The Contribution of Glacier Melt to the River Discharge in an Arid Region

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Abstract

The contribution of glacier melt to discharge in an arid region was assessed based on the water budget equation. The study basins were those of the Yurungkax and Keriya rivers. Both rivers flow into the Taklamakan Desert, where precipitation is very limited, from the West Kunlun Mountains of China. Each term of the equation was estimated based on a few hydrological data. The total amount of glacier melt runoff was estimated as a residual of the equation. The average values of glacier melt in the two river basins were 80mm for the Yurungkax River and 42.3mm for the Keriya River. The average ratios of melt water to discharge were about 50 per cent and 42 per cent respectively. It was shown that glacier melt plays a great role in the hydrological processes in this arid region.

Introduction

The arid regions of the earth make up about 30 per cent of the total land mass, and a great part of them are located in developing countries. Deserts are essentially formed under dry weather conditions and, in some cases, human activities hasten their formation. These latter have attracted special interest recently. We must make the causal relationship between desertification and natural conditions clear in order to elucidate the mechanisms behind desertification and work out counter measures against them.

Cities in oases surrounding the southern margin of the Taklamakan Desert, where the precipitation is limited, derive their water supply from rivers that rise from the West Kunlun Mountains where there are many glaciers in the alpine zone. The goals of our study were to reconstruct the palaeoclimatic and hydrological environment around the Taklamakan Desert by analysing ice cores from glaciers in the area. As the first step in the hydrological study we investigated the contribution of glacier melt to river discharge based on the water budget in the basins.

Study Basins

The study basins are those of the Yurungkax and the Keriya rivers, which flow into the Taklamakan Desert from the West Kunlun Mountains. The Yurungkax River basin has elevations ranging from 1,650 to 7,167m and has an average height of 4,750m above sea level. The values for the Keriya River are 1,880 to 6,500m and 4,878m respectively. There are many glaciers in the alpine zone of both basins above 5,000m in elevation. The glacier area of the Yurungkax and the Keriya river basins are 20.37 per cent and 9.30 per cent in Table 1(b) of the basin areas respectively. The locations of the basins and some gauging stations are shown in Figure 1. Maps of the basins are given in Figures 2a and b. The geographical characteristics of the basins at intervals of 500m in elevation are summarised in Table 1.

