Role of Glacier Meltwater in Discharge from the Glaciated Watersheds of Langtang Valley, Nepal Himalaya

Tomomi YAMADA*, Hideaki MOTOYAMA* and Khadga Bdr THAPA**

Glaciological Expedition of Nepal, Contribution No. 91
**Institute of Low Temperature Science, Hokkaido University, Sapporo 060, Japan*
***Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal*

Abstract

Hydrological characteristics in a glaciated region have been studied by measuring the amount of runoff in the Langtang Khola watershed (LAW) and the Lirung Khola watershed (LIW), of Langtang Himal in the Nepal Himalaya, during the period from August 27 to October 26, 1982, that is, from the late monsoon to the postmonsoon season, with the following findings: throughout over one month on rainless days in the postmonsoon season when the runoff of rain water seems to be zero, the daily amounts in the heights of runoff of glacier meltwater in LAW and LIW estimated by the observed air temperature using the degree-day method are smaller than the total runoff by some 1.7 mm/day in LAW and nearly equal to total runoff in LIW. Thus, in LIW the change in groundwater storage, Δr_g, is negligibly small; then, the runoff coefficient is approximately equal to 1 on the assumption of a negligibly small amount of evapotranspiration; then in LAW Δr_g is some 1.7 mm/day. The height of runoff due to rainfall can be evaluated fairly well from the measured amount of rainfall on the assumption that rainfall occurred uniformly in the amount over the whole rainfall area in Langtang Valley and the total amount is drained into the river with the runoff coefficient considered 1. It is concluded that the runoff characteristics in a glaciated watershed can be explained fully from the topographical features of a glacier or glaciers in the watershed.

1. Introduction

River water in the Nepal Himalaya contains a large amount of meltwater from glaciers, because they cover the head areas of it. As the abundant river water is expected to be one of the important water resources in Nepal, to develop and use effectively it requires an understanding of the roles of glacier meltwater as the source of it. Glacio-hydrological studies of the glacier meltwater are, however, few in the Nepal Himalayas except the studies in the Khumbu region (Higuchi et al., 1976) and in Hidden Valley (Nakawo et al., 1976). The present work has been conducted for making clear hydrological characteristics of the flow of glacier-fed rivers in Langtang Valley.

2. Hydrological observations

Langtang Valley is located in the southern front of the Great Himalayas called Langtang Himal on the border region of Nepal and China, some 100 km northward from Kathmandu and is the head area of the River Trisuli in the Narayani River System. For comparing the characteristics of discharges running off from a large and a small glaciated watershed, the amount of runoff was measured in two watersheds, large and small, in Langtang Valley from

August 27 to October 26, 1982, that is, from the late monsoon season to the postmonsoon season. The large one belongs to the Langtang Khola, the main river of Langtang Valley consisting of many glaciated subwatersheds, and the small one belongs to the Lirung Khola, one of the tributaries of the Langtang Khola, which is fed only by Lirung Glacier. The sites of hydrological observations are located at 3840 m a.s.l. in the Langtang Khola watershed and at 4000 m a.s.l. just the vicinity of Lirung Glacier terminus in the Lirung Khola watershed. In addition, meteorological data were measured at Base House in Kyangchen Gompa (3920 m a.s.l.) near the two sites. The sites are respectively marked by S1, S2 and BH in Fig. 1. At the observation sites the Langtang and the Lirung Khola were respectively 25–13 m and 8–3 m in width, 0.9–0.5 m and 0.6–0.3 m in mean depth in the maximum and the minimum runoff time during the observation period. Of 333 and 13.8 km², the total areas of the Langtang Khola and the Lirung Khola watershed, 127 and 6.2 km², or 38 and 45% were covered with glaciers and a glacier, respectively.

At both the hydrological observation sites, the relations between water level and runoff were temporarily observed at various water levels continuously measured by the self-recording gauges, so that the stage discharge curve was obtained; the amount of runoff was measured from the vertical cross sectional area of the river and the flow velocity at the 60% depth level from the surface at 10-odd points at equal in intervals across the river; the flow velocity was measured by the water current meter of the electric-generator-type. Then, the amount of runoff in each watershed was converted from the water levels using the above curve. In addition, measurements were continuously made of water temperature of the Langtang Khola by using the long-term temperature recorder designed by Akitaya (1978). At Base House meteorological data were observed; that is, air temperature was measured by the recorder of the above type; precipitation was observed twice a day during 06–18h and 18–06h (next day) in Nepal Local Time (= GMT+5h40m); and cloudness and weather were observed every three hours at 06, 09, 12, 15 and 18h.

