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Water and Sediment Discharges from a Glacier-covered Basin under Maritime Climate in Kamchatka Peninsula, Russia

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ABSTRACT

In order to clarify the characteristics of water and sediment discharges from glacier-covered basins under maritime climate, hydrological observations were carried out within a drainage basin which contains Koryto Glacier in Kamchatka Peninsula, Russia. Water discharge of a proglacial stream near the glacier terminus varied between 3 and 12 $m^3 s^{-1}$ during the summer of 2000. Variation in suspended sediment concentration was positively correlated with water discharge, and values of sediment concentration ranged from 1.0 to 0.1 $g l^{-1}$. A runoff model which consists of two linear reservoirs in series was applied to the basin for simulating discharge variation. Considering a seasonal change in glacier drainage systems, this model can simulate stream discharge well. Three different models based on rating curve, multiple regression and sediment storage for suspended sediment transport estimation yield the total suspended sediment load during the observation period to be 10×10^6 kg. The sediment storage model assuming a reservoir beneath the glacier could bring the best estimate of variation in suspended sediment load. However, the multiple regression model gives a reasonable result and is also applicable for prediction.

Keywords: Glacier-covered basin, Runoff, Suspended sediment, Koryto Glacier, Kamchatka Peninsula

INTRODUCTION

Changes in hydrological cycle due to global climatic change should exhibit spatial differences associated with regional climate and land surface conditions. Glacier-covered drainage basins are widely distributed in mid- and high-latitudes and they show peculiar characteristics of hydrological regimes because glaciers represent frozen reservoirs of fresh water exerting a strong control on drainage characteristics of alpine regions. Volume of glaciers fluctuates responding to weather and climate conditions in various time scales, and such fluctuations lead to significant changes in water balance, runoff variations and other hydrological regimes [1]. Although the mountain glaciers and sub-polar ice caps are smaller in volume that the polar ice sheets, the former can strongly influence the physical environment globally. For example, contribution of mountain glaciers and ice caps to global sea-level change over the recent past has been simulated to be almost same as, or larger than that of Greenland ice sheet [2, 3]. However, it is difficult to clarify the characteristics of changes in hydrological regimes of glacier-covered basins, because such changes are influenced by many factors such as local climate and glacier dynamics. Erosional processes beneath melting glacier tend to be much stronger than those in

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other areas on the earth, and change in landforms in glacier-covered basins progresses quite rapidly. Thus, fluvial sediment flux to the ocean from such basins tends to be quite large [4]. Knowledge on sediment transport in glacier-covered basins is important for studies related to the records in marine and lacustrine sediments and the present terrestrial environment. However, we have not yet enough information on the relationship between sediment transport and hydrological regime within glaciers for such a reconstruction of paleohydrological environment.

Most features of hydrological regimes in a glacier-covered basin result from drainage systems of glaciers [5]. The main characteristics of drainage systems of temperate glaciers (ice temperature is 0°C everywhere during summer season) which exhibit large water and sediment fluxes are summarized as follows [6, 7]: There are various drainage systems (flow paths) on the surface of, within and beneath the temperate glaciers (*supraglacial, englacial* and *subglacial* drainage systems, respectively). Nearly all meltwater which is generated on the glacier surface first flows through supraglacial and englacial drainage systems, and reaches the glacier bed, then, is drained out from the terminus as proglacial streams. There is presently a broad agreement among hydrologists and glaciologists that water flows at the glacier bed consist of one or two qualitatively different flow systems, commonly termed as "the channelized drainage system" and "the distributed drainage system."

The channelized system comprises an arborescent network of conduits, similar to subaerial stream network, and the distributed system, which is nonarborescent. It covers a relatively large fraction of the glacier bed and may involve a variety of complicated flow paths at the bed. As a result of intensive investigations at an Alpine glacier, it was found that the subglacial drainage systems exhibit temporal and spatial variations in the course of the melting season [8]. Little supply of meltwater to the glacier bed during the winter is unlikely to form a channelized drainage. The presence of the distributed system is postulated for this period. In the beginning of melting season, increasing quantities of meltwater is delivered to the bed. This leads to the disappearance of the winter configuration of the distributed system replacing by a channelized system. Beneath the lower area of a glacier, meltwater is drained through the channelized system, whereas the upper area by the distributed system. In the course of the season, the channelized system migrates upglacier closely following the retreat of the transient snowline (the lower limit of snow-covered area) on the glacier surface. After the melting season, large channels which can no longer maintain their size gradually get closed by deformation of the ice. Therefore, during the winter, the distributed system once again becomes widely established.

