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Runoff modeling of a river basin with a debris-covered glacier in Langtang Valley, Nepal Himalaya

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Abstract

A conceptual runoff model is used to simulate the daily runoff from 67% glacierized basin of Lirung Khola. To estimate the melt from the debris-covered areas of the glacier, a simple calculation requiring global radiation, air temperature and albedo of debris-free ice and critical thermal resistance is introduced in the model. The sensitivity of the albedo and the thickness of the debris -cover are tested ; the calculations with the albedo of 0.1 and 0.2 resulted in similar daily discharge. Under the assumption of the debris thickness 0.5-1 m, simulated results agreed fairly well with the observed discharge.

1. Introduction

In Nepal, it is very important to know the processes of glacier ice melt and to evaluate them for runoff modeling, as main river sources are glaciers. Previous glacio-hydrological researches were carried out in the Langtang region, in central Nepal by Yamada *et al.* (1984), Fukushima *et al.* (1987), Yamada and Motoyama (1988), Fukushima *et al.* (1991) and Braun *et al.* (1993), and they tried to explain quantitatively the discharge from the drainage basin.

Hydrometeorological observations were conducted for a full year from July 1985 to June 1986 for three different drainage basins, namely, Langtang, Lirung and Khimsung Khola watershed of Langtang Valley as shown in Fig. 1. The seasonal variation in discharge from glacier-covered watersheds seems to depend mainly on the variation in air temperature rather than the distribution of precipitation. The tendency of the seasonal variation of discharge in both Lirung Khola and Khimsung Khola watershed is almost the same as that in Langtang Khola watershed. The discharge rate in Lirung Khola watershed, however, was about twice of both Langtang and Khimsung Khola watershed for almost a year (Fukushima *et al.*, 1987).

One of the most common characteristics of glaciers in the Nepal Himalaya is the presence of debris at the surface in the ablation zone. For example, in the Khumbu Himal, eastern Nepal, 37 glaciers are debris-covered while 89 glaciers are debris-free, for glaciers with total area above 0.1 km^2 (Fujii and Higuchi, 1977). Although the number of debris-covered glaciers is less than of debris-free glaciers, the average area of the debris-covered glaciers is fifteen times larger than that of debris-free glaciers (Fujii and Higuchi, 1977). In the Langtang Valley, 14 glaciers are debris-covered while 58 are debris-free (Shiraiwa and Yamada 1991).

The debris-free glaciers have developed in the altitudinal range between 5,060 m (terminus altitude) and 5,900 m (upper altitude) with an average area of 0.7 km^2 each. On the other hand, debris-covered glaciers have developed from 4,625 m to 6,545 m, which is more than double of the altitude range for debris-free glaciers. The area of individual glacier is about 6.7 km^2 as an average, more than nine times larger than the debris-free glaciers. The total debris-covered part occupies 21% of the total glacier area in the Langtang Valley ; such debris-covered parts locate at the lowest portion of glaciers where the intensive glacier melting is expected. Consequently, for proper prediction of runoff from debris-covered glacier basins, it is important to evaluate the ice melt from the debris-covered portions of glaciers for estimating river discharges. The main objective of the present paper is to simulate such runoff behavior using a hydrological model which includes the effect of debris-cover on glacier melting.

2. Studied basins

Studied basins are located in the Langtang Valley, approximately 60 km north of Kathmandu, Nepal. Figure 1 shows the three different drainage basins with hydrological observation sites (S1, S2, and S3) and a meteorological observations site (BH) at an altitude of 3,920 m a.s.l. The climate of the Nepal Himalayas is considerably influenced by the Indian monsoon. In Langtang Valley, the onset of the monsoon was at end of June in 1985 and continued until mid-October. The dry season was from October to next May. The total precipitation from July to September was 543.6 mm, 44% of the yearly precipitation (Takahashi *et al.*, 1987). The discharge rate maintains flood stage and fluctuated at intervals of several days during this period (Fukushima *et al.*, 1987). The discharge (mm/day) is discharge (cumecs) divided by area of the basin. The winter precipitation accounts only about 20% of the yearly total. The yearly mean temperature at BH was 2.7 °C.

The total basin area of Langtang (S1) is 333 km² of which 6% is the glacier area with debris, and 6.6 km² for Khimsung (S3) drainage basin, whose glaciers are debris-free (Fukushima *et al.*, 1987). In the present paper, we analyze the Lirung drainage basin (S2). The total basin area is 13.8 km² of which 51% is debris-free, 16% debris-covered glacier and the rest 33% is steep rocky walls. From the maps published by the Austrian Alpine Club 1 : 50,000 (1990), distributions of the basin area, the glacier area of debris-free and of debris-covered were derived at 200 m altitudinal span for the present model calculation as shown in Fig. 2. Lirung Glacier is heavily debris-covered at lower elevations. The average debris thickness at the active terminus, around 4,400 m a.s.l. of the glacier was approximately 0.5 m (Fujita, private communication). This value is comparable with the average debris thickness at the active terminus of Khumbu Glacier (Nakawo *et al.*, 1993). The albedo of the debris surface varied from 0.1 to 0.3 with a mean value of 0.1 (Kojima *et al.*, unpublished).