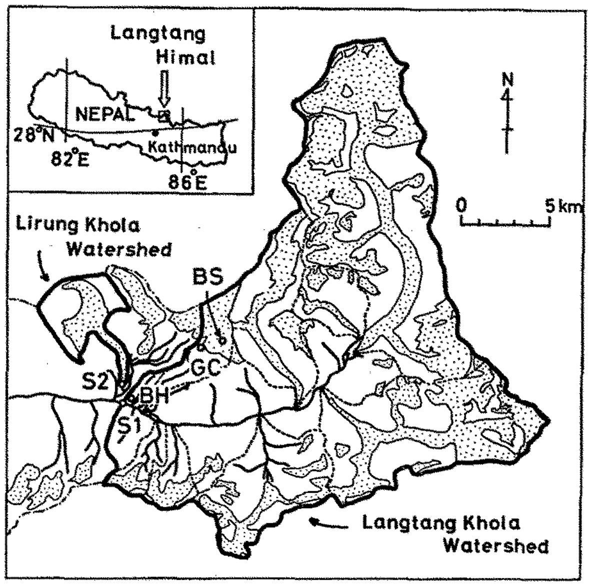

Fig. 1. A topographical map of Langtang Valley. Thick solid lines indicate the boundaries of the Langtang Khola watershed (observation site at S1) and the Lirung Khola watershed (observation site at S2). BH: Base House for meteorological observations. GC: Glacier Camp. BS: Boring Site.

3. Results of observations

Daily variations in hourly runoff in the Langtang Khola and the Lirung Khola watershed are shown in Fig. 2, together with those in hourly water temperature in the Langtang Khola and in hourly air temperature at Base House. As seen from the daily amount of precipitation in Fig. 2, in 1982 the monsoon season was over around the middle of September in Langtang Valley.

The runoff, Q, shows a distinctive behavior in its daily variation in both the watersheds, as found in Fig. 2; that is, the daily range of runoff, ΔQ, decreased with time; the daily range of runoff against daily runoff in the Lirung Khola watersheds, $\Delta Q_{Li}/Q_{Li}$, was markedly larger than $\Delta Q_{La}/Q_{La}$ in the Langtang Khola watershed; in the Lirung Khola watershed the daily maximum runoff was some two times larger than the daily minimum runoff. This extremely large value of $\Delta Q_{Li}/Q_{Li}$ suggests that the amount of runoff due to a change in groundwater storage may be markedly small in the Lirung Khola watershed. The daily range decreased in two to a few days after the watersheds were covered with snow, which might have resulted from a little melting due to high albedo values of the ground surface. Comparing the amount of runoff with air temperature in Fig. 2, the daily variation in runoff was correlated with that in air temperature measured at Base House. The time lag between air temperature and a resultant change in runoff was 10–13 hours for the Langtang Khola and 4–6 hours for the Lirung Khola. The maximum and the minimum air temperature were observed around 12–13h and 5–6h, respectively.

The daily range of air temperature varied with the weather conditions; that is, the range increased to some 15°C on fine days in the postmonsoon season and decreased to some 3°C on rainy, snowy and cloudy days. The daily minimum water temperature was as cold as 2–3°C even in the Langtang Khola and near 0°C in the Lirung Khola; as shown in Fig. 2, the daily