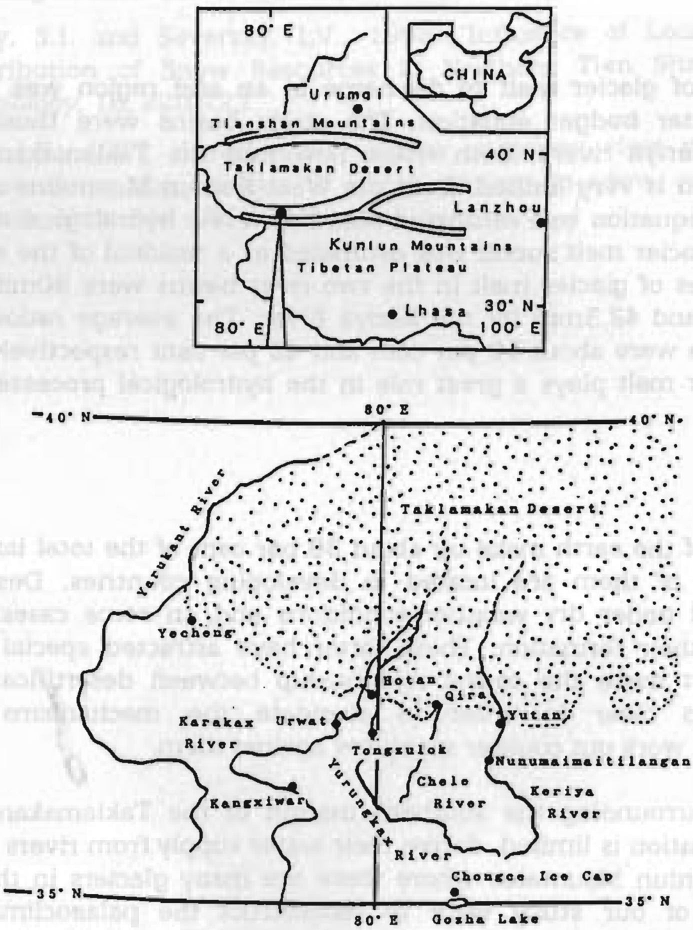


Figure 1: Location Map of the Study Basins

Records of hydro-meteorological variables have been measured for 35 years at the hydrological stations of Tongguzlok on the Yurungkax River and Nunumaimaitilangan (Langan) in the Keriya River basin. The mean annual precipitations over 35 years at Tongguzlok and Langan are 54mm and 123mm