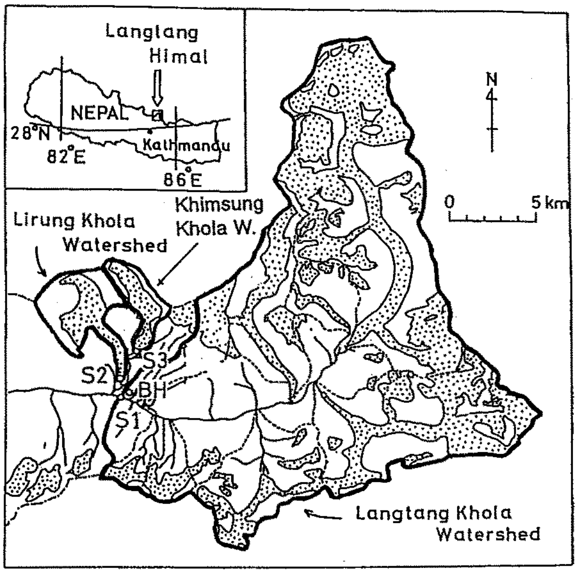

Fig. 1. Topographical map of the Langtang Valley. Thick solid lines indicate the boundaries of the Langtang Khola watershed (observation site at S1), Lirung Khola watershed (observation site at S2) and Khimsung Khola watershed (S3). BH : Base House for meteorological observations.

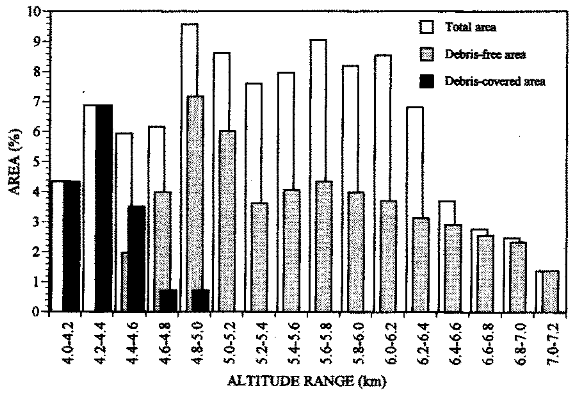

Fig. 2. Altitudinal distribution of the Lirung drainage basin and the glacier areas included at 200 m intervals (the area of debris-free glacier is 51%, debris covered glacier 16% and the rocky wall 33% of the total basin).

3. The model and data used

3.1. Precipitation and melt for debris-free glacier surface

The HYCYMODEL was introduced in the present analyses. This model is a kind of conceptual runoff models developed for a small forested mountain catchment by Fukushima (1988). This model was used to simulate the stream flow with daily precipitation and daily mean air temperature data for 45% glacierized Langtang drainage basin in the Nepal Himalaya (Fukushima *et al.*, 1991). The observed streamflow was simulated comparatively well from July to next April, but not so well from May to June.

The tendency that precipitation increases with the increase of altitude is usually recognized in glacier areas in the Nepal Himalaya (Higuchi *et al.*, 1982). In Langtang Valley, the precipitation at 5000 m in altitude was 1.3 times larger than at 4000 m (Seko, 1987). From this observation, the precipitation was assumed as a function of altitude as follows, since we have precipitation data at BH only.

$$P_Z = P_{BH} \qquad z < 4000 \text{ m}$$
$$P_Z = P_{BH}\{1 + 0.0003(z - 4000)\} \qquad 4000 \text{ m} \leq z \leq 5000 \text{ m}$$
$$P_Z = 1.3P_{BH} \qquad z > 5000 \text{ m}$$

where,

P_Z : precipitation at altitude z meters (mm)

P_{BH} : precipitation observed at BH, located at 3,920 m *a.s.l.* (mm)

The drainage basin was distributed into 16 altitude zones of 200 m interval. Rainfall and snow and ice-melt was calculated at each zone. The critical air temperature between snowfall and rainfall was estimated as 2.0 °C (Ageta *et al.*, 1980). A temperature gradient for the altitude was taken as −0.6 °C/100 m (Takahashi *et al.*, 1987).