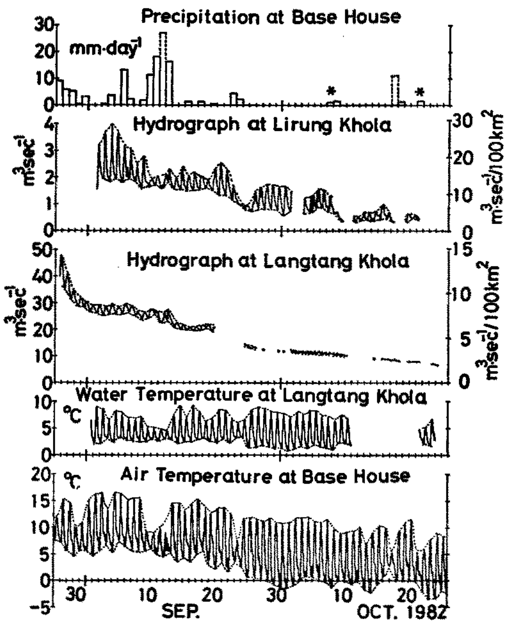

Fig. 2. Seasonal variation in the daily amount of precipitation at Base House (*: solid precipitation); daily variations in runoff in the Langtang Khola and the Lirung Khola watershed, water temperature in the Langtang Khola and air temperature at Base House.

minimum water temperature shifted to the lower level in the postmonsoon season, which might have been caused by the absence of runoff of rather warm rainwater; the daily variation in water temperature agreed with that in air temperature with the time lag of 1–2 hours as a trend; the daily range of water temperature varied also with that of air temperature did. Thus, the daily variations in air and water temperature were markedly related to the weather conditions, i.e. the daily variation in shortwave radiation.

The observational results indicate that the runoff of both the watersheds contains a large amount of glacier meltwater; and that the amount of runoff evidently correlates with air temperature, which depends on the amount of shortwave radiation, i.e. weather conditions.

For comparing the amount of runoff in the Langtang Khola watershed with that in the Lirung Khola watershed, the seasonal variations in height of daily runoff, r ($= Q/A$, where A is the watershed area), in both the watersheds are shown in Fig. 3, with the seasonal variations in $\bar{T}_a$, the daily mean air temperature, and, z_m, the uppermost altitude of the ablation area or the altitude of the 0°C line in the daily mean value in Langtang Valley, which varied from 5300 to 4200 m a.s.l. during the observation period.

The height of daily runoff in the Lirung Khola watershed, r_{Li}, is extremely larger than that in the Langtang Khola watershed, r_{La}, especially during the earlier period of the observation; the heights of r_{Li} and r_{La} decreased with a fall in $\bar{T}_a$ (or a decrease in z_m). As a result of the larger decreasing rate of r_{Li} with time than that of r_{La}, the height of r_{Li} becomes to almost the same height of r_{La} around the end of the observation period in the postmonsoon season; then, it seems that the change in $\bar{T}_a$ with time is more effective in the change of r_{Li} than that of r_{La}.

These differences in the hydrological characteristics between the two watersheds may be attributed to the differences in the amount of glacier meltwater, which results from the differences in topographical features of the glacier such as the altitudinal distribution of the glacier

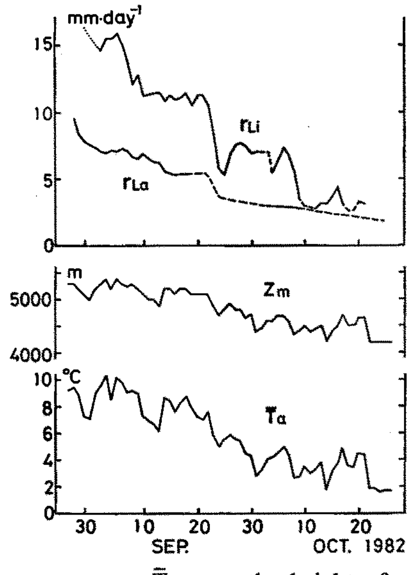

Fig. 3. Seasonal variations in r_{La}, r_{Li}, z_m, $\bar{T}_a$. r_{La}: the height of runoff in the Langtang Khola watershed; r_{Li}; that in the Lirung Khola watershed; z_m; the daily mean uppermost altitude of the ablation area in Langtang Valley; $\bar{T}_a$: the mean daily air temperature at Base House.

area, the ratio of the glacier area to the total area of the watershed, etc. Let us then assess the contribution of glacier meltwater to runoff by the analysis of daily runoff in the watershed in the following section.

