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Contribution of glacier meltwater to runoff in glacialized watersheds in the Langtang Valley, Nepal Himalayas

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Abstract

One-year long hydrological and meteorological data in glacier-fed rivers were obtained for a period from July 1985 to July 1986 in the Langtang Khola and the Lirung Khola watershed in the Langtang Valley, Nepal Himalayas. A simple method was developed to estimate the amount of mass input consisting of meltwater and rainwater in the watersheds using full-year hydrological and meteorological data including the amount of runoff, precipitation and air temperature in addition to the areal distributions of watersheds and those of glaciers obtained from readings of the topographical map of Langtang Himal. The contribution of glacier/snow meltwater to runoff in the glacialized watershed has been evaluated by estimating the amount of mass input, by the simple method so that the amount of mass input came to be consistent with the observed amount of mass output, i.e., runoff. It was concluded that the amount of glacier meltwater accounted for some 54 % of annual runoff in the Langtang Khola watershed and 76 % in the Lirung Khola watershed.

1. Introduction

For the effective utilization of latent and undeveloped water resources on the earth in the near future, hydrological studies are becoming necessary in glacialized watersheds in the world. In fact, as the case of the Nepal Himalayas, the development of water resources is called for as hydroelectric energy instead of using firewood, which is the only energy resources for hillside residents in the Nepal Himalayas, because, with an increase in population and an enhancement of living standards, as we are worried about, timber resources tend to be exhausted especially in high mountain areas, where forest resources are scanty because of the severe climate. Disappearance of forests causes landslides and floods. As a result, we are called on to develop water resources for hydroelectric power so that a natural environment will be conserved.

To develop and use effectively the water resources we have to understand hydrological characteristics of glacier-fed watersheds in the Himalayas because river water in high mountain regions is supplied by glacier meltwater in a large amount. Glacio-hydrological knowledge in the Nepal Himalayas still remains unknown because it is difficult to obtain necessary data by measurements in such remote regions.

First systematic glacio-hydrological investigations in the Nepal Himalayas were carried out in glacialized watersheds of the Langtang Valley, Langtang Himal, from August to October, 1982, from the monsoon to the postmonsoon season.

Following a preliminary study, one-year long hydrological observations were conducted from July 1985 to July 1986 as well as observations of meteorological elements at the same observation sites as were made in 1982. Seasonal variations in runoff were obtained then for the first time (Fukushima *et al.*, 1987a).

The Langtang Valley is located in Langtang Himal on the border of Nepal and China, some 60 km northward from Kathmandu and the head area of the River Trisuli in the Narayani River System. For comparing differences in discharge varying with the basin scale and also with the altitudinal distribution of

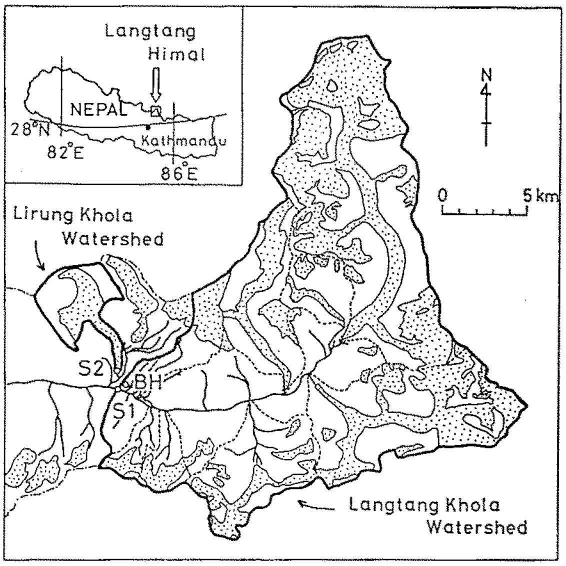

Fig. 1. Topographical map of the Langtang Valley. Thick solid lines indicate the boundaries of the Langtang Khola watershed (observation site at S1) and the Lirung Khola watershed (observation site at S2). BH: Base House for meteorological observations.

glaciers, two watersheds were chosen for hydrological investigations. They are the Langtang Khola watershed and the Lirung Khola watershed. The former is a large watershed belonging to the Langtang Khola (Khola means a river in Nepalese), the main river of the Langtang Valley consisting of many glacialized watersheds; and the latter is a small watershed belonging to the Lirung Khola, one of the tributaries of the Langtang Khola, which is only fed by Lirung Glacier as shown in Fig. 1. Hydrological observation sites are situated at 3840 m a.s.l. in the Langtang Khola watershed (LAW) and at 4000 m a.s.l. just in the vicinity of the Lirung Glacier terminus in the Lirung Khola watershed (LIW). In addition, meteorological observations were carried out at Base House in Kyangchen Gompa (3922 m) near the two sites. The sites are respectively marked by S1, S2 and BH in Fig. 1. Of 333 and 13.8 km^2, the total areas of LAW and LIW, 127 and 6.2 km^2, or 38 and 45 % are covered with glaciers or a glacier, respectively.

