituent with the highest concentration of all solutes was Na^+ in the 1996 period, and was the estimated HCO_3^- in the 1997 period. During the period after 10:20 on September 12, the solute concentrations fluctuated with two patterns of diurnal cycle. Mg^{2+} , Ca^{2+} and HCO_3^- are almost stable in their falling limb and rising limb stages, but decrease around the maximum discharge. Na^+ , Cl^- and SO_4^{2-} fluctuated like a hysteretic loop. In the same period, SSC varied linearly correlating with the discharge, from 0 to 0.2 g l^{-1} .

The mean value of ${}_{\text{nsp}}\text{SO}_4^{2-} / ({}_{\text{nsp}}\text{SO}_4^{2-} + \text{HCO}_3^-)$

ratio of meltwater in Left Koryto River, which is an index of dominant reaction of chemical weathering in glacier drainage systems, was slightly higher in the 1997 period than in the 1996 period, in contrast with the results of Tranter *et al.* (1996). This may indicate that inflow of surface meltwater had started affecting subglacial drainage system and solute concentration of stream water in the period when the most part of the glacier was still covered by seasonal snowpack. Using the chemically based mixing model, a separation of the hydrograph from September 12 to 13, 1997 was performed. For the marker ion constituent, ${}_{\text{nsp}}\text{SO}_4^{2-}$ was selected according to the results and suggestions of Sharp *et al.* (1995). As the result, the quick flow component reached its daily maximum after four hours from the solar noon. It never decreased to zero even in the time when the total discharge reached its minimum. The delayed flow component varied advancing four hours to the total discharge.

In order to clarify the characteristics of glacier drainage system of Koryto Glacier and hydrological processes in it, it must be necessary to obtain much more information on discharge variation and solute, isotopic and SS concentrations during the entire ablation period, and moreover, to attempt intensive dye tracing and borehole-based studies.

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