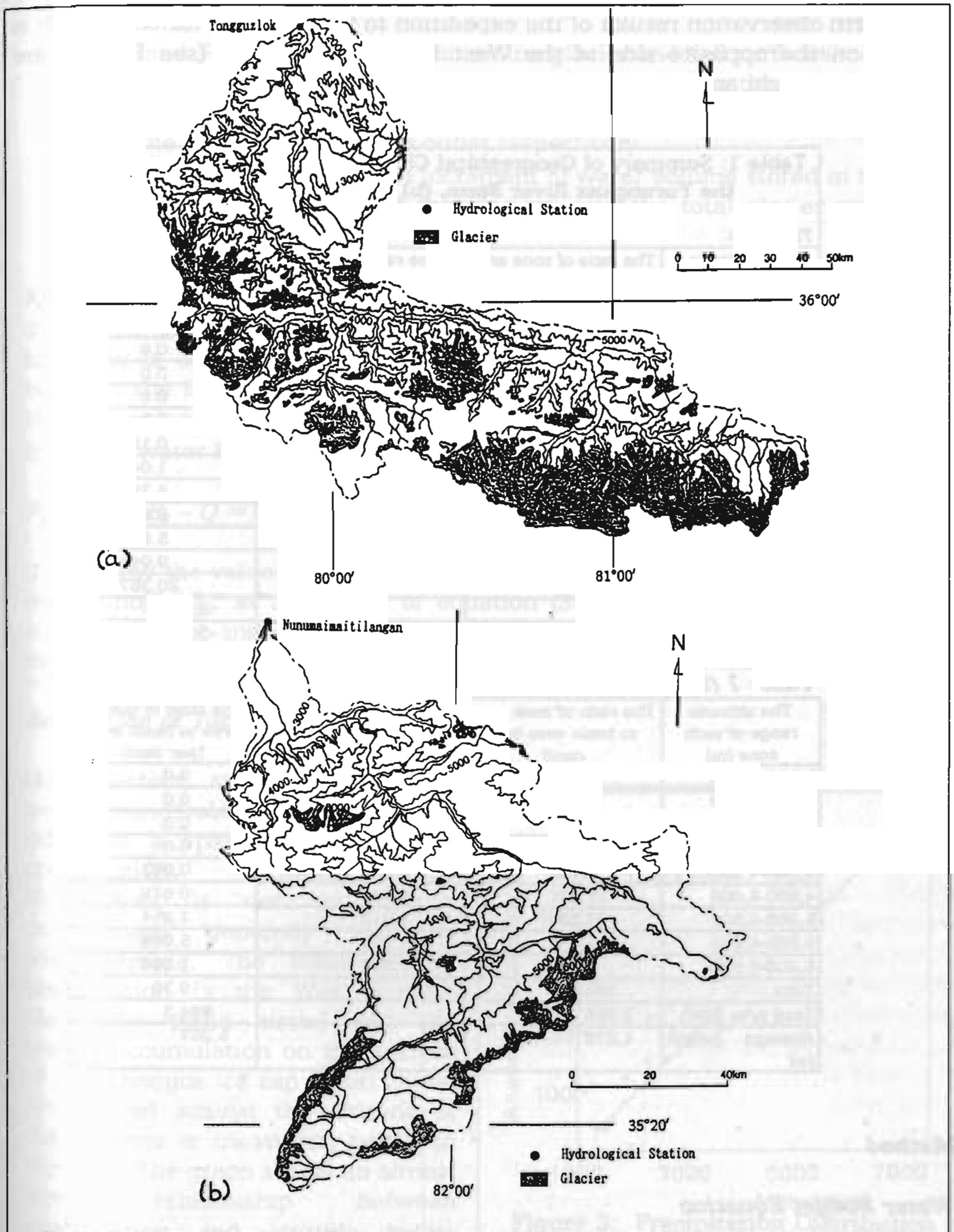


Figure 2: Maps View of the Basins. (a) Yurungkax River, (b) Keriya River

respectively. Precipitation generally increases with altitude, although the weather conditions of these basins are very dry. Few meteorological elements from the stations on the edge of the basins, Hotan and Kangxiwar, are available (see Fig. 1). We used the precipitation and air temperature data measured at Hotan meteorological station mainly because of their accuracy. Although no systematic data have been collected in the alpine zone of the two basins, the short-term observation results of the expedition to the Chongce ice cap, which is located on the opposite side of the West Kunlun Mountains (see Fig. 1), are available (Higuchi and Xie 1989).

Table 1: Summary of Geographical Characteristics of the Basins: (a) the Yurungkax River Basin, (b) the Keriya River Basin

Table 1(a)

The altitude range of each zone (m)	The ratio of zone area to basin area (per cent)	The ratio of glacier area to zone area (per cent	The ratio of glacier area to basin area (per cent)
1,500-2,000	0.184	0.0	0.0
2,000-2,500	3.512	0.0	0.0
2,500-3,000	6.207	0.0	0.0
3,000-3,500	9.831	0.0	0.0
3,500-4,000	7.156	0.0	0.0
4,000-4,500	6.378	2.87	0.183
4,500-5,000	12.580	8.27	1.049
5,000-5,500	24.163	18.18	4.393
5,500-6,000	20.131	44.18	8.894
6,000-6,500	9.686	59.92	5.804
6,500-7,000	0.072	61.11	0.044
Total	100.0		20.367
Total area (km^2)	14,575		2,968.5
Average height (m)	4,750		5,722

Table 1 (b)

The altitude range of each zone (m)	The ratio of zone area to basin area (per cent)	The ratio of glacier area to zone area (per cent)	The ratio of glacier area to basin area (per cent)
2,000-2,500	1.571	0.0	0.0
2,500-3,000	3.072	0.0	0.0
3,000-3,500	4.759	0.0	0.0
3,500-4,000	3.293	0.0	0.0
4,000-4,500	7.145	0.009	0.063
4,500-5,000	25.122	2.464	0.619
5,000-5,500	37.690	4.919	1.854
5,500-6,000	15.790	32.096	5.068
6,000-6,500	1.548	71.318	1.104
Total	100.0		9.30
Total area (km^2)	7,358		684.3
Average height (m)	4,878		5,267

Method

Water Budget Equation

The water budget equations of a basin which has many glaciers are written as

$$P_G + P_S - E_G - E_S - Q = \Delta S + \Delta G \quad (1)$$

$$\Delta G = P_G - G_M - E_G \quad (2)$$

where,

P_G and P_S are the precipitation on the glacier and soil surfaces,

E_G and E_S the evaporation and/or sublimation from the glacier and soil surfaces, and

Q the outflow at the basin outlet respectively.

ΔS, ΔG and G_M denote the increment of water volume stored in the basin, the net mass balance of the glaciers, and the total glacier melt runoff respectively.

Although it is difficult to assess directly the term ΔS, it is negligible when the discharges at the beginning and end of a hydrological year are close, since the low flow is a function of the basin storage, S. The differences in discharge between the beginning and end of hydrological years are small in both basins. Hence, neglecting ΔS and substituting equation (2) into equation (1), we get the following water budget equation (3):

$$P_S + G_M - E_S - Q = 0 \quad (3)$$

If we know the values of the terms, P_S, E_S and Q, we can assess the total glacier melt runoff, G_M, as a residual of equation (3). As described before, however, since no hydro-meteorological data have routinely been measured in high mountain areas, we estimated P_S and E_S using the methods described below.

