Annals of Glaciology 16 1992

Study of glacier meltwater resources in China

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ABSTRACT. Glacier meltwaters are an important component of surface water resources in western China. Based on glacier inventories, the total glacier area in China is 5.87 × 10^4 km^2, the second largest for an Asian country. The total storage of water in glaciers is about 5132 × 10^3 km^3, and the mean annual amount of glacier melt runoff is about 5.64 × 10^{10} m^3, or 2% of the total surface water resources of China. From the late 1950s to the present, measurements have been undertaken of about twenty mountain glaciers, and data on hydrology and meteorology obtained. The relationship between heat balance and glacier ablation has been investigated but for glacierized areas where there are no data, ice-melt runoff can be estimated from climatic data. Runoff of glacier meltwater decreases with increasing aridity of the climate. The impact of glacier meltwater on the regimes of mountain streams in different environments are described in this paper.

INTRODUCTION

Studies of glacier water resources for agricultural water supply were first carried out in 1958 in western China. Glaciers in the Qilian mountains were investigated and a field station was established between 1958 and 1962 at Lauhugao Glacier in the western Qilian mountains. Later, a station was established at Ürümqi Glacier No. 1 in the eastern Tien Shan mountains (1959 to 1966, 1980 to present). This is the only station at which long-term multiscientific measurements have been achieved at an alpine glacier in China. Based on

Table 1. Basic characteristics of different types of glaciers in the mountainous areas of western China

	Type of glacier		
	Continental	*Sub-continental*	*Maritime*
mean annual precipitation at ELA (mm)	300 to 700	700 to 1200	1200 to 3000
mean annual air temperature at ELA (°C)	−15.0 to −9.0	−5.0 to −9.0	about −4.0
temperature in glaciers (°C)	−12.8 to −5.0	−1.0 to −5.0	0
glacier flow velocity (m a^{-1})	10 to 30	30 to 100	> 100
glacier terminus elevation (m)	4000 to 5000	spread to forest belt	2400 to 3000
period of glacier ablation (d)	~150 (May–September)	~180 (May–October)	~210 (April–October)
glacial meltwater runoff (mm)	200 to 600	~700 to 1000	> 1000

hydrometeorological measurements at permanent and semi-permanent stations, and on glacier inventories, estimation of glacial water resources in China was carried out in the 1980s. This paper attempts to use the regional trend of specific discharge from glaciers to estimate such runoff where there are no direct measurements, and to describe the compensating effect of glaciers on runoff in mountain streams.

GLACIERS IN CHINA

Excluding the polar regions, glaciers cover $2.24 \times 10^5 \text{km}^2$ of the Earth's surface. About 26% ($5.87 \times 10^4 \text{km}^2$) of their area is located in China. Thousands of small glaciers occur over an extensive area that spans about 2700 km from east to west (103°45′ to 73°55′ E), and about 2400 km from south to north (27° to 49° N). All are found in high mountains and plateaus in western China, and most are valley glaciers. The glaciers can be classified into three types, depending on climatic, thermal and physical characteristics. Most glaciers belong to the continental type, while sub-continental and maritime types occupy only a small area. The continental-type glaciers occur in arid and semi-arid climatic regions which experience lower air temperatures and receive less precipitation than the maritime-type glaciers which are located in areas with moist climate, with abundant precipitation nourishment and higher air temperatures. The flow velocity of continental-type glaciers, in general, is much lower than that of the maritime type (Shi and Xie, 1964; Shi and Li, 1981; Li and Zhen, 1982; Huang and Sun, 1982; Xie and Zhen, 1982; Ren, 1988) and the yield of glacier meltwater runoff from continental-type glaciers is much smaller than from maritime-type glaciers (Yang, 1991) (Table 1).

GLACIER ABLATION

Heat sources for glacier melt

The main heat source for glacier ablation is net radiation, accounting for 60.5 to 92.1% of the total budget. Sensible heat can contribute from 6.6 to 35%. The latent heat is usually considered to be small (Zeng and Dong, 1966; Zeng and Kou, 1975; Xie and Cao, 1965). The composition of heat budgets has an obvious regional pattern. The radiation heat flux increases with increasing aridity, decreasing latitude and increasing altitude. For sensible heat, the opposite applies, because the influence of moist air from southeastern and southwestern monsoons becomes more important, and the percentage contribution of sensible heat increases (Table 2). Different glacier surface types (firn, ice–snow and debris-covered)