This study examines the characteristics of water and suspended sediment discharge from Koryto Glacier, a temperate mountain glacier under maritime climate in Kamchatka Peninsula, Russian Far East. A simple modelling approaches based on the field data collected during the summer of 2000 has been used.

DESCRIPTION OF THE STUDY AREA AND FIELD OBSERVATIONS

Study Area

Koryto Glacier is the third largest glacier in Kronotsky Peninsula which is situated at the eastern coast of Kamchatka, Russian Far East (Fig. 1). The area of the drainage basin, which contains Koryto Glacier (7.8 km^2) and Kudelyko Glacier (0.3 km^2) to the north, is 12.2 km^2. Koryto Glacier extends from 1220 m to 320 m a.s.l. towards northwest, with a relatively large accumulation area and a narrow ablation area near the terminus. The drainage basin is geologically composed of Paleogene lava flows, volcanic breccia, tuff and volcaniclastic rocks [9]. Two proglacial streams emerge from the glacier terminus and join into a single stream (hereafter referred to as "Koryto River") at around 0.2 km downstream. A hydrological gauging station (HS) was installed on Koryto River at about 0.8 km downstream from the terminus. Climatic condition on the eastern coast of Kamchatka Peninsula is characterized by heavy snowfall early and late in the winter season and is strongly affected by activities of the Aleutian Low and the intrusion of maritime air masses from the southeast [10]. According to the results of meteorological observations by an automatic weather station at the uppermost ridge (1160 m a.s.l.) from July 1996 to September 1997 [11], monthly mean air temperature varied between −13.6°C in February and 9.8°C in August. The mean summer and winter mass balance in recent 60 years was estimated to be −4.03 m and 3.41 m water equivalent (w.e.), respectively [12].

Methodology

Hydrological and meteorological observations were carried out from August 1 to September 14,

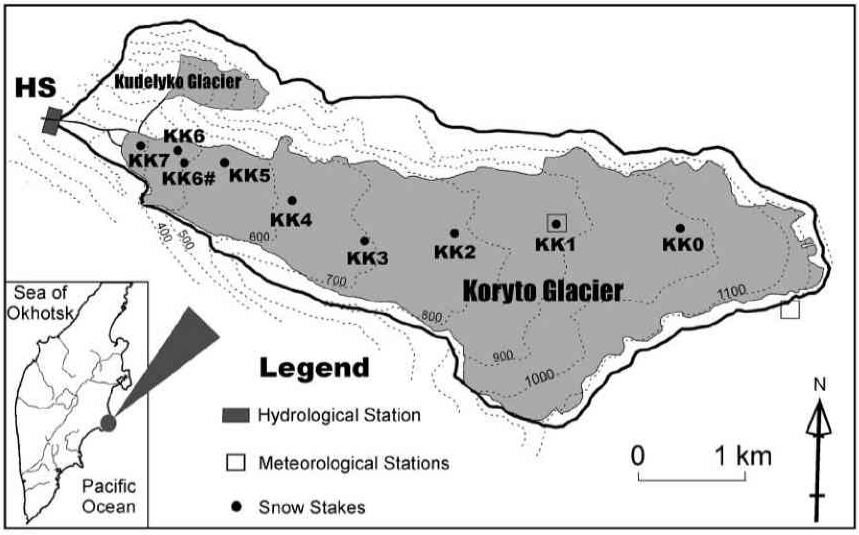

Fig. 1 Map of Koryto Glacier basin with 100 m contours based on the 1960 map.