4. Analysis of a daily mass balance on rainless days

In general, a daily mass balance in a watershed is represented by

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

in units of mm/day, where r is the height of daily runoff in the watershed; ΔS_g and E are respectively the daily change in groundwater storage and the daily amount of evapotranspiration in the areal mean values; P_m and P_r are respectively the daily areal amounts of ablation and rainwater in the areal mean value of the watershed. It is assumed that E is negligibly small because of comparatively low air temperature and absence of a vegetative cover in Langtang Valley situated in the alpine zone.

For evaluating the contribution of P_m to r, the daily mass balance has been studied on rainless days in the postmonsoon season when P_r seems to be zero. Then the heights of r in the Langtang Khola and the Lirung Khola watershed are given by

$$r = P_m \pm \Delta S_g \tag{2}$$

and also

$$r = aP_m \tag{3}$$

where a is the runoff coefficient in the watershed. Now, let us estimate the amount of P_m in each watershed on the basis of air temperature observed at Base House and the topographical map of Langtang Valley on suitable assumptions.

The amount of P_m is generally given by

$$P_m = \frac{1}{A} \int_{z_e}^{z_m} m(z) A_g(z)\, dz \tag{4}$$

where $A_g(z)dz$ is the glacier area between the altitudes z and $z+dz$; z_m and z_e are respectively the uppermost altitude of the ablation area and the altitude of the glacier terminus; $m(z)$ is the daily amount of ablation at z. Adopted for estimating $m(z)$ is the degree-day method, which is commonly used for the estimation of $m(z)$ in terms of air temperature as given by

$$m(z) = kT_a(z) \tag{5}$$

where the constant k is called the degree-day factor; $T_a(z)$ is the mean daily air temperature higher than 0°C at z. The value of $T_a(z)$ is given by

$$T_a(z) = T_a(z_0) - \Gamma(z - z_0) \tag{6}$$

where $T_a(z_0)$ is the air temperature measured at Base House at the altitude z_0 and Γ is the lapse rate of air temperature.

Glacier melting occurs only in the ablation area between the altitudes z_e and z_m, the value of z_e being constant around 4000 m a.s.l. in both the watersheds but z_m varying momentarily with the variation in air temperature, as provided by

$$z_m = T_a(z_0)/\Gamma + z_0 \tag{7}$$

Therefore, a marked variation occurs every day in the ablation area, depending on the daily variation in z_m. The ablation area expands in the daytime and shrinks at night from which

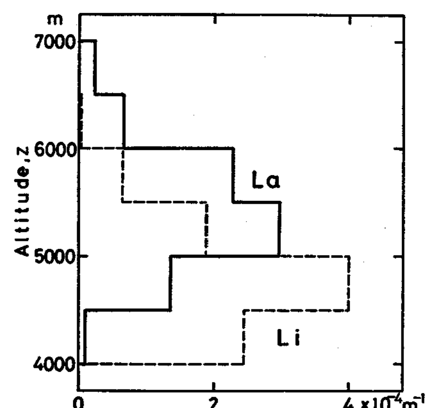

Fig. 4. Altitudinal distribution of ratio $(A_g)_z/A$ for the Langtang Khola watershed (solid line) and the Lirung Khola watershed (dashed line), where $(A_g)_z$ is the glacier area in the section bounded by two adjacent contour lines graduated every 500 m with the mean altitude of z and A is the watershed area.

it follows that the most reasonable estimation can be made of P_m by the summation of its hourly amount, $(P_m)_t$. This summation may be rather better than the direct estimation of P_m by using eqs. 4 and 5. On the other hand, because of the limitation in the accuracy of the map of Langtang Valley, an estimation can be made of the glacier area in each section bounded by two adjacent contour lines graduated every 500 m such as the glacier area between the altitudes 4000 and 4500; 4500 and 5000 m a.s.l., and so on. The altitudinal distribution of ratio of the glacier area in the section to the total watershed area was obtained then, as is shown in Fig. 4. Thus, $(P_m)_t$ was obtained by the summation of the area mean hourly ablation in each section.

