Study on the glacier variation and its runoff responses in the arid region of Northwest China *

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Abstract The glaciers in the arid region of Northwest China are viewed as an independent system, and glacier variation and mass balance fluctuation since the Little Ice Age and in the recent decades are estimated. Based on the estimation, the threshold time of glacier runoff against the backgrounds of the current and future varying climate conditions is simulated.

Keywords: glacier variation, mass balance, glacier runoff.

As a major component of water resources in the arid region of Northwest China, the glacier variation and its effect on runoff and river replenishment, as well as the increase or decrease in the amount of glacial water resources against the background of global warming, have become a focus of world attention. Therefore, the monitoring of glacier variations, analyzing of their responses to climate, estimating and predicting of the change of glacier runoff have a very important scientific and practical significance.

The correlation model between glacier, climate and runoff was established on the glaciers with a series of long-term observation data[1]. The application of the model to the research of glacier system, including drainage basins and districts, marks the development tendency of glaciology. Meanwhile, the estimation and prediction of glacier runoff also need systematic state data including glacier lengths, areas, mass balances and other elements.

Based on the estimation of glacier variations since the Little Ice Age and in the recent decades, with the arid region of Northwest China as an independent glacier system, the state of glacier runoff and its probable variation tendency are appraised in this paper, to provide a scientific basis for the rational utilization of glacier resources.

1 Glacier resources and their distribution

The arid region in Northwest China refers to the vast inland territory north of 35°N and west of 106°E. There, from north to south are successively distributed the Altay, Tianshan, Pamir, Karakorum, Kunlun and Qilian Mountains (fig. 1), which intercept a large amount of moisture carried by the westerly and South Asian monsoon, forming plentiful precipitation and numerous glaciers, and maintain the relative stability of river runoff.

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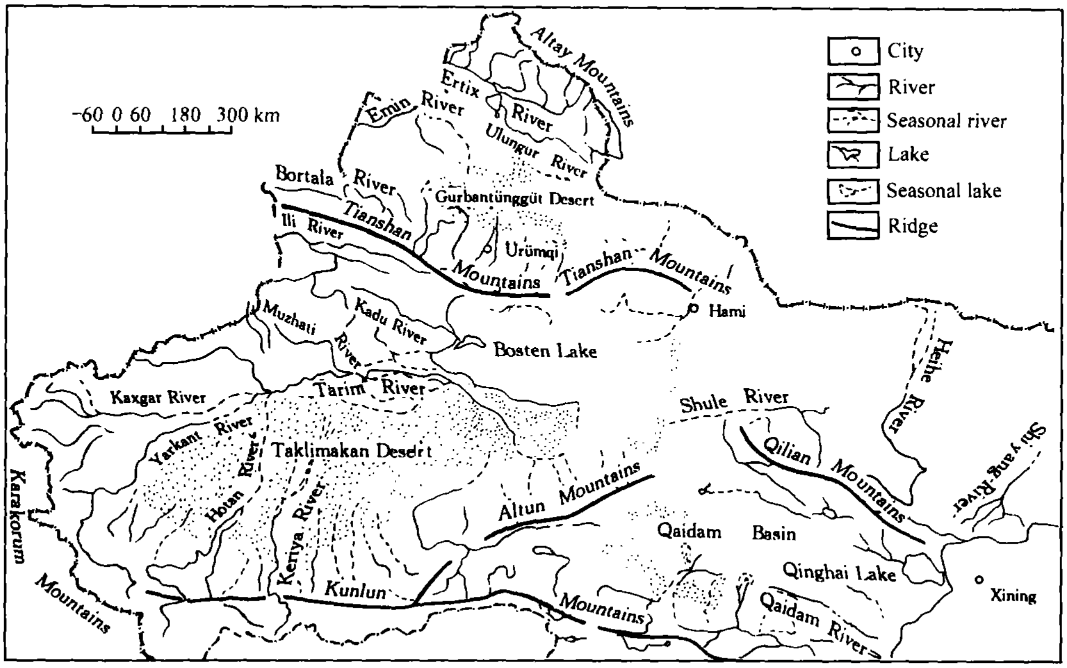

Fig. 1. Distribution of mountains and water systems in the arid region of Northwest China.

There are 22 699 glaciers in the arid region of Northwest China, with an area of 28 330.57 km^2 and an ice volume of 2 847.093 3 km^3[2], constituting 50.0%, 48.2% and 53.6% of the China's total. In all of the water systems the glacier number of the Tarim River ranks the first (table 1). Its annual glacier meltwater averages 202.26×10^8 m^3[3], accounting for 0.8% of the glacier volume (expressed by water equivalent) in the arid region of Northwest China.