2000 in the Koryto Glacier basin. This observation period is regarded as the later stage of the ablation season for the year 2000, because daily mean air temperature at the uppermost ridge remained higher than 0°C after mid-June. The transient snowline was located at the site KK4 (Fig. 1) on August 4, at KK3 on August 17 and at KK2 on August 25.

Water level of Koryto River was measured with 10-minute intervals at HS. Hourly discharge was calculated from the water level and the stage-discharge curve obtained during the observation period. Daily melting rates were determined by the traditional stake method. Eight snow stakes were installed on the surface (KK0 to KK7), and melting rates were obtained by measuring changes in stake height on almost daily basis and by measuring the density of snowpack nearby. Density of ice was assumed to be 900 kg m^{-3}. To calculate the amount of water input, the whole basin was divided into 20-m elevation intervals. The volume of meltwater and rainwater entering each elevation interval in the basin was calculated each day. The mean daily melting rate in each interval was obtained by linear interpolation using the measured melting rates at the nearest two stakes, or by the degree-day method [13]. For measurements of suspended sediment concentration (SSC), samples of hundreds millilitres of stream water were taken with polyethylene bottles at HS 4 times a day, in average. Sampled water was filtered at the camp using a handy vacuum pump and glass fiber filters (pore size = 0.6 μm). SSC was obtained by measuring dry weights of those filter papers in laboratory.

Results

Variation in discharge, electric conductivity (EC) and SSC of Koryto River, precipitation at site HS and the area-weighted-average of daily melting rate of the glacier during the entire observation period are shown in Fig. 2. Discharge in Koryto River varied between 3 and 12 $m^3 s^{-1}$ during the observation period. During ten days in early August, discharge remained around 6 $m^3 s^{-1}$ until a sudden increase to 12 $m^3 s^{-1}$ which occurred in the night of August 9. In early September, discharge increased sharply in response to the rise of air temperature. Besides, EC varied inversely with discharge, from 0.8 to 1.5 mS m^{-1}. According to the result of water balance calculation [13], the total water input, output and the total storage change during the observation period were 16.3, 25.7 and -9.4×10^6 m^3, respectively. This result indicates that 37% of water output from the basin originated from stored water within the basin during this period.

SSC varied in phase with discharge, as usually seen in proglacial streams from mountain glaciers [14]. The maximum and the minimum SSC measured in the period were 1.0 and 0.1 g l^{-1}, respectively. SSC remarkably increased on August 10, corresponding to an abrupt increase in discharge. The relationship between discharge (Q in $m^3 s^{-1}$) and SSC (C in g l^{-1}) in Koryto River for this period is shown in Fig. 3. A regression equation (rating curve) for the whole dataset is:

$$C = 0.0148Q^{1.54} \quad (r^2 = 0.67) \tag{1}$$

When the observation period is divided into four

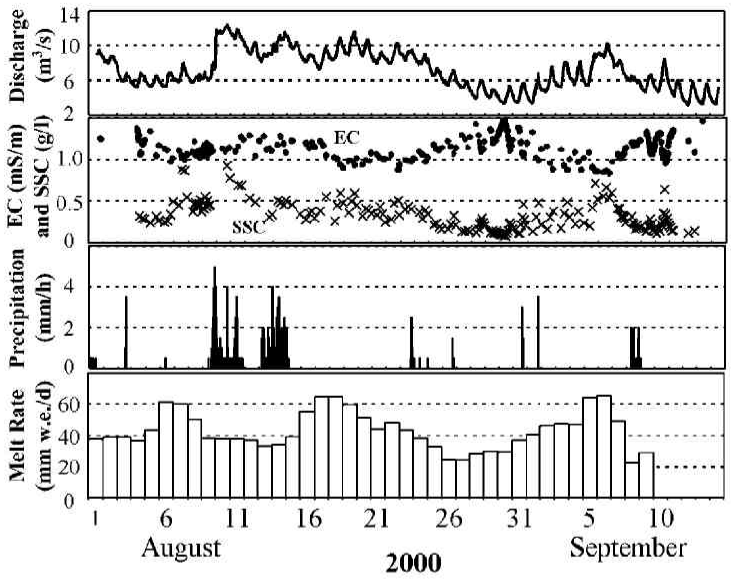

Fig. 2 Variations in discharge, electric conductivity (EC) and suspended sediment concentration (SSC) of Koryto River, precipitation at the site HS and the area-weighted mean melting rate of Koryto and Kudelyko Glaciers in the summer of 2000.

subperiods corresponding to the rising and falling trends of the daily mean discharge, regression equations with better correlation can be obtained for each subperiod [15].