Table 2. The composition of heat balance in various glaciers during the ablation season

Source	*Glacier name*	*Location*		*Elevation*	*Ice surface*	*Period*	*Constitution of the total heat input*			*Constitution of heat output*		
		E	N	m			%			%		
							Net radiation	*Sensible heat*	*Condensation*	*Heat for ablation*	*Sensible heat*	*Evaporation*
Zeng and Dong, 1966	Qieerganbulake, Pamir, China	75°	38°	4750	firn	July–August 1960	92.1	7.9		58.5		41.5
Zeng and Kou Jouguam, 1975	Rongbu, Himalaya, Tibet	86°	28°	5440	debris	May 1960	89.5	2.5	8.0	33.0	42.8	15.9
Xie and Cao, 1965	Ürümqi Glacier No. 1, Tien Shan	87°	43°	3820	firn	June–August 1962	84.4	10.3	5.3	88.1		11.9
Wang and others, 1982	Shuiguanhe Glacier No. 4, Qilian	102°	37°	4200	ice–snow	August 1963	82.7	14.3	3.0	90.5		9.5
Wang and others, 1982	Guxiang Glacier No. 3, Nianqintangula	96°	30°	4400	ice–snow	July–August 1965	63.0	26.4	10.6	96.9		3.1
Kou and Zhang, 1985	Qiongtailan, Tien Shan, China	80°	42°	4000	ice	July 1978	59.0	36.0	5.0	82.0		18.9
					debris		73.0	23.0	4.0	41.0	30.0	29.0
Bai and Zhang, 1980	Batura, Karakoram, Pakistan	75°	37°	3368	debris	July–August 1974	89.2	8.7	2.1	83.3	1.0	11.1

influence heat budgets through different albedos (Zeng and others, 1984).

The relationship between glacier meltwater and radiation balance can be expressed as

$$Q = aQ_B^n, \quad (1)$$

where Q is the discharge from an experimental plot of ice surface ($m^3 s^{-1}$), Q_B is the radiation balance value ($MJ\ m^{-2} d^{-1}$), a is an empirical coefficient and n is an empirical exponent.

The relationship between ablation and air temperature

Although Equation (1) provides a useful relationship for estimating glacier meltwater runoff, the value of Q_B is difficult to obtain. Air temperature is often used as an index of energy balance for establishing an empirical relationship to estimate ablation of ice. The synthetic empirical equation can be approximated as follows:

$$A = \phi(T + 4.0)^{2.7}, \quad (2)$$

where A is glacier ablation rate (mm d^{-1}), T is air temperature (°C) at the median elevation of the glacier, and ϕ is a coefficient reflecting the influence of climatic conditions in different regions (Yang, 1981):

$$\phi = 0.382b^2 \quad (3)$$

in which $b = Q_B/Q_T$, where Q_B is the radiation balance and Q_T the total heat received during the melt season. It is similar to the method of estimating glacier ablation at the equilibrium line, proposed by Khodakov (1975). Where there is no direct measurement of air temperature on the glacier surface, air temperature gradient can be used and an approximate relationship is:

$$T = T_0 + H(\mathrm{d}T/\mathrm{d}H) - J_t \quad (4)$$

$$\log J_t = 0.281 \log L - 0.07. \quad (5)$$

T_0 is the air temperature (°C) at the meteorological station, H is the altitude difference (m) between the meteorological station and the median elevation of the glacier, $\mathrm{d}T/\mathrm{d}H$ is the air temperature gradient (°C 100 m^{-1}), J_t allows for the increase of air temperature gradient with elevation (Khodakov, 1975) and L is the glacier length (km).

Some estimates of ablation shown in Equation (2) are in close agreement with the results of measurements from ablation stakes (Yang, 1991).

GLACIER MELT RUNOFF

Characteristics of glacier melt runoff

For more then six months, air temperatures in high mountain areas remain below 0°C, until late spring or early summer, when they rise above 0°C. Snow on the glacier surface begins to melt in late April or early May on continental-type glaciers, and in early April on maritime-type glaciers. The melt is weak, and the melwater is absorbed in the snow layers. During the cold nights, the meltwater is refrozen and surface runoff is arrested. As the season advances, the melt increases to sustain continuous runoff on the glacier surface, forming a network of channels. In small glaciers of the continental type, such as in Ürümqi Glacier No. 1, the meltwater moves along the major channels which enter mountain streams directly. However, in larger glaciers, or maritime-type glaciers, much of the meltwater disappears through cracks and moulins, to emerge from under the terminus in one or more large streams. This outflow is sometimes maintained even during winter (Yang, 1988). Quntailan Glacier in Tien Shan (subcontinental-type) and Gongga Glacier in Henduan Shan (maritime-type) are such examples.