Table 1 Distribution of glaciers of major water systems in the arid region of Northwest China

Water system	Number	Percentage	Area/km^2	Percentage	Ice volume /km^3	Percentage	Average area/km^2	Meltwater $\times 10^8/m^3$
Ertix River	403	1.78	289.29	1.02	16.395 3	0.58	0.72	3.62
Junggar Inland River	3412	15.03	2 254.10	7.96	137.241 9	4.82	0.66	16.89
Tarim Inland River	12 182	53.67	20 271.02	71.55	2 347.316 5	82.45	1.66	136.02
Ili River	2 373	10.45	2 022.66	7.14	142.179 1	4.99	0.85	26.41
Turpan-Hami Inland River	446	1.95	252.73	0.89	12.633 0	0.44	0.57	2.34
Hexi Inland River	2 194	9.67	1 334.75	4.71	61.549 4	2.16	0.61	9.99
Qinghai Inland River	1 581	6.97	1 865.05	6.58	128.528 0	4.51	1.18	6.31
Huanghe River (Datong River)	108	0.48	40.97	0.15	1.250 1	0.05	0.38	0.68
Total	22 699	100.00	28 330.57	100.00	2 847.093 3	100.00	1.25	202.26

The glaciers in the arid region of Northwest China are distributed in Xinjiang, Qinghai and Gansu, among which Xinjiang has 18 816 glaciers, of an area of 25 089.8 km^2 and an ice volume of 2 655.8 km^3, accounting for 82.9%, 88.8% and 93.3% of their totals respectively. The glaciers in Gansu and Qinghai are fewer smaller, but are of great significance to the water supply because they are located in the arid areas of Hexi Corridor and Qaidam Basin.

2 Glacier variations of one-hundred-year scale in the Little Ice Age

The Little Ice Age refers to a relative cold period estimated in terms of one-hundred-year scale in the recent several centuries, when the mountain glacier all over the world advanced and finally left behind 3 terminal ridges at their terminus. Their surface features, scale, weathering degree and vegetation are distinctively different from those of earlier times, so they can be used to reconstruct the glacier scale and their environment during that period.

Several representative glacier basins were selected from each mountain system to determine the length, area and other elements of glaciers of the Little Ice Age[4] and calculate their area (S_L) and variability ($\Delta S/S_L$) in accordance with area classes. Then the glacial scales of similar rivers and mountains at the height of the Little Ice Age were estimated using the obtained data (table 2).

Table 2 Glacier variations of major river basins since the Little Ice Age in the arid region of Northwest China

River	Mountain	Glacier area	Glacier area of the Little Ice Age	$S_L - S$	$\Delta S/S_L$ (%)
		S/km^2	S_L/km^2	ΔS/km^2	
Shiyang River	Qilian Mountains	64.82	103.49	36.87	37.4
Heihe River	Qilian Mountains	420.55	500.84	80.28	16.0
Shule River	Qilian Mountains	849.38	949.07	99.69	10.5
Hotian River	Kunlun Mountains	5 336.98	5 665.56	328.58	5.8
Yarkant River	Karakorum Mountains	5 924.85	6 530.38	605.53	9.3
Kaxgar River	Pamirs	2 247.28	2 513.23	265.95	10.6
Turpan-Hami Inland River	Tianshan Mountains	252.72	300.65	47.92	15.9
Aksu River	Tianshan Mountains	4 670.40	5 069.83	399.43	7.9
Ili River	Tianshan Mountains	2 022.66	2 446.73	424.07	17.3
Junggar Inland River	Tianshan Mountains	2 254.10	2 585.38	331.28	12.8
Ertix River	Altay Mountains	289.29	338.87	49.58	14.6
Total		24 333.04	27 004.02	2 670.99	9.9

Based on an estimation of 9.9% in variability, the glacier area at the height of the Little Ice Age was 31 443 km^2 in the arid region of Northwest China, which is 3 112 km^2 bigger than that of today. Since the Little Ice Age the variability of the glacier area has been shown a great difference from place to place. In the marginal mountains and regions with higher humidity, the glacier area fluctuated greatly, particularly in the Lenglong Ridge of the east Qilian Mountains. In addition, the variability decreased with increasing distance from the moisture source areas, with its minimum occurring in the western section of the Qilian Mountains and the West Kunlun Mountains. The glacier area variability of the representative drainage basins in the region shows a negatively exponential correlation with the median value of the glacier area class, suggesting that the glacier area variability decreases with increasing glacier area class. Therefore, it is quite practical to estimate the glacier area at the height of the Little Ice Age by the variability of glacier area class. However, if the estimation is carried out using a uniform variability within a drainage basin or mountain, the result will be overestimated[5].