In a preliminary study using data of 1982, we analyzed the daily mass balance of LAW and LIW to evaluate the contribution of glacier meltwater to runoff. The amount of runoff as the amount of mass

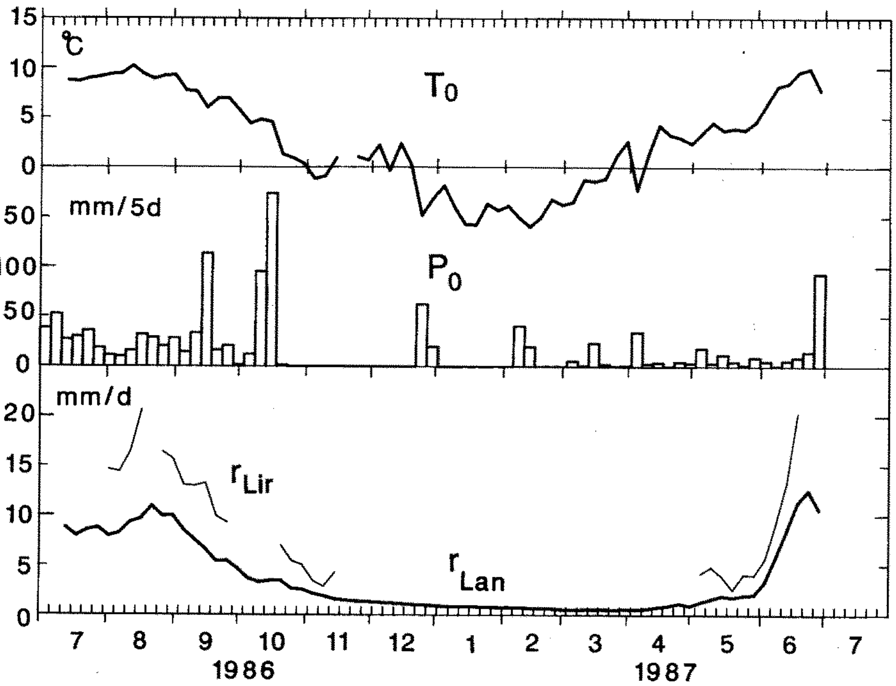

Fig. 2. Seasonal variations in 5-day mean air temperature and 5-day amount of precipitation at BH (upper figure); 5-day mean runoff in the Langtang Khola watershed (thick solid line); that in the Lirung Khola watershed (thin solid line).

output from the watershed was compared with the amount of mass input (glacier/snow meltwater and rainwater). The amount of mass input was estimated by a simple method so that it was consistent with the amount of mass output observed (Yamada *et al.*, 1984). In this paper, first of all, we will apply the same simple method to the full-year data and examine whether the method is adaptable or not to estimate the amount of mass input in the watersheds for a period of one year, which was to consist with the observed amount of mass output. Second, we should find out more reliable values of parameters in the method as the estimated amount of mass input agrees more accurately with the observed amount of mass output. Finally we will evaluate the contribution of the amount of meltwater to the amount of runoff.

The details of hydrological and meteorological observations and those features in the Langtang Valley have been presented for the full year from 1985 to 1986 by Fukushima *et al.*(1987a and b) and Takahashi *et al.* (1987a and b). Seasonal variations in runoff in LAW and LIW, and those in air temperature and precipitation at BH in five-day mean values are shown in Fig.2.

2. Procedure for estimating mass input

Presented here is a procedure for estimating the amount of mass input employed in the analysis of 1982–data.

In general, the daily mass balance of a watershed is represented by

$$r+\Delta S_g+E=P_m+P_r, \tag{1}$$

in the areal mean value of the watershed in a unit of mm, where r, ΔS_g and E are respectively the amount of runoff in the watershed, the change in groundwater storage and the amount of evapotranspiration; P_m and P_r are respectively the amounts of glacier/snow meltwater and rainwater. The amount of E is assumed to be negligibly small in comparison with the other balance terms, because air temperature is comparatively low and the watersheds are denuded. The maximum air temperature of 16.3 ℃ even in summer and the relatively low annual mean air temperature of 2.7 ℃ were observed at BH during the full year of 1985–86 (Takahashi *et al.*, 1987a and b).