MODELLING OF WATER DISCHARGE

Description of the Model

As already introduced, the channelized drainage system expands headward at the expense of the distributed system during the melting season in an Alpine glacier, and this growth of the channels closely follows the upglacier retreat of the transient snowline on the glacier surface [8]. On Koryto Glacier, two evidences which imply the seasonal change in drainage system configuration, namely continuous subsidence of the glacier surface [13] and changes in chemical composition of meltwater in Koryto River [15] were found during this observation period. Here, a simple runoff model including an algorithm which expresses this result is applied for the Koryto Glacier basin. The objectives were to simulate discharge variation during the melting season and to validate the occurrence of such a seasonal change in the subglacial drainage system configuration.

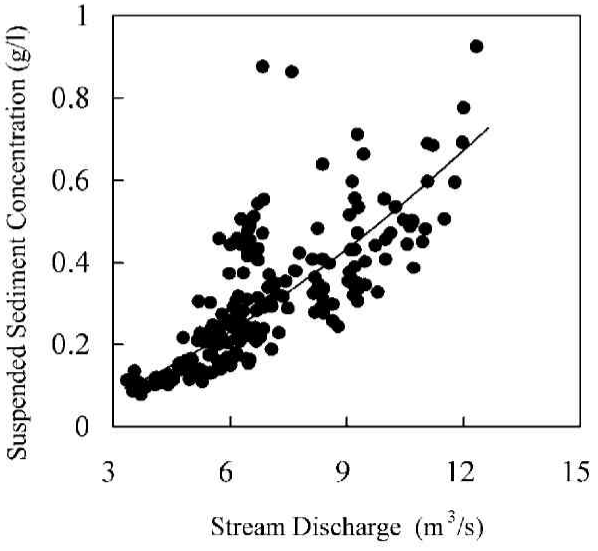

Fig. 3 The relationship between discharge and suspended sediment concentration of Koryto River.

In this study, a model which is expressed as two linear reservoirs in series is used to calculate runoff from the glacier basin as in many previous studies on glacier hydrology [16, 17]. The structure of the model is presented in Fig. 4.

The amount of water storage (V) in each reservoir at any time can be expressed as:

$$V(t) = kQ(t) \tag{2}$$

where Q and k are outflow from a reservoir and a constant coefficient. By an integral equation of the continuity, V may be related to the rates of inflow R and outflow Q:

$$dV/dt = I(t) - Q(t) \tag{3}$$

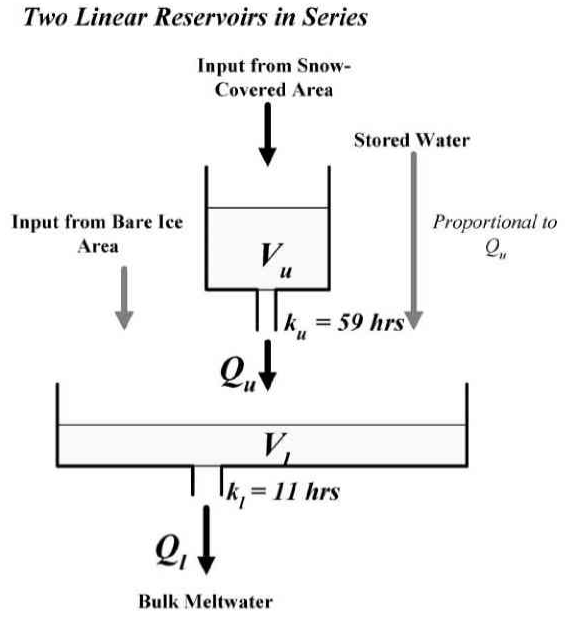

Fig. 4 Schematic representation of the linear reservoir model adopted for Koryto Glacier basin.