Consequently, P_m is evaluated by the equations modified from eqs. 4 and 5 as

$$P_m = \Sigma\,(P_m)_t = \Sigma\left(\frac{1}{A}\,\Sigma m_{z,t}\,(A_g)_z\,\Delta z\right) \tag{8}$$

and

$$m_{z,t} = \frac{k}{24}\,(T_a)_{z,t} \tag{9}$$

where $m_{z,t}$ and $(T_a)_{z,t}$ are the hourly ablation and the hourly air temperature in the section at the mean altitude z. When the mean altitude of the section is lower than z_m, the section is regarded as the ablation area in the watershed. And if it is larger, the section is regarded as the accumulation area. Now we can estimate P_m only from air temperature measured at Bace House using eqs. 6, 7, 8 and 9 and the reasonable valued of Γ and k.

The value of Γ is assumed to be 1.0×10^{-2} on the clean glacier (snow and bare ice area) and 0.6×10^{-2} °C/m on the debris-covered glacier and the area free from the glacier on the basis of the observed air temperature at Base House (3920 m a.s.l.), Glacier Camp (GC in Fig. 1, 5090 m a.s.l.) and Boring Site (BS in Fig. 1, 5405 m a.s.l.) in Langtang Valley during the period of hydrological observations and also on the basis of the values of Γ obtained by Ageta (1983) and Yamada (1970) in the Nepal Himalaya. Meanwhile, k is sought, using the plots of $m(z)$ against $\overline{T}_a$ in a temperature range not higher than 3°C in Glacier AX010 in the

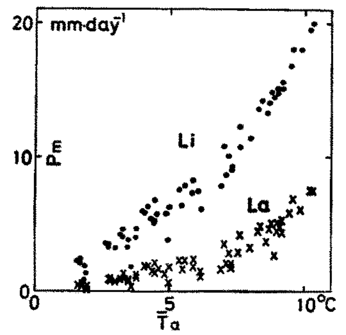

Fig. 5. Relations of the mean daily air temperature measured at Base House, $\bar{T}_a$, with the areal amount of daily ablation in the areal mean value estimated in the Langtang Khola watershed, La, and that in the Lirung Khola watershed, Li.

Nepal Himalaya (Fig. 6 of the paper by Ageta et al., 1980). For temperature higher than 3°C, values of $m(z)$ are obtained by linear extraporation; then, k is obtained, as 10 mm/°C/day from eq. 5. This value of k is applied, to first approximation, to the whole ablation area regardless of the surface conditions.

The amounts of P_m estimated by eqs. 6, 7, 8 and 9 in the Langtang Khola and the Lirung Khola watershed, which are respectively shown by La and Li, are plotted against the mean daily air temperature, $\bar{T}_a$, in Fig. 5. Comparing P_m with r in both the watersheds on rainless days, as shown in Fig. 6, it is revealed that $r = P_m + 1.7$ mm/day in the Langtang Khola watershed and $r = P_m$ mm/day in the Lirung Khola watershed. In Fig. 6, the seasonal variations in r_{La} and r_{Li} (the same as in Fig. 3) are shown by the thick solid lines and the residual value ($= r_{La} - 1.7$) is shown by the thin solid line (the lower figure).

In the Lirung Khola watershed, it is clarified from the above result that the amount of ΔS_g in eq. 2 is negligibly small as expected in Section 3 and that the runoff coefficient in eq. 3 is approximately equal to 1. Then, almost all the height of runoff in the Lirung Khola watershed consists of only glacier meltwater, where r_{Li} is regarded as the height of runoff, r_m, due to glacier melting, i.e., $r_{Li} = r_m$ on the rainless days. Since the runoff coefficient is assumed to be 1 for rainwater runoff in the same way as glacier meltwater runoff, P_r in eq. 1 can be regarded as the height of runoff, r_r due to rainwater. Then, the height of runoff, r_{Li}, in the Lirung Khola watershed is represented as,

$$r_{Li} = P_m + P_r = r_m + r_r \tag{10}$$

The absence of ΔS_g in the Lirung Khola watershed may be considered to have resulted from the absence of the rich sediment as the groundwater basin because of the active movement of the glacier on the bedrock and such steep slopes of areas almost free from glaciers that have no sediments.