Estimation of Total Precipitation on Soil

Many factors, such as topography and meteorological conditions, influence a spatial distribution of precipitation. Although the distribution is not so simple, precipitation generally increases with altitude. The mean annual precipitation in the West Kunlun Mountains (solid circle) and the annual accumulation on the surface of the Chongce ice cap (open circle) are plotted against the altitude of the stations or measuring points in Figure 3. The graph shows an almost linear relationship between precipitation and altitude below 4,000m. The open circles are far from the line because of the water loss due to evaporation and sublimation. When we consider that the loss ranges from 150mm to 250mm, the circles are seen to be

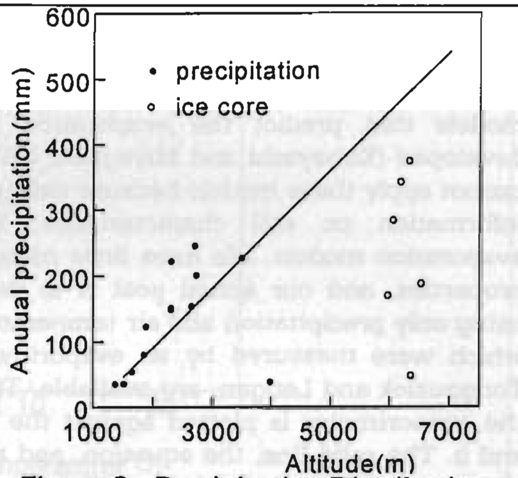


Figure 3: Precipitation Distribution in the West Kunlun Mts. (Solid circles denote the Mean Annual Precipitation and open circles the annual accumulation at the surface of the Chongce Ice Cap.)

close to the line, and we can extrapolate the precipitation in the alpine zone based on the same relationship at low altitudes. Hence the mean annual precipitation in the West Kunlun Mountains is obtained by

$$P_Z = 0.09\,(Z - 1{,}300) + 28 \qquad (4)$$

where,
P_Z is the mean annual precipitation at height Z.

Assuming that the variation in annual precipitation at any altitude is the same as that of Hotan, and using monthly data at Hotan and equation (4), we estimated the monthly precipitation by

$$P_{zip} = r_1 \quad (1 + r_2) \quad P_{oj}$$

where,

$$r_1 = P_z / P_{om}, \qquad r_2 = C_r \; (P_{oi} / P_{om} - 1)$$

P_{zij}, P_z, P_{om} and P_{oi} being respectively the precipitation at the height Z in metres in the j-th month and i-th year; the mean annual precipitation at an elevation of Z in metres; the mean annual precipitation at the standard meteorological station, Ḥotan; and the precipitation at Hotan in the i-th year. C_r is the coefficient of variation of the j-th month at Hotan.

Estimation of the Total Amount of Evaporation from Soil

As mentioned above the two basins are in an arid region, so that evaporation can be considered as one of the dominant factors in the hydrological process. Various models that predict the evaporation from a bare soil surface have been developed (Kobayashi and Miyagawa 1991; Kondo 1993a; 1993b). However, we cannot apply these models because they require many meteorological factors and information on soil characteristics. Moreover, they are hourly or daily evaporation models. We have little meteorological data and information on soil properties, and our actual goal is to develop the monthly hydrological model using only precipitation and air temperature. Fortunately some evaporation data, which were measured by an evaporimeter over 2,000cm^2 of surface area at Tongguzlok and Langan, are available. The monthly amount of evaporation from the evaporimeter is plotted against the monthly air temperature in Figures 4a and b. The solid line, the equation, and r indicate a regression line, a regression equation, and a correlation coefficient respectively. Both coefficients are high values, 0.896 and 0.927; hence we can estimate the total amount of monthly evaporation from the evaporimeter by using the following equations:

Yurungkax River, tongguzlok: $P_{pan} = 8.7\ T_Z + 31.4$ (6)

Keriya River, Langan: $P_{pan} = 8.42\ T_Z + 77.4$ (7)

where,
P_{pan} is the evaporation from the evaporimeter, and
T_Z the monthly air temperature at height Z in metres. However, the evaporation measured by the evaporimeter is not the loss of water from soil surfaces but from a water surface.