From the equations 2 and 3, outflow at time t can be expressed as follows:

$$Q(t) = Q(t-1)e^{-1/k} + I(t) - I(t)e^{-1/k} \quad (4)$$

In this model, the upper reservoir roughly implies the processes as infiltration in and flow through snow and ice, and flow through the distributed system beneath the snow-covered area. The lower reservoir implies mainly the process as flow through the channelized system beneath the bare ice area. Water input in the snow-covered area is first entered into the upper reservoir, and then flows into the lower one. Water input in the bare ice area is put into only the lower reservoir, mixed with the other water component and flow out as the output of the model which roughly indicates the total meltwater discharge from the basin. Ratio of water input in the snow-covered area to that in the bare ice area is tuned as the ratio of the snow-covered area to the total glacial area (the transient accumulation area ratio). Mixing ratio in the lower reservoir in each time step indicates the contribution of two runoff components. Because no detailed information on location and timing of removal of water storage could be obtained, it is assumed in this study that the stored water during the period flows into the lower reservoir with a rate proportional to the outflow from the upper reservoir.

In order to acquire input data to the runoff model, hourly melting rates for elevation intervals are estimated from daily melting rates. Global radiation has generally been recognized as a major source of heat for melting [18]. Therefore, diurnal variation in melting rate on Koryto Glacier is possibly controlled by global radiation. Here, it is assumed that the pattern of diurnal variation in global radiation in the entire basin is the same as that measured at KK1, and that hourly melting rate at time i for an elevation interval M_i (mm h^{-1}) can be expressed as follows [15]:

$$M_i = \{(R_{KK1i} + n) / \Sigma(R_{KK1} + n)\} \Sigma M \quad (5)$$

where R_{KK1} is the measured global radiation at KK1 (W m^{-2}), and Σ indicates daily sum value of melting rate (i.e. melting rate determined by the stake method) and global radiation. The empirical constant n, which is added to express the minimum melting in the nighttime ($R_{KK1i} = 0$), is tuned as 10 W m^{-2} to best fit to hourly melting rate at KK1 obtained by the heat balance method [19]. The storage constants of the upper and the lower parts of the reservoir, k_u and k_l are determined as the best-fit to the measured meltwater runoff, as 59 (hrs) and 11 (hrs), respectively.

Results and Discussion

Figure 5 shows the measured and simulated runoff from Koryto Glacier basin, the contributions of two runoff components (meltwater from the snow-covered area and the bare ice area) and variation in the ratio of the bare ice area. Except for 10 days in the beginning, this model can simulate the trend and also the pattern of diurnal variations in the measured discharge. Especially, the trend of the simulated runoff looks quite similar to that of the measured runoff. Moreover, this model can express increase of the amplitude of diurnal variation during the course of the ablation season. Figure 5 suggests that the trend of variation is controlled by the component from the snow-covered area, and the diurnal variation is influenced by the transient AAR. This model, however, overestimates discharge in early-August and underestimates during the remarkable increase occurred during the night of August 9. We suppose that the reason is the simple assumption of release of stored water which was already present in the glacier at the beginning of the observation period. For further improvement of this type of runoff model, it might be important to consider seasonal water storage and its short-term changes.

In Fig. 6, the result of Test 1 is compared with the simulated discharge assuming that the transient snowline does not retreat upglacier, and stays at some height throughout the period (Tests 2, 3 and