Each glaciated subwatershed constituting the Langtang Khola watershed is assumed to have the same hydrological features as the Lirung Khola watershed. Therefore, as for the Langtang Khola watershed, almost all the amount of glacier meltwater and rainwater in the subwatersheds is believed to discharge into the main river of the Langtang Khola in the same way as in the Lirung Khola watershed. Then, r_{La} is also represented as

$$r_{La} = P_m + P_r + 1.7 = r_m + r_r + 1.7 \tag{11}$$

in units of mm/day. The value of 1.7 mm/day in eq. 11 implies the height of daily runoff due

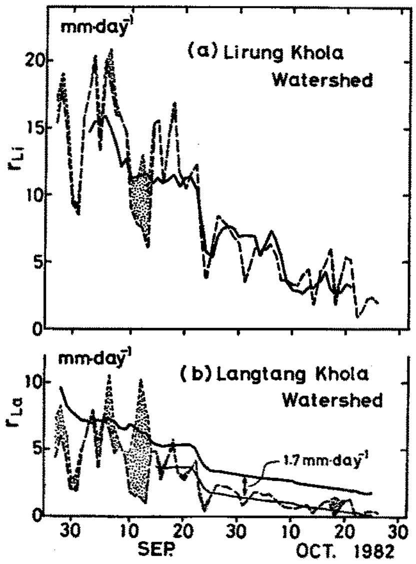

Fig. 6. Comparison in the Langtang Khola and the Lirung Khola watershed between the observed height of daily runoff in the watershed (thick solid lines) and the sum of the estimated areal mean value of daily ablation in the glacier (thick dashed lines) and that of daily areal amount of rainfall (dotted areas). A thin solid line in the lower figure shows the residual ($r_{La}-1.7$ mm/day) in the Langtang Khola watershed.

to the change in groundwater storage, this height being comparatively large in comparison with the height of r_{La} in the postmonsoon season, as shown in Fig. 6. The groundwater basin in the Langtang Khola watershed may consist mainly of the abundant sediment accumulated in the bottom of the large U-shaped valley of Langtang Valley, in which a large amount of water has been contained as groundwater during the monsoon season.

5. Conversion of the measured amount of rainfall to the height of runoff due to rainwater

Since we can estimate the height of daily runoff due to glacier melting, r_m, we can simply calculate the height of daily runoff due to rainwater, r_r, on rainy days as the residuals, $r_{La}-(r_m+1.7)$ and $r_{Li}-r_m$, in the Langtang Khola and the Lirung Khola watershed, respectively. Now, let us convert the daily amount of rainfall, P, measured at Base House to r_r in the watersheds.

The relation of r_r to P is assumed as

$$r_r = \frac{\alpha P}{A} \int_{z_l}^{z_r} A_r(z)\, dz \tag{12}$$

where the integration covers the rainfall area in the watershed between the uppermost altitude, z_r, of rainfall and the lowermost altitude, z_l, of the watershed; α is the correction factor of making P the resonable value applicable to the whole rainfall area when multiplied by α. In practice, the approximate equation given by

$$r_r = \sum (r_r)_t = \sum \left(\frac{1}{A} \sum \alpha\beta P_t (A_r)_z\, \Delta z\right) \tag{13}$$

is used for the conversion of P to r_r because of the same reason as was discussed in the estimation of r_m. The meanings of the suffixes are the same as in eq. 8; β is the probability of rainfall when the ground air temperature is near 0°C.

As the residuals, $r_{La}-(r_m+1.7)$ and $r_{Li}-r_m$, agree with the heights of r_r calculated by eq. 13 in both the watersheds, the most fit value of α is determined on rainy days.

In general, it shows even when the ground air temperature is slightly above 0°C; that is, there is such a transitional range of ground air temperature as $T_S < T_a(z) < T_R$, beyond which precipitation is liquid as in $T_a(z) \geq T_R$ and solid as in $T_a(z) \leq T_S$; and the altitudinal range of the transitional precipitation zone is calculated by eq. 7 as

$$(T_a(z_0)-T_R)/\Gamma+z_0 < z < (T_a(z_0)-T_S)/\Gamma+z_0 \qquad (14)$$

From the field observations of the relations between the type of precipitation and ground air temperature, $T_a(z)$, made by Ageta (1980), the probability, $(1-\beta)$, of solid precipitation is represented by

$$1-\beta = (-34T_a(z)+118)/100 \qquad (15)$$

for precipitation in the daytime from 6–18h in the transitional temperature range of $0.5 < T_a(z) < 3.5$°C and

$$1-\beta = (-38T_a(z)+106)/100 \qquad (16)$$

at night from 18–06h (next day) in $0.2 < T_a(z) < 2.8$°C. Hence, the areal amount of rainfall in the transitional precipitation zone provided with eq. 14 was estimated by considering the probability of rainfall, β, given by eqs. 15 and 16.