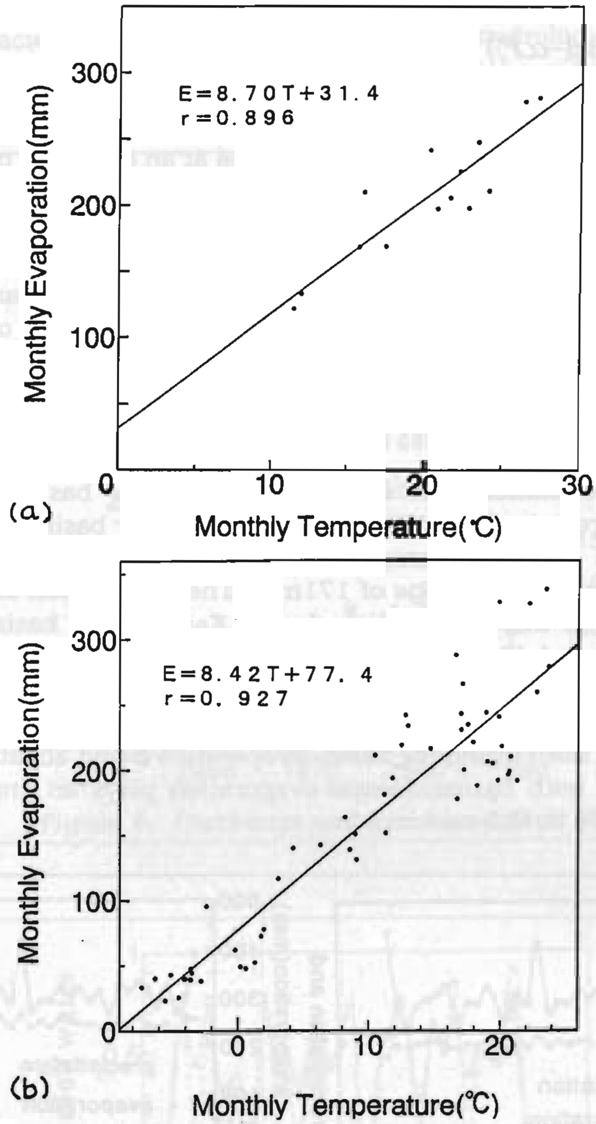


Figure 4: The Relationship between Monthly Evaporation and Air Temperature
a) Tonggzulok, b) Langan

The evaporation from bare soil was measured near the Chongce ice cap (5,260m) from 17 July to 23 August in 1987 when a joint Sino-Japanese glaciological expedition to the West Kunlun Mountains took place (Takahashi et al. 1989). The total amount of evaporation during the 38-day period, in which the mean air temperature was 2.54°C, was 51.6mm, and the daily mean value 1.36 mm/day. The evaporation is about 0.4 times as much as the estimated evaporation from the evaporimeter using equation (5). The evaporation from soil generally depends not only on meteorological conditions but on soil moisture. Taking into account these facts, we estimated evaporation from the soil by the following equation:

$$E_z = C_E E_{pan}, C_E = 1-\exp(-\alpha P_z) \quad (8)$$

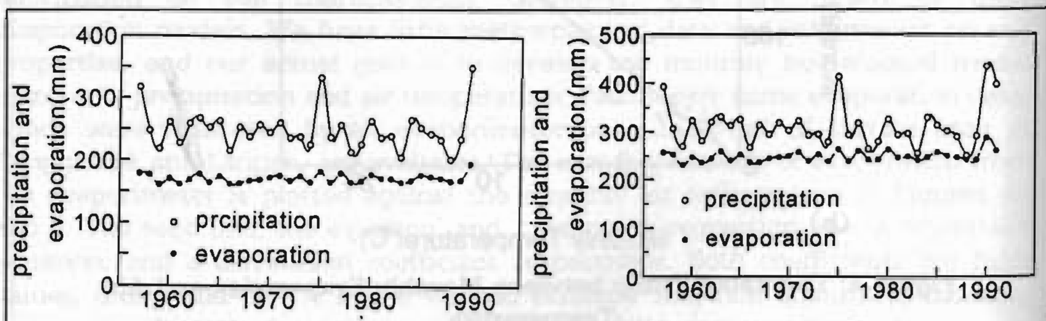
where,

E_Z is evaporation from the soil in the zone at an elevation of Z in metres
α (=0.0061) constant value, and
P_Z the precipitation in the zone.