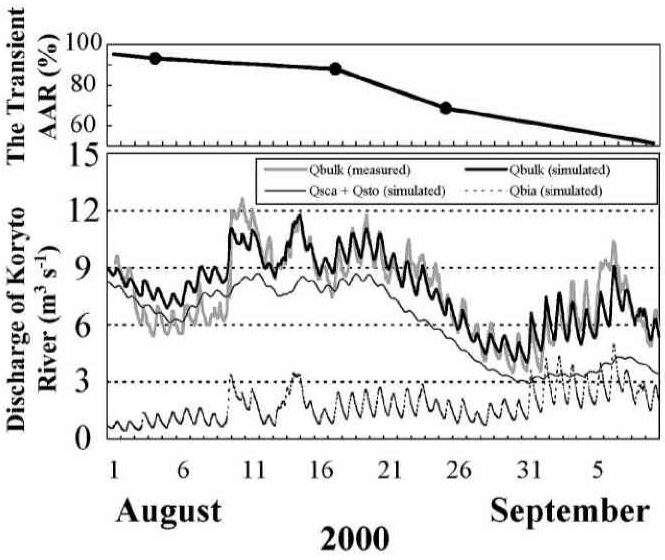

Fig. 5 Measured and simulated discharge of Koryto River and the variation in the transient accumulation area ratio (AAR) in the summer of 2000. Thick grey line and thick black line indicate measured and simulated bulk meltwater discharge. Thin line and dotted line indicate the component of meltwater from the snow-covered area plus stored water within the glacier, and the component of meltwater from bare ice area.

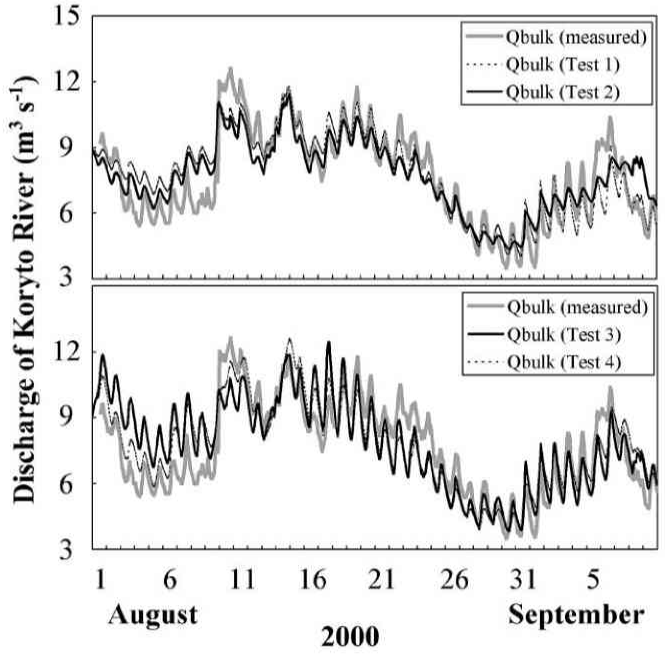

Fig. 6 Results of runoff model simulation with different assumptions on spatial changes in the transient snowline. Test 1: assuming the measured snowline retreat, Test 2: assuming fixed snowline at the height on August 1 (tuned coefficients), Test 3: assuming fixed snowline at the height on September 1 (tuned coefficients), Test 4: assuming fixed snowline at the height on September 1 (the same coefficients as those of Test 1).

4). If the transient snowline is assumed to be fixed at a height corresponding to the snowline observed on August 1 (Test 2), the pattern of the diurnal variation is found to be quite different from that of the measured discharge in the latter half of the period, especially in September. Tests 3 and 4 show the results for the case when the transient snowline is assumed to be fixed at the height of the snowline on

September 9. The storage constants k_u and k_l in Test 3 are determined as the best-fit, as quite unrealistic values, 19 and 19, respectively. In Test 4, $k_u = 59$ and $k_l = 11$ are adopted. Anyway, with regard to the residual sum of squares (RSS) and coefficient of determination (r_2), we can conclude that Test 1 leads to the best estimate of discharge variation in Koryto River. Thus, the upglacier retreat of the transient snowline which implies systematic change in configuration of glacial drainage systems is very important for the diurnal and seasonal variations in discharge.

MODELLINGS OF SUSPENDED SEDIMENT DISCHARGE

Description of the Models

In this section, to clarify the general features of sediment transport in Koryto River, we try to construct suspended sediment models which can simulate SSC and suspended sediment load (SSL) of the river with simple forms using the data on water discharge and meteorological condition. Then, we compare the results of these models with those obtained from another model which was previously adopted to Koryto River [20].