In the calculation of r_r by eq. 13, the parameter α is changed in a range from 0.5 to 1.5 and each calculated value is compared with the residuals. Then, the most fit value of α is determined by the rule of trial and error. Concludingly, it is revealed that r_r accords best with the residuals when $\alpha = 1$. The heights of r_r calculated by eq. 13 are shown by the dotted area in Fig. 6. As a result r_{La} and r_{Li} can be roughly estimated by eqs. 6, 7, 8, 9, 13, 15 and 16, as indicated in Fig. 6.

As seen in Fig. 6, the runoff of glacier meltwater is revealed to play an essentially important part in the total runoff in both the watersheds in the season under observation.

6. Relations between runoff characteristics and topographical features of glaciers in the glaciated watershed

As shown in Figs. 2 and 3, a great difference is noted in the runoff characteristics of the Lirung Khola and the Langtang Khola watershed. Discussions are made in this Section to explain the difference from the topographical features of the glacier or the glaciers in the watershed.

For the altitudes in which ablation tends to occur, the ratio $(A_r)_z/A$ in eq. 13 in the Langtang Khola watershed is little larger than that in the Lirung Khola watershed according to the reading taken from the topographical map of Langtang Valley. Since the same values of α, P_t and z_r are employed in both the watersheds and z_l is almost the same altitude, 4000 m a.s.l., the heights of r_r in the watersheds are not so much different from each other, as shown by the dotted areas in Fig. 6. Therefore, a great difference between r_{La} and r_{Li} shown in Fig. 3 is concluded to be attributed to a great difference in r_m between the two watersheds. Because the amount of $m(z)$ is almost the same in the two watersheds, this difference in r_m is mainly caused by a great difference in altitudinal distribution of ratio, $(A_g)_z/A$, in eq. 8 between the two watersheds, as shown in Fig. 4. As stated in Section 3, melting occurred in the area below the daily mean altitude of 5300 to 4200 m a.s.l. during the period of observation. Therefore, the amount of ratio $(A_g)_z/A$ in the melting area was markedly larger in the Lirung Khola watershed than in the Langtang Khola watershed, which results in the large height of r_m in the Lirung Khola watershed than that in the Langtang Khola watershed.

As seen in Fig. 5, P_m or r_m in the Lirung Khola watershed is remarkably more sensitive to $\bar{T}_a$ than P_m or r_m in the Langtang Khola watershed; the decreasing rate of r_m with decreasing $\bar{T}_a$ in the former watershed is much larger than that in the latter watershed; with a decrease in $\bar{T}_a$, r_m decreases; then the height of r_m in the former approaches the height of r_m in the latter with decreasing $\bar{T}_a$; conversely, with an increase in $\bar{T}_a$, an increase comes about in the difference in r_m between the two watersheds. These differences in the relation between r_m and $\bar{T}_a$ in the two watersheds result in a large difference in the characteristics of runoff between the two watersheds such as $\Delta Q_{Li}/Q_{Li} > \Delta Q_{La}/Q_{La}$, $r_{Li} > r_{La}$, $dr_{Li}/dt > dr_{La}/dt$, etc., as stated in Section 3.

As a conclusion, the runoff characteristics in the glaciated watershed can be explained fully from the topographical features of a glacier or glaciers in the watershed.

7. Conclusion

Hydrological characteristics of runoff in a glaciated region have been studied by measuring the amount of runoff in the Langtang Khola watershed (333 km^2) and the Lirung Khola watershed (13.8 km^2) in Langtang Valley, of Langtang Himal in the Nepal Himalaya during the period from August 27 to October 26, 1982, that is, from the late monsoon season to the postmonsoon season. The former watershed consists of many glaciated subwatersheds in this valley.