3 Recent glacier changes

3.1 Recent glacier variation events

There were few glaciers monitored *in situ* in China. So a large number of data were derived indirectly from repeated measurement of the fixed marks at the end of glaciers, ground stereophotogrammetry, as well as repeated aerial photogrammetric mapping. Taking the Qilian Mountains and the Tianshan Mountains as examples, the variations of glacier area are described as follows.

3.1.1 The Qilian Mountains. Various measurement data obtained at the east, middle and west parts of the Qilian Mountains in the 1970s and mid-1980s showed that the glaciers retreated slower in the mid-1980s than in the mid-1970s (table 3), while the glaciers in the east part of the Qilian Mountains were still in retreat. The glaciers in the middle and west parts of the Qilian Mountains had turned to a stable state due to continuous reduction in temperature and concurrent increase in precipitation from the 1960s onwards[6].

Table 3 Recent variations of representative glaciers in the Qilian Mountains

Glacier	Length /km	Area /km²	Glacier type	Measurement period/a	Change of terminal			Change of area	
					m	m/a	(%)	km²	(%)
Shuiguanhe Glacier No. 4	2.1	1.86	Cirque	1956—1976	-320.0	-16.0	0.76	-0.2650	0.71
				1976—1984	-69.7	-8.7	0.47	-0.0142	0.10
"July First" Glacier	3.8	3.04	Cirque valley	1956—1975	-40.0	-2.1	0.06	-0.024	0.04
				1975—1984	-10.0	-1.1	0.03	-0.005	0.02
Laohugou Glacier No. 12	10.0	21.91	Valley	1962—1976	-71.8	-5.0	0.05		
				1960—1976				-0.131	0.04
				1976—1985	-11.7	-1.3	0.013	-0.007	0.003

3.1.2 The Tianshan Mountains. The variation data of Glacier No. 1 in the source area of the Urumqi River (hereinafter Glacier No. 1) indicate that the retreat of Glacier No. 1 has speeded up since the Little Ice Age; particularly from the early 1970s to the early 1980s, the glacier area shrank by 0.007 6 km² per year. This period is the fastigium of glacier recession. Observations in recent few decades show that before the 1970s the glacier varied greatly at an average retreat rate of 6.0 m per year. Afterwards, the recession became somewhat slow, but in the 1990s it has speeded up again.

The glacier variation data of the Urumqi River obtained from 1964 to 1992 aerial photogrammetric mapping show that all the 155 glaciers were in retreat, and the glacier area and ice volume decreased simultaneously[7]. During the period, the glacier length shortened by 12.4%, or 98 m, averaging 3.5 m per year, and the glacier area shrank from 48.04 km² in 1964 to 41.393 km² in 1992, at a shrinkage rate of 13.8%. Meanwhile, the ice volume decreased by 2.8×10^8 m³, or 16.8%. Simultaneously, the glacier surface altitude dropped by 5.9 m, the ablation area thinned averagely by 10.2 m, and the equilibrium-line altitude (ELA) uplifted by 30 m on an average.

By repeated aerial photogrammetric mapping of four mountainous glacier drainages, we acquired the variation data of 30 glaciers from 1962 to 1990 in the Sikeshu River, situated on the northern slope of the Boluokenu Range, in the west part of the north Tianshan Mountains, which indicate that one of them advanced about 35 m, three of them maintained stable, and others were all in retreat (table 4).

All the observed 64 glaciers in the Kashi River retreated averagely 149 m in length, with a variability of 7.0%, their area shrinking by 4.809 km², the equivalent of 3.5% of the glacier area of 1962 (table 5).

Table 4 Recent variation in the Sikeshu River

Coding	Drainage Basin	Number	Change of glacier terminal			Change of glacier area			
			m	m/a	(%)	area/km^2		km^2	(%)
						1962	1990		
5Y742B	Dongduguole	3	- 170	- 6.0	4.8	13.504	13.076	- 0.428	3.2
5Y742C	Haxiatingguole	10	- 131	- 4.7	5.7	38.988	38.198	- 0.790	2.1
5Y742F	Dongduguole	11	- 153	- 5.4	5.0	27.705	26.698	- 1.007	3.6
5Y742G	Xibaiti	6	- 131	- 4.7	4.1	22.018	21.566	- 0.452	2.1
Total		30	- 140	- 5.0	4.9	102.215	99.538	- 2.677	2.6