Rating Curve Model

The simplest method of SSC modelling utilizes a rating curve (Eq. 1) which is obtained from measured data on concurrent discharge and SSC. In previous studies, some workers have derived separate rating curves for different subperiods by splitting the observations into the rising and falling limbs of daily discharge hydrographs [21] or early and late melting season [22]. As presented earlier, four separate rating curves for different subperiods were also obtained in this basin during the observation period. However, we did not pursue this way further because such arbitrary distinctions are subjective.

Multiple Regression Model

The rating curve model assumes that the sediment concentrations are largely controlled by the capacity of the stream rather than by sediment supply and storage [23]. The inclusion of variables other than discharge may remove some of the scatter around the rating curve (see Fig. 3). Willis et al. [23] suggested that this scatter might be linked with the following factors which can be represented by surrogate variables for use in regression analysis.

1. Long-term seasonal exhaustion of sediment. A variable measuring 'days since the beginning of summer (melting season)' accounts for this.
2. Medium-term sediment supply variations. To account for this possibility, a variable measuring 'days since discharge was equaled or exceeded' is introduced.
3. Short-term diurnal sediment supply variations. To account for this, a variable measuring 'rate of change of discharge' should be appropriate.
4. Short-term rainfall-induced variations in sediment supply from extra-glacial sources. To account for such factors, the amounts of rainfall in the previous 1, 2, 3, 4 and 5 hours may be introduced.

These variables together with discharge were entered into a multiple regression model. As a result, we found that short-term rainfall-induced variations are not significant controls on SSC variation in Koryto River, as found for a proglacial stream from Midtdalsbreen, Norway [23]. On the other hand, days since the beginning of melting season (assumed to be June 12) was quite significant in explaining SSC variation in Koryto River unlike in Midtdalsbreen [23]. The multiple regression model is defined as follows:

$$\log_{10}C = 2.01 + 1.31 \log_{10}Q + 0.077\,\Delta Q + 0.019\,T_{dee} - 0.0057\,T_{ms}, \quad (6)$$

where ΔQ, T_{dee} and T_{ms} indicate rate of change of discharge ($m^3\,s^{-1}$), days since discharge was equaled or exceeded (day) and days since the beginning of melting season (day), respectively.

Sediment Storage Model

To compare with preceding two models, result of simulation by yet another suspended sediment model based on a different idea [20] is presented. This model assumes that glacier always serves as a site for washing out of material by proglacial and subglacial streams. Intensity of outwash G ($kg\,s^{-1}$) is assumed as a constant. Suspended sediment load L ($kg\,s^{-1}$) in a proglacial stream is assumed to depend on discharge Q and the amount of material stored beneath the glacier S (kg):

$$L = aSQ^p \quad (7)$$

where a and P are the empirical constants. By an integral equation of the continuity, S may be related to the rates of G and L:

$$dS/dt = G - L \quad (8)$$

where t is time. From the equations 7 and 8, the following equation can be derived:

$$dL/dt = bQ^{p}L + (PL/Q)\ (dQ/dt) \quad (9)$$

where b = aG. Numerical solution of this equation allows evaluation of hourly values of SSL during the observation period. Parameters a, b, P are found using powerful optimization method.

Results and Discussion

The results of simulation on SSL variation in Koryto River during the observation period by the rating curve (RC) model, the multiple regression (MR) model and the sediment storage (SS) model are shown in Fig. 7. For comparison of the results of three models, SSL values are calculated from SSCs obtained by RC and MR models multiplied by concurrent discharge. Total SSL from August 15 to September 13 is estimated by RC, MR and SS models as 9.8×10^6, 10.0×10^6 and 9.8×10^6 kg, respectively. Dividing these values by the area of the basin, the mean specific SSL can be obtained as about 8×10^5 kg km^{-2}.

Rating curve model can simulate well the general pattern of variation in SSL, however, as implied by Fig. 3, it frequently yields large residuals from the measured SSL. Especially during the periods of increasing discharge, this model tends to underestimate SSL. MR model brings better estimates even in such periods, and SSL simulated by this model exhibits larger diurnal amplitudes than by RC model. We believe that SSL was much larger than 10 kg s^{-1} at the onset of sudden increase in discharge on the night of August 9, because large short-term pulses of sediment which are associated with short-term increases in discharge have been often observed [24].