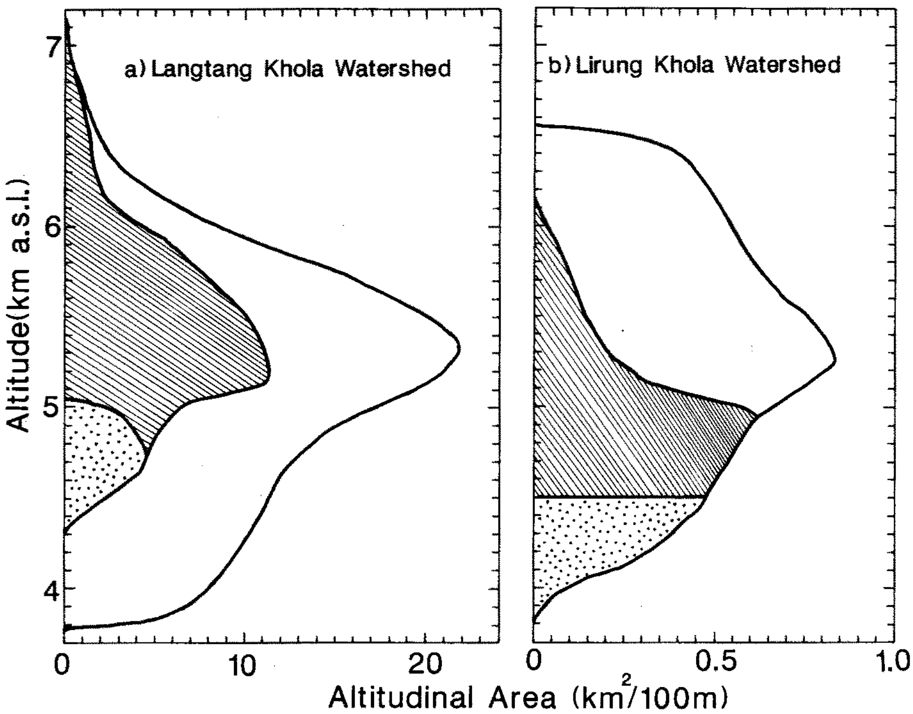

Fig. 3. Altitudinal distributions of the area of watersheds and glaciers every 100m in altitude. Dotted and hatched areas respectively represent the parts of debris-covered glaciers and debris-free glaciers.

In the analysis of 1982-data, the terms of mass input, P_m and P_r in the watersheds were estimated only from time-series data of air temperature, T_0, and precipitation, P_0, observed at BH; the altitudinal distributions of the watersheds, A(z), and those of glacier covered areas, Ag(z), which were obtained by readings of the topographical map of Langtang Himal, as shown in Fig. 3a (LAW) and Fig. 3b (LIW).

The flow chart for estimating the terms of daily mass input is shown in Fig.4. The amount of P_m is calculated by

$$P_m=\frac{1}{A}\int_{z_e}^{z_m} m(z)Ag(z)dz \qquad (2)$$

where m(z) is the amount of meltwater at the altitude z; A is the total area of the watershed; z_m and z_e are respectively the uppermost altitude of glacier/snow melting area and lowermost altitude of the snow covered area/glacier terminus. The amount of meltwater m(z) is assumed to depend only on z regardless of surface conditions, the direction and inclination of the slope. The amount of m(z) is estimated by the degree-day method, i. e., m(z) is presumed to be a linear function of air temperature T(z),

$$m(z)=k\ T(z), \qquad (3)$$

where k is called degree-day factor. T(z) is calculated using the altitudinal lapse rate of air temperature, Γ, obtained by observations,

$$T(z)=T_0-\Gamma(z-z_0), \qquad (4)$$

where z_0 is the altitude of BH (3922 m a.s.l.).

P_r is calculated by

$$P_r=\frac{1}{A}a(1-b)P_0\int_{z_l}^{z_r} A(z)dz \qquad (5)$$

where z_r and z_l are respectively the uppermost altitude of the rainfall area and the lowermost altitude of the watershed; the correction factor "a" is introduced because no reasonable data are available for the areal distribution of precipitation in the watershed; aP represents the average amount of precipitation in the watershed; b is the probability of solid precipitation. In general, solid precipitation even occurs when ground air tempera ture is slightly above 0 ℃; that is, there is such a transitional range of ground air temperature T as $T_s<T<T_r$; precipitation is solid in $T<T_s$ and liquid in $T>T_r$; and the altitudinal range of transitional precipitation is calculated by eq. 4 as

$$(T-T_r)/\Gamma+z_0<z<(T-T_s)/\Gamma+z_0. \qquad (6)$$

In the calculation of snow melting, the snow-covered area is estimated by considering eq. 6 and A(z). As for the snow-covered area, if the amount of m(z) calculated by eq. 3 is larger than the amount of snow cover in water equivalent, H_w, i.e., $m>H_w$, the true amount of snowmelt is evaluated as H_w.