For calculating snow and ice-melt from debris-free areas, the relation which was empirically derived for Glacier AX 010, east Nepal (Ageta *et al.*, 1980), was used :

$$SM_O = 0 \qquad T \leq -3.0$$
$$SM_O = 0.1(3.0 + T)^{3.2} \qquad T > -3.0$$

where,

SM_O : daily snow and ice-melt from debris-free areas (mm)

T : daily mean air temperature (°C)

For simplicity, the evaporation was neglected, because it is very humid in summer monsoon, which is the major melting season.

3.2 Ablation under a debris layer

To estimate the ablation of glacier ice under a debris layer, a simplified model after Nakawo and Takahashi (1982) was used. The required data for the estimation are global radiation, air temperature, albedo of the debris-covered and debris-free glacier, critical thermal resistance of the debris cover and the degree-day factor of fusion at a debris-free surface.

The average thermal conductivity of debris materials, K_m was taken as 2 $Wm^{-2}deg^{-1}$ (Nakawo and Young, 1981) to calculate the thermal resistance, R of the debris layer ; $R = h/K_m$, where h is the debris thickness. The degree-day factor K_O, was calculated using equation (1). The thermal resistance of the debris layer was estimated assuming an uniform debris thickness of 0.5 m as described in section 2. To calculate the critical thermal resistance, the surface albedo of the debris-covered glacier was assumed to be 0.1 (Nakawo and Young, 1982) and for debris-free ice, which was assumed to be 0.4 (Paterson, 1994). The critical thermal resistance R_C, was calculated from equation (2). This is the thermal resistance at which the ablation rate under debris and debris-free ice is same. The following set of equations (Nakawo and Takahashi, 1982) were used to calculate the ablation under debris layer, SM :

$$K_O = \frac{L_f \rho SM_O}{T} \tag{1}$$

$$R_c = \frac{G(a_0 - a)}{K_0[(K_0 + K_r)T - G(1 - a_0)]} \tag{2}$$

$$\frac{C}{C_0} = \frac{C_0 + G(a_0 - a)}{C_0 + G(a_0 - a)(R/R_c)} \tag{3}$$

$$K^* = \frac{1 + G^*}{1 + G^*R^*} \tag{4}$$

$$\frac{SM}{SM_0} = \frac{C}{C_0} = \frac{K}{K_0} = K^* \tag{5}$$

SM : ablation rate under debris layer, m sec^{-1}

SM_O : ablation rate of debris-free ice, m sec^{-1}

C : conduction heat flux through debris layer, W m^{-2}

C_O : heat used for melting ice per unit time for debris-free ice, W m^{-2}

K : degree day factor for debris-covered ice, W $m^{-2}deg^{-1}$

K_O : degree day factor for debris-free ice, W $m^{-2}deg^{-1}$

K_r : $4\sigma(273)^3$, 4.615 W m^{-2} k^{-1}
R : thermal resistance of debris layer, m^2deg W^{-1}
R_c : critical thermal resistance of debris cover, m^2deg W^{-1}
R^* : R/R_c
G : global radiation, W m^{-2}
α : albedo of debris-covered glacier
α_0 : albedo of debris-free glacier
G^* : $G(\alpha_0-\alpha)/C_0$
L_f : latent heat of fusion, 3.34×10^5 J Kg^{-1}
ρ : density of glacier ice, 900 kg m^{-3}
T : air temperature, °C

Once G^* and R^* are known, the ablation under a debris layer, SM can be easily estimated by using equation (5).

4. Results and discussions

Runoff from three watersheds in Langtang Valley was calculated with an assumption that the whole glacier surface is debris-free. Khimsung Khola watershed, comprising of Khimsung Glacier is completely debris-free, and Langtang Khola watershed has debris-covered area which however is comparatively small. The calculation for the two basins agreed well with observations (Fig. 3). In Lirung basin, however, the calculation predicts approximately two times larger values than the observations. This could be attributed to the fact that the debris area is much large and the melting under debris layer should be suppressed by the debris layer.

In Fig. 4, a result calculated in case of no melt from debris-covered area in Lirung basin, as a extreme case, is shown with the former calculation and the observed discharge. Comparing with the observed discharge, the calculated discharge in case of no melt in debris-covered area is under-estimated, while the former calculation in assumption of debris-free surface is over-estimation. As the ablation area of Lirung Glacier is covered with thick debris layer, ice melting under the debris layer should be considered for the discharge calculation. Braun *et al.* (1993) also introduced a reduction factor of 0.5 of glacier melt over debris-covered parts of glaciers and concluded that the debris-covered parts are very sensitive with respect to modeled daily discharge.

The ablation rate under a debris layer is a function of external variables including radiation and temperature, as well as physical characteristics of the layer such as thickness, albedo and thermal conductiv-

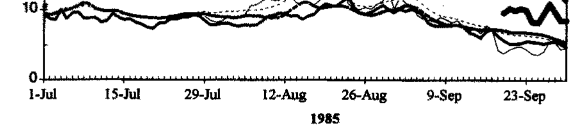

Fig. 3. Comparison of the daily observed discharge to simulated runoff for Langtang(S1), Lirung(S2) and Khimsung(S3) drainage basins using HYCYMODEL.