Synchronous co-variation between air temperature and meltwater runoff is more significant in continental- than maritime-type glaciers. Analysis shows the relationship between discharge and air temperature when there is no precipitation can be given as follows

$$Q = \alpha \exp(\beta T) \quad (6)$$

$$Q = a + bT + cT^2 \quad (7)$$

where Q is the glacier melt discharge ($m^3 s^{-1}$), T is mean air temperature (°C) on the glacier during the ice-melt period , and α, β, a, b, and c are empirical coefficients (Kang, 1983; Hu and Li, 1989; Yang, 1988).

The compensating effect of melt runoff

Most mountain streams in western China receive glacier meltwater. The percentage of glacier melt in runoff increases with increasingly arid climate. For example, in the internal drainage rivers of the Heshi region, from east to west, the percentage of glacier melt in runoff increases from 4 to 32%. During dry warm summer periods with scarce precipitation, large percentages of glacier meltwater augment low flow. When abundant precipitation with low air temperature occurs, generally it has a negative influence on glacier melt runoff. In streams dominated by glacier melt runoff, the coefficient of variation of mean annual runoff ($C_v = 0.10$ to 0.20) is smaller than that of rain- or snow-fed streams ($C_v = 0.20$ to 0.45).

GLACIER MELTWATER RESOURCES

The main problem in estimating the amount of glacier meltwater runoff is the lack of hydrometeorological data. Specific runoff from glaciers M_g($l\ s^{-1} km^{-2}$) has been obtained from several glacierized areas in China. As it has an obvious regional regularity, M_g can be estimated from glacierized areas without direct measurement as follows:

$$M_g = K\left\{M_{g_0} + \left[\mathrm{d}H_0\frac{\mathrm{d}T}{\mathrm{d}H} + \mathrm{d}T'\right]\frac{\mathrm{d}M_g}{\mathrm{d}T}\right\}, \quad (8)$$

where K is the modification coefficient of ablation area, $K = f_g/f_{g_0}$, f_g is the percentage of ablation area for the glacier where the specific runoff is to be determined, f_{g_0} is that for the glacier where the runoff (M_{g0}) has been measured, dH_0 is the difference in the elevation of the equilibrium lines between the two glaciers, dT/dH is the air temperature lapse rate, usually equal to 0.65°C per 100 m, dT' is the air temperature modification value owing to the climatic difference between two glaciers at the same elevation. dM_g/dT is the increment of M_g with air temperature, empirically found to be 5.0 l s^{-1} km^{-2} per °C.

For two glaciers located not only in the same climatic region, but also having similar equilibrium line altitudes, the equation reduces to

$$M_g = K(M_{g0}). \quad (9)$$

The difference in M_g is caused only by the difference in the percentage of ablation area.

Using Equation (8) the total volume of glacier meltwater (m^3) produced during the ablation season is

$$W_g = 86.4\, M_g\, t\, F_s\,, \quad (10)$$

where t is the melt period, about 150 days for continental-type glaciers, 180 days for subcontinental-type and 210 days for maritime-type glaciers. F_s is the glacier area (km^2).

The mean annual amount of glacier meltwater runoff in western China is estimated to be about 56.4 km^3 or 5.64 × 10^{10} m^3 (Table 3). It is about 10% of the total amount of runoff from all sources in the four provinces in western China.

Table 3. Glacier areas and annual meltwater runoff

No.	Mountains	Area of glacier km^2	Meltwater runoff 10^8 m^3	Ablation period
1	Altay	293.20	3.85	May–September
2	Tien Shan	9196.00	95.92	May–September/October
3	Qilian	1972.50	11.56	May–September
4	Kulun	12 482.20	62.98	May–September
5	Pamir	2992.85	17.05	May–September
6	Karakoram	4647.17	28.71	May–September
7	Qiangtang plateau	3108.81	16.03	May–September
8	Tanggula	2082.00	16.33	May–September
9	Gangdisi	1667.75	8.88	May–September
10	Nianqin-tanggula	7536.00	150.24	April–October
11	Hengduan	1617.62	51.16	April–October
12	Himalaya	11 055.00	100.71	May–September
	Total	58 651.10	563.42	

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