From a field observation made by Ageta (1980) on Glacier AX010 in Shorong Himal, east Nepal, the probability b is represented by

$$b=(118-34T)/100 \qquad (7)$$

for precipitation in the daytime from 6-18h at the transitional temperature of $0.5<T<3.5$ ℃ and

$$b=(106-38T)/100 \qquad (8)$$

at night from 18-6h(next day) of $0.2<T<2.8$ ℃.

The value of Γ was determined to be 0.6×10^{-2} ℃/m on the area free from glaciers and debris-covered glaciers, and 1.0×10^{-2} ℃/m on the clean (debris-free) glacier on the basis of air temperatures at BH and other two points at the different altitudes of 5090 and

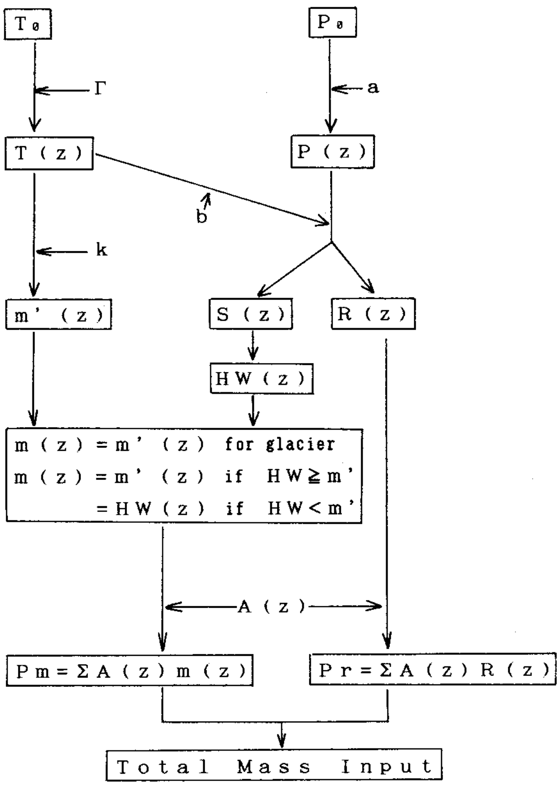

Fig. 4. Flow chart for calculating the amount of mass input. Notations are indicated in the text.

5405 m a.s.l observed in 1982 and 1985–86; the value of degree-day factor, k, was employed as 10 mm/°Cday by extrapolating linearly the relationship be tween m and T obtained by Ageta (1980) in the temperature range of 0 to 3 °C; the correc tion factor, a, was derived as nearly equal to 1 by the rule of trial and error, as the estimated value, P_r, is mostly fitted to the observed runoff (Yamada *et al.*, 1984).

3. Daily mass balance estimation in the full year

At first, the amount of mass input during the full year 1985/86 was estimated by applying the same method and parameters used for 1982–data analysis just mentioned above and compared with the observed amount of mass output i.e., runoff. The amount of daily mass input was practically derived by the summation of hourly amounts of glacier/snow meltwater and rainwater as the most reasonable estimation because the daily variation in air temperature resulted in marked variations in melting area in the watershed; thus the mass balance terms varied considerably during the day. The estimation of the meltwater and rainwater was actually made in each sectional area bounded by two adjacent contour lines graduated every 100 m.

The result of estimation indicates a big discrepancy between the estimated amount of mass input, $P_m + P_r$, and the observed amount of mass output, r, as shown in Fig. 5, especially in the Langtang Khola watershed. The estimated amount of mass input and the observed amount of mass output are illustrated by histograms and a solid line in the figure, which represents the average values of every five days so that large daily fluctuations are smoothed. The estimated amount of mass input is unquestionably too small especially in the monsoon season comparing with the amount of mass output. A careful examination shows that this discrepancy is considered to result mainly from the lack of reliability in the used values of parameters, k and a, which are respectively derived under the assumption of linear approximation in the relation of m to T and from the result of a mass balance study analyzed from the data observed in the limited duration in 1982.