MR model is the only model which can simulate such a large pulse of sediment. SS model gives the best estimate of SSL in Koryto River among three models, although underestimates may be noticed as in RC model. Besides, RSS of the result of this model is about half of those of other models. Thus, SS model should be one of the useful methods for interpolation of variation in measured SSL. However, it is not certain now whether this type of model with many assumptions and tuning parameters is applicable for prediction of SSL with small number of observations. Thus, we suppose that MR models are more suited for prediction due to simple form.

Short-term variations in SSC, not related to remarkable changes in discharge have been observed at many glacier-covered basins [21, 23]. At Koryto Glacier, Matsumoto [15] has reported such a change

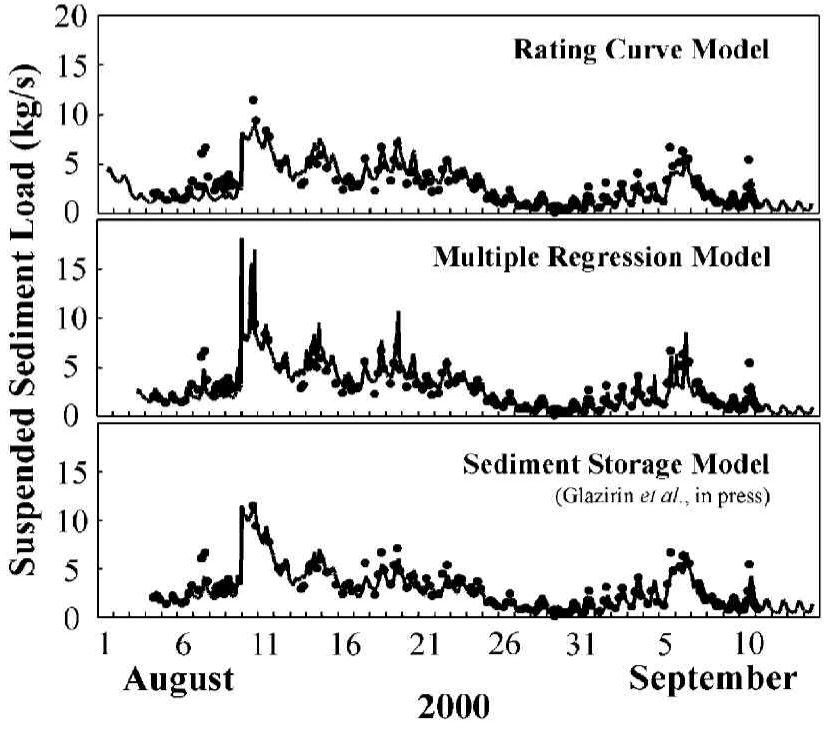

Fig. 7 Simulated suspended sediment load of Koryto River using the rating curve model, the multiple regression model and the sediment storage model.

in SSC which may be associated with a change in the configuration of subglacial drainage systems around the sudden increase in discharge in August 9. Thus, it is important to clarify the relationship between sediment dynamics and glacier drainage systems for more accurate evaluation of sediment transport from glacier-covered basins.

CONCLUSIONS

During the observation period from August 1 to September 14, 2000, discharge of Koryto River varied between 3 and 12 $m^3 s^{-1}$, and SSC varied positively correlating with discharge between 1.0 and 0.1 $g l^{-1}$. A runoff model with a series of linear reservoir considering the upglacier extension of the channelized drainage system, well simulated the variation in runoff of Koryto River. Three different models were constructed to simulate the variation in SSC and SSL. The sediment storage model assuming a subglacial reservoir of sediment gave better estimate of SSL than the rating curve and the multiple regression models which have much simpler forms. The estimated total SSL during the observation period was 10×10^6 kg. Consideration of seasonal changes in glacier drainage systems is recommended for improvement of both water and sediment discharge models.

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