When we calculated the total amount of precipitation on soil and evaporation from the soil surface, we divided each whole basin into 10 or 11 zones at intervals of 500m (see Table 1).

Results and Discussion

The estimated precipitation and evaporation over the basins are shown in Figures 5a and b. Precipitation over the Yurungkax River basin is in the range of 200mm to 350mm with an average of 250mm; evaporation in the range of 160mm to 196mm with an average of 171mm. The evaporation attains values of around 70 per cent of the precipitation. In the Keriya River basin, precipitation varies between 250 and 433mm, with an average of 311mm. The average value is about 60mm greater than that of the Yurungkax basin. Evaporation is in the range of 288 to 230mm, with an average of 249mm. The mean value is 80mm greater than that of the Yurungkax basin, evaporation being about 70 per cent of the precipitation in both basins. Hence evaporation plays an important role in the hydrological cycle in this arid region.



Yurungkax River Basin   Keriya River Basin

Figure 5: Estimated Precipitation and Evaporation over the Basins

The estimated annual total amount of glacier melt water is compared to the discharge in Figures 6a and b, and the ratios of glacier melt to discharge are shown in Figure 7. In the Yurungkax River basin, the average value of the melt water, 80mm, is about double that of the Keriya River, 42.3mm. The mean value of the melt water ratio in the Yurungkax River is about 50 per cent and ranges from approximately 30 to 80 per cent, with a few extraordinary values. In the Keriya River basin the contribution rate of melt water ranges from 20 to 90 per cent, with an average of 42.7 per cent, with a few extraordinary values. The averages of the ratio of melt water are slightly smaller than the results throughout the expedition (Cao and Ai 1989; Ai, 1989). It has been shown that the role of glacier melt is very important in the hydrological processes in this arid region.

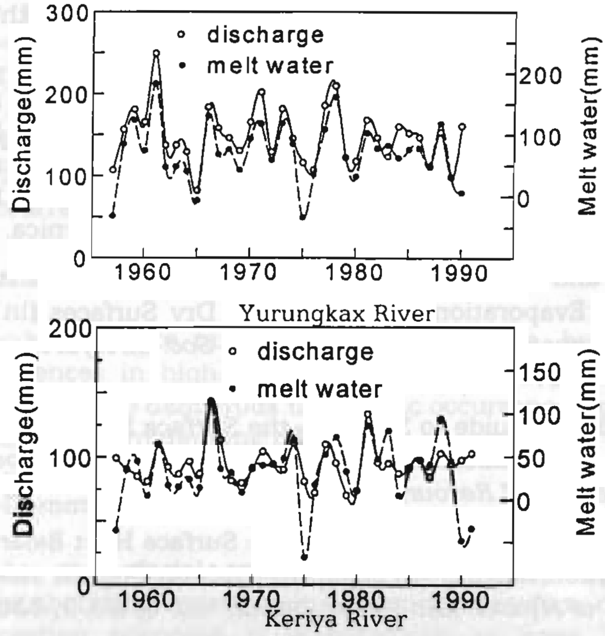


Figure 6: Discharge and Estimated Melt Water

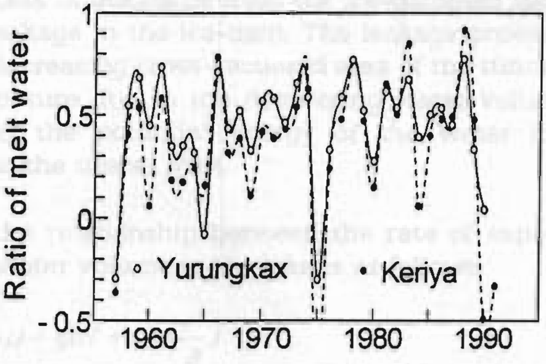


Figure 7: Contribution of Glacier Melt Water to the Total Discharge

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