Next, we made an effort to find out the most reliable parameters without changing the estimation method. The annual mass balance in the watersheds was assumed to be preserved in equilibrium; the annual change in groundwater storage may be zero; the annual amount of evapotranspiration, E, was also assumed to be negligibly small; the runoff coefficient was regarded as 1 for the full year. Then, the value of a was obtained as 1.12 for LAW and approximately 2.0 for LIW as the ratio of the total runoff, r_a, to the total amount of precipitation at BH, R_a, in both LAW and LIW during the full year: $a = r_a / R_a$. The most fit value of k was determined by the rule of trial and error. The value of Γ was used as the same value as used above since it is believed to be reliable enough; the value of b is also calculated from eqs. 7 and 8. The seasonal variation and the total estimated amount of mass input over the watershed were compared with those of mass output observed, respectively. Then we found out that the most fit value of k was 20 mm/°Cday for LAW and 10 mm/°Cday for LIW. A comparison between seasonal variation of estimated mass input and observed mass output is shown in Fig. 6a for LAW and Fig. 6b for LIW.

4. Discussion

A large discrepancy was found out between the estimated amount of mass input and the observed amount of mass output in the analysis of 1985/86 data when we employed the same parameter as used in the analysis of 1982–data (Fig. 5). For inspecting the sensitivity of the values of parameters, both the old and new values of parameters were applied to 1982–data in terms of the same analysis. Figures 7 and 8 show the results in LAW and LIW, respectively. In both the figures, figures a and b show respectively the results using old parameters, $a = 1.0$ and $k = 10$ mm/°Cday and new parameters, $a = 1.12$ and $k = 20$ for LAW; $a = 2.0$ and $k = 10$ for LIW. Comparing between figures a and b in both the watersheds, discrepancies between the estimated amount of mass input and observed amount of mass output are almost the same degree between the old and new parameters. That is, for such data for a short period as obtained in 1982, the value of parameter was found to be not so sensitive when the amount of mass input is estimated as to fit the amount of mass output. The new parameters derived from a full-year data is surely more reliable.

In conclusion, during the period from 10 July, 1985 to 30 June, 1986, which covers almost the full year, runoff as the amount of mass output is 1316 mm and