For investigating the role of glacier meltwater in the amount of runoff in the watersheds, the daily mass balance was studies by the degree-day method employing the value of 10 mm/°C/day as the degree-day factor on rainless days in the postmonsoon season, when runoff due to rainwater seems to be zero. As a result, as for the Lirung Khola watershed, the total amount of daily ablation was found to be approximately equal to the daily amount of runoff throughout almost one month in the postmonsoon season. Thus, in this watershed the change in groundwater storage was revealed to be negligible; then, the runoff coefficient was determined to be nearly equal to 1 on the assumption of the negligibly small amount of evapotranspiration. By applying this finding to the Langtang Khola watershed, the change in groundwater storage was clarified to be 1.7 mm/day. Consequently, the amount of runoff in a glaciated subwatershed of this watershed consists only of glacier meltwater on rainless days in the postmonsoon season because of the lack of a sediment which serves as a groundwater basin. Since the Langtang Khola watershed, however, is covered with a rich sediment in the bottom of the large U-shaped Langtang Valley, a groundwater storage occupies comparatively a large amount of runoff, especially in the postmonsoon season.

As for the rainwater runoff, it was revealed that the amount of runoff due to rainwater can be evaluated fairly well from the amount of rainfall measured at the foot of the watershed on the assumption that the rainfall precipitates uniformly over the whole rainfall area in Langtang Valley and is drained into the river with the runoff coefficient considered 1.

Concludingly, the height of runoff in the Langtang Khola watershed, r_{La}, and that in the Lirung Khola watershed, r_{Li}, are represented by $r_{La} = r_m + r_r + 1.7$ and $r_{Li} = r_m + r_r$ mm/day, where r_m and r_r indicate the heights of runoff due to glacier meltwater and rainwater, respectively. Now, we can roughly predict the amount or height of runoff in any subwatershed of Langtang Valley by a simple calculation using the data of air temperature and amount of rainfall.

The observational results show great difference in runoff characteristics between the two watersheds. This difference is mainly attributed to a difference in r_m because a difference in r_r is not so great. Since r_m depends on the altitudinal distribution of the glacier area in the watershed, a full explanation can be given to runoff characteristics by the topographical features of a glacier or glaciers in the glaciated watershed.

Acknowledgments

We would like to express our appreciation to the members of Glaciological Expedition of Nepal—Boring Project, 1982, supervised by Prof. K. Higuchi of Nagoya University for the laborious assistance given us throughout the field work. We also wish to express our thanks to Prof. G. Wakahama, Prof. Y. Suzuki and Dr. D. Kobayashi of Hokkaido University for reading the manuscript and offering useful criticisms, to Dr. Akitaya, also of the above university, for making the field equipments available for us and to Dr. H. Ikeda of Tsukuba University for calibrating the water current meter. The research has been supported by a grant-in-aid for scientific research from the Ministry of Education, Science and Culture, of the Japanese Government.

References

Ageta, Y., Ohata, T., Tanaka, Y., Ikegami, K. and Higuchi, K., 1980: Mass balance of Glacier AX010 in Shorong Himal, East Nepal during the summer monsoon season. Seppyo, **41** (Special Issue), 34–41.

Ageta, Y., 1983: Nepal Himalaya no kaki kanyô gata hyôga ni okeru shitsuryô shûshi no tokusei (I) (Characteristics of mass balance of the summer-accumulation type glacier in the Nepal Himalaya (I)). Seppyo, **45**, 81–90.

Akitaya, E., 1978: Development of a long-term temperature recorder. Low Temp. Sci., Ser. A, **37**, 167–169.

Higuchi, K., Ageta, Y. and Kodama, H., 1976: Water Discharge of Imja Khola in Khumbu Himal. Seppyo, **38** (Special Issue), 22–26.

Nakawo, M., Fujii, Y. and Shrestha, M. L., 1976: Water Discharge of Rikha Samba Khola in Hidden Valley, Mukut Himal. Seppyo, **38** (Special Issue), 27–30.

Yamada, T., 1970: Nepal no kikô ni kansuru oboegaki (On the climate of the Nepal). Sangaku, **65**, 188–198.