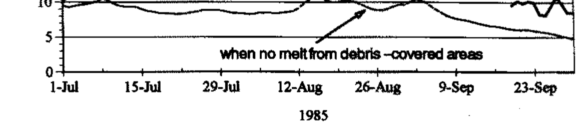

Fig. 4. Comparison of daily observed discharge to simulated runoff of Lirung drainage basin using HYCYMODEL.

ity. The debris thickness has been measured by Fujita, (private communication) to be 0.5 m at rather upstream. We calculate the melt from the debris-covered area, hence, assuming the average debris thickness of either 0.5 m or 1 m. Figure 5 shows a comparison of the daily runoff for debris thickness of 0.5 m and 1 m when the albedo of the debris-covered glacier to be 0.1. It shows that the daily runoff including ice melt under 0.5 m thick debris is larger than the runoff with 1m thick debris by about 20%. It is reasonable, since the ablation rates decrease with an increase in debris cover thickness after the effective melting rate (Fujii, 1977 ; Nakawo and Young, 1981 ; Mattson *et al.*, 1993).

The runoff from Lirung basin with debris albedo of 0.2 was compared in Fig. 5 with that of 0.1 to examine the effect of albedo. As seen in this figure, the calculated discharge did not change significantly with the change of albedo from 0.1 to 0.2, suggesting that ice melt is not sensitive to albedo.

Figure 5 indicated that the average melt calculated for debris thickness between 0.5−1 m would be roughly appropriate for Lirung Glacier, although the simulated results are still underestimated during the mid-July period. Mean observed discharge and calculated discharge values for debris thickness of 0.5 m and 1 m and albedo of debris surface 0.1 and 0.2 are shown in Table 1. The calculated mean runoff do not deviate from the observed mean runoff±17% in all the cases. However, the distributions of the surface debris thickness has to be obtained by field observations over Lirung Glacier. The surface temperature distribution with an energy balance study of the debris-covered glacier area would help to understand and estimate the distribution of the thermal effect of the debris and to calculate the ice melt under it.

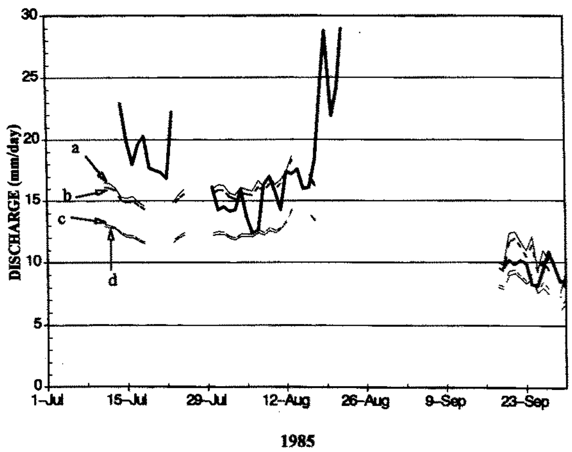

Fig. 5. Comparison of the daily observed discharge to simulated runoff of Lirung drainage basin including the melt from debris zones with different debris thickness and different albedo. Thick bold line represents observed discharge.
a) debris thickness 0.5 m, albedo 0.1
b) debris thickness 0.5 m, albedo 0.2
c) debris thickness 1 m, albedo 0.1
d) debris thickness 1 m, albedo 0.2

Table 1. Mean observed and calculated runoff (mm/day) for Lirung basin during August and September, 1985 (d : debris-thickness, m; a: albedo of debris).

		Mean runoff (mm/day)			
		August 1-13, 1985		September 13-30, 1985	
	Observed runoff	15.0	100%	9.4	100%
Calculated runoff for debris-thickness, d(m)					
a	d=0.5m, a=0.1	16.5	110%	10.6	113%
b	d=0.5m, a=0.2	16.1	107%	10.1	107%
c	d=1m, a=0.1	12.7	85%	8.3	88%
d	d=1m, a=0.2	12.5	83%	8.0	85%

5. Concluding remarks

By introducing the effect of debris-cover on snow and ice melt processes, the runoff estimation has been improved compared to the former calculations which either neglect the ice melt from debris-covered zones or assumes the drainage basin to be debris-free. For Lirung Glacier, the calculation of discharge agreed well with the observed value with the debris thickness of 0.5−1 m. The debris-albedo was found less sensitive to the runoff calculation. However, a further study is required, taking into account the distribution of debris characteristics, for better evaluation of ice melt from debris zone.

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