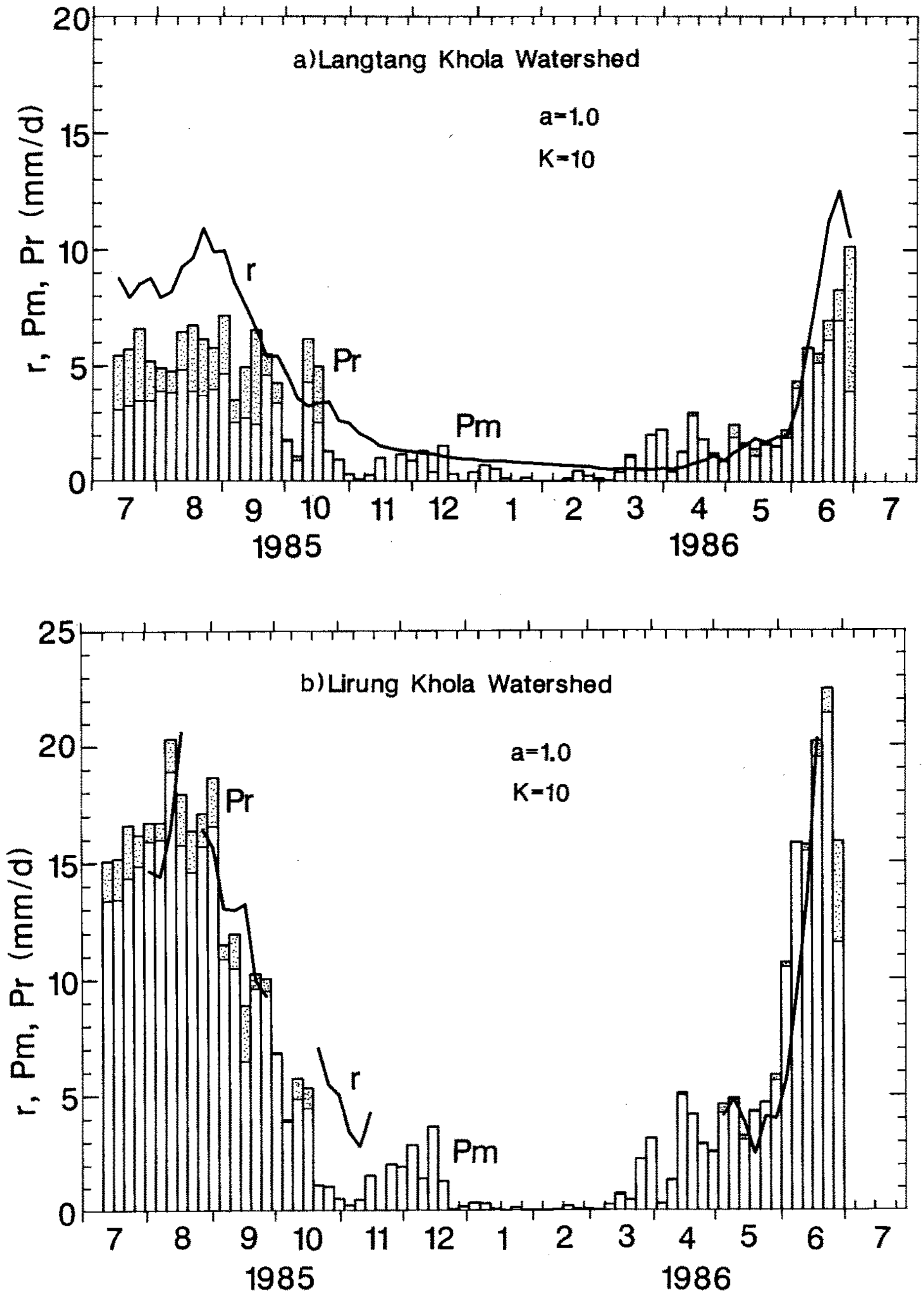

Fig. 5. Comparison between the amount of runoff and the amount of mass input in 5-day mean values from 10 July, 1985 to 30 June, 1986. Parameters a and k adopted are 1.0 and 10 mm/°Cday in both the watersheds. the thick solid line represents the amount of runoff, r; histograms represent the amount of mass input in which dotted bars are the amount of rainwater, P_r, and blank bar the amount of glacier/snow meltwater, P_m.

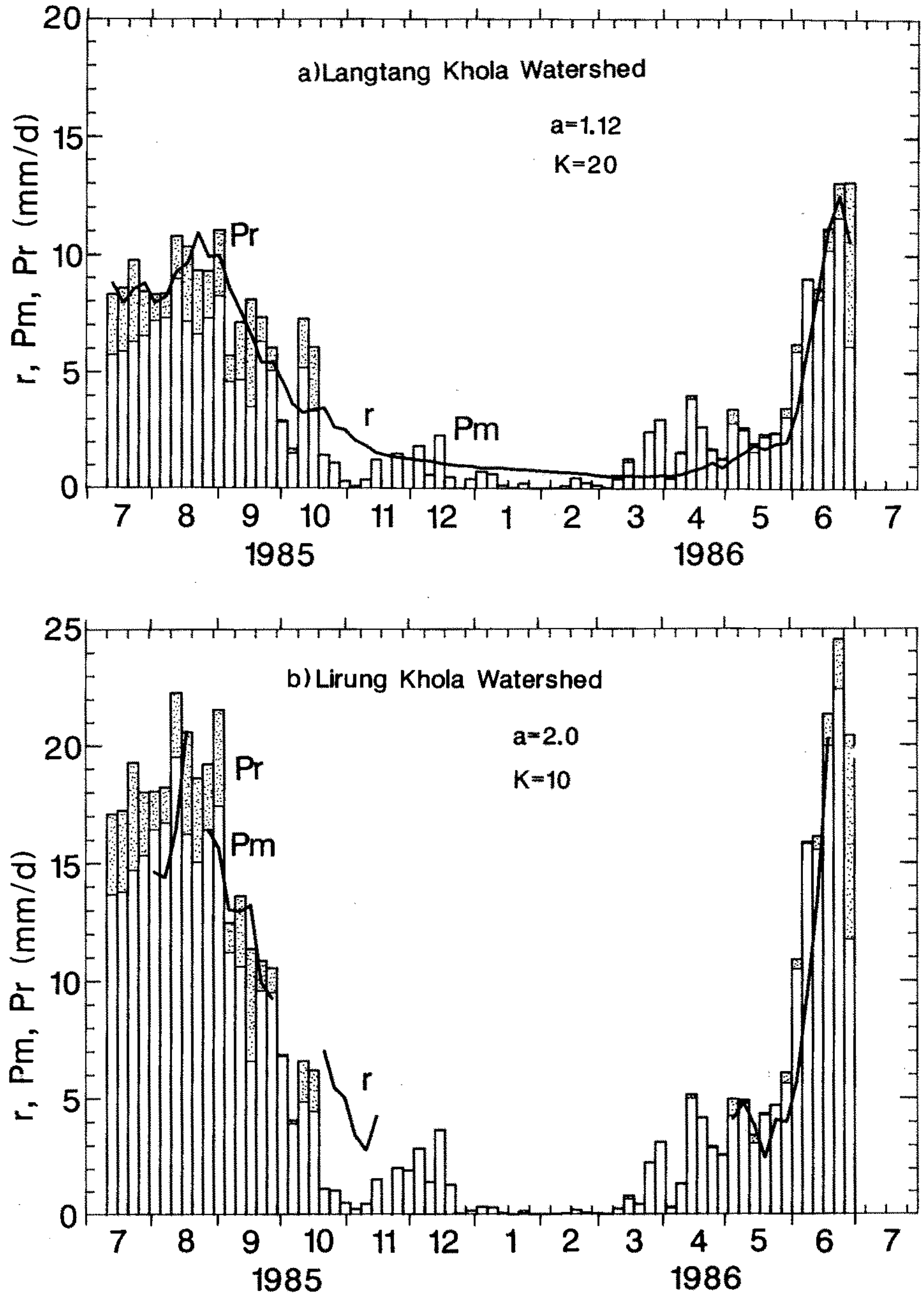

Fig. 6. Comparison between the amount of runoff and the amount of mass input in 5-day mean values from 10 July, 1985 to 30 June, 1986. Parameters a and k adopted are respectively 1.12 and 20 mm/°Cday for (a), the Langtang Khola watershed and 2.0 and 10 mm/°Cday for (b), the Lirung Khola watershed. Notations are the same as in Fig. 5.

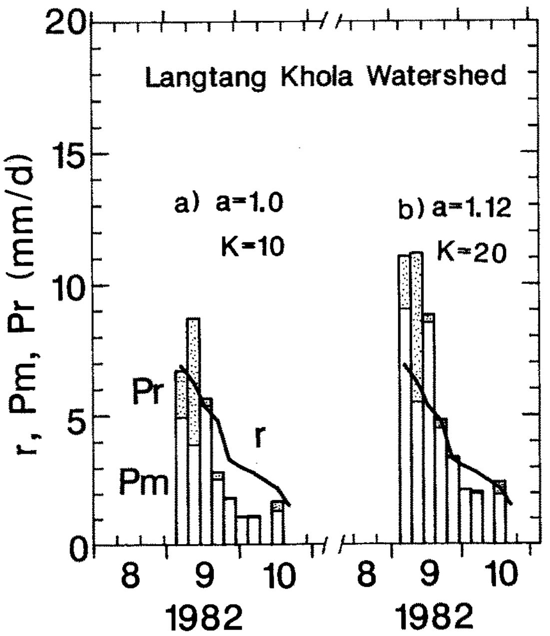

Fig. 7. Comparison between the amount of runoff and the amount of mass input in 5-day mean values in the Langtang Khola watershed from September to October in 1982. Parameters a and k adopted are 1.0 and 10 mm/°Cday at left and 1.12 and 20 mm/°Cday at right. Notations are the same as in Fig. 5.

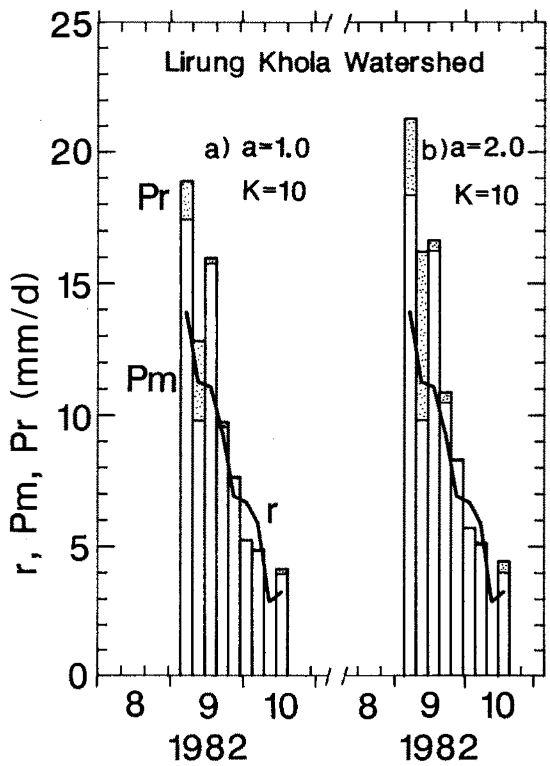

Fig. 8. The same as in Fig. 7 except in the Lirung Khola watershed; a=2.0 and k=10 mm/°Cday at right.

glacier/snow meltwater P_m and rainwater P_r as the amount of mass input are respectively estimated 1127 mm and 278 mm for the Langtang Khola watershed; mass balance of the watershed was found to be slightly positive as 89 mm. Considerable part, 80 %, of the amount of mass input consists of meltwater; and only less than 20 % of it consists of rain water. As for the Lirung Khola watershed, although we could not obtain the total amount of runoff because we were not able to obtain data especially in winter because of freezing of the river, the total precipitation in the same period as mentioned above was assumed to be total runoff, which is aP, that is, $2.0\times1174=2348$ mm; P_m and P_r were respectively estimated as 2133 mm and 344 mm, which occupied respectively 86 % and 14 % of total mass input. Then mass balance may be 129 mm.

To the amount of P_m, the contributions of meltwater from glaciers or a glacier were respectively estimated as 753 mm for LAW and 1887 mm for LIW, which occupied 54 % and 76 % of the total mass input.

We now found out that the great part of discharge, over 80 % of mass input, consists of glacier/snow meltwater in LAW and LIW. It has been reported by Fukushima *et al.* (1987a) that the coefficient of the river regime is only 25.6 for LAW. In general, precipitation has large annual fluctuations but air temperature shows no large annual fluctuations. As the amount of meltwater markedly depends on air temperature, annual fluctuations in river discharge are concluded to be relatively more stable in meltwater-fed watersheds than in rain-fed watersheds.

From a comparison between Fig. 6a (LAW) and Fig. 6b (LIW), it is seen that the amount of runoff in LIW is some two times larger than that in LAW. Why does this large difference occur between the two? It will be the most reasonable answer to consider that the amount of precipitation in LIW is some two times larger than that in LAW. According to the observations of precipitation in Khumbu and Shorong Himal in the East Nepal (Ageta, 1976; Yasunari and Inoue, 1978), the amount of precipitation at ridges and peaks in a mountain is reported to be two to five times larger than that at the bottom of the deep and wide valley due to the diurnal variation of clouds caused by the local circulation associated with orographic convection. LAW includes the deep and wide Langtang Valley in a great ratio to the total watershed area than LIW, which is located in the part of the steep slope area of Langtang Himal and the valley area is comparatively small. That is why precipitation in LIW should be much larger than that in LAW. In LIW, this large amount of precipitation balances with the relatively large amount of glacier/snow melting, which results from the presence of glaciers in low altitudes. If LIW and LAW have the same amount of precipitation, the large amount of mass output in LIW should be attributed only to the large amount of glacier melting, with quick shrinking and retreating of Lirung Glacier. This is believed to be obviously impractical. Thus, it may be reasonable to consider that the value of correction factor of precipitation, a, is derived as 2.0 for LIW. The relatively small value of a, i. e., 1.12, for LAW may mean that the amount of precipitation gradually decrease from downstream to upstream along the Langtang valley.

As seen in Fig. 6a, the comparatively large discrepancies of $P_m + P_r$ and r are found out in the postmonsoon and the premonsoon season in LAW. It indicates that the estimation method is reasonable because the phenomena are considered to occur practically in the glacier-fed watershed in the monsoon region. After the monsoon season, P_m and P_r suddenly decrease since air temperature abruptly decreases and there is no precipitation. Meanwhile, the amount of groundwater storage may reach the maximum immediately after the monsoon season. Therefore, r is larger than $P_m + P_r$ through the postmonsoon season to winter. On the contrary, in the premonsoon season just after winter and just before the monsoon season, the amount of groundwater storage may reach its minimum. The meltwater and rainwater in the premonsoon season may be stored in the groundwater basin. Thus, $P_m + P_r$ is larger than r in this season. As no melting and no rainfall take place in winter, meltwater in the bottoms of the glaciers and waters suspended in the glacier bodies may contribute to river discharge (Motoyama *et al.*, 1987). In fact, even in LIW where it is considered that there is no rich sediment, that is, no development of groundwater basin (Yamada *et al.*, 1984), water was found streaming throughout winter.

The value of k is derived as 10 mm/°Cday for LIW and 20 mm/°Cday for LAW. Although the amount of meltwater is decided by a heat balance on the ice/snow surface, we assume in this paper that the amount of meltwater is proportional to air temperature and that the value, k, is defined as the proportional constant. As discussed in detail by Takahashi *et al.* (1981), k varies with the contribution ratio of each heat balance term to the quantity heat used for ice/snow melting. For instance, at a fixed air temperature, a large contribution of shortwave radiation causes to increase; a higher wind speed also causes it to increase. The differences of k in both the watersheds are attributable to the amount of shortwave radiation, wind speed and other local meteorological conditions which affect the surface heat balance in the areal average of the watershed. In fact, for example, it was observed that LIW was covered by clouds earlier than LAW in the morning during the monsoon season; thus, the contribution of shortwave radiation in LIW is regarded as smaller than that in LAW.

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