Table 5 Recent variation in the Kashi River

Code	Drainage Basin	Number	Change of glacier terminal			Change of glacier area			
			m	m/a	(%)	area/km^2		km^2	(%)
						1962	1990		
5X043H	Aleshalang	12	- 149	- 5.3	6.5	27.430	26.330	- 1.100	4.0
5X043I	Tulugenqiagan	13	- 166	- 6.1	6.9	25.499	24.442	- 1.057	4.1
5X043J	Aersangsayi	10	- 150	- 5.4	6.0	40.021	39.154	- 0.867	2.2
5X043K	Teliansayi	17	- 146	- 5.2	7.6	36.024	34.753	- 1.271	3.5
5X043L	Mengkedesayi	12	- 130	- 4.7	7.0	9.681	9.167	- 0.514	5.3
Total		64	- 149	- 5.3	7.0	138.655	133.846	- 4.809	3.5

Xitailan Glacier, rising at the Tumur Peak, is a dendroid glacier with an area of 108.15 km^2 and an ice volume of 22.23 km^3. The glacier retreated 600 m from 1942 to 1976, averaging 17.6 m/a[8]. Ground stereophotogrammetry conducted in 1997 once again indicated that the glacier is still retreating at an annual rate of 17 m and its area has shrunk by 0.374 km^2.

As described above, the glaciers grew in number and in in the Tianshan Mountains are tending to shorten in length, shrink in area and reduce in ice volume. From the late 1950s to the early 1970s, retreating glaciers grew in number and in magnitude. The retreat rate, however, slowed down from the early 1970s to the late 1980s, but went up again in the 1990s.

3.2 Estimation of recent glacier variation

The relationships between glacier scale and development conditions are similar in the Little Ice Age and modern times. Development conditions of glaciers in the Little Ice Age such as altitude, moisture source and atmospheric circulation patterns are roughly similar to those of today. So the ratios of glacier variations in similar areas are stable. The glacier retreat regimes since the 1960s can be estimated by the following equations:

$$\frac{a_i}{a_b} = \frac{A_i}{A_b}, \tag{1}$$

$$\bar{a} = \frac{1}{S}\Sigma a_i \cdot s_i, \tag{2}$$

where a_i and a_b are the annual variability of each glacier area class of the analogized and the standard drainage basins, respectively, A_i and A_b are the variability of the same area class of analogized and standard drainage basins since the Little Ice Age, S is the total glacier area of the statistic region, and s_i is the glacier area of each area class.

The glacier area of the region reduced by 1 338 km^2 in the recent 35 years, which constitute 4.9% of the total existing glacier area. The highest area variability occurred in the west Tianshan Mountains and the east part of the Qilian Mountains with a relatively humid climate, and the variability decreased with increasing continentality and distance from moisture source areas, its minimum occurring in the west part of the Qilian Mountains and the West Kunlun Mountains.

4 Variation of glacier runoff and its trend prediction

4.1 Modeling principle and method

When a glacier is in the stable state (namely the mass balance is 0), the glacier meltwater discharge (R_0) is the product of runoff depth (r_0) and the glacier area (S_0):

$$R_0 = r_0 \cdot S_0. \tag{3}$$

The glacier runoff in the stable state is equal to the total accumulation or ablation, which could be expressed by the mean value of the sum of the long-term total accumulation ($\bar{C}$) and total ablation ($\bar{A}$):

$$r_0 = \frac{1}{2}(\bar{C} + \bar{A}). \tag{4}$$

When the glacier ablation increases due to air temperature rise, the negative mass balance will increase correspondingly[9], and so will the same value increment in the glacier runoff depth (r_d). Meanwhile, the glacier area (S_d) will shrink due to the mass deficiency. Then the glacier runoff (R) will be

$$R_0 = (r_0 + r_d)(S_0 - S_d). \tag{5}$$

When a glacier returns to its initial state (point $R = R_0$ is defined as the threshold state of its runoff), the variables r_d and S_d for eq. (5) are, respectively,

$$r_d = \frac{r_0 S_d}{S_0 - S_d}, \tag{6}$$

$$S_d = \frac{r_d S_0}{r_0 + r_d}. \tag{7}$$

By influencing the location of ELA, the variations of temperature and precipitation change the glacier mass balance, resulting in variations of glacier length and area. Then the two-dimensional variables of glacier mass balance and area can be used to estimate the change of glacier runoff and the time required to reach the threshold state.

4.2 Variation of glacier runoff

If the current climate keeps unchanged, i.e. r_d and the area variability of a glacier remain constant, the time required for the glacier to reach the threshold state is quite different for different states and dimensions of glaciers. Among the selected 5 glaciers, the Laohugou Glacier No.12, located in the west part of the Qilian Mountains, took as long as 349 years to reach the threshold state. However, the Shuiguanhe Glacier No.4, situated in the east part of the Qilian Mountains, has long reached its threshold state (table 6). From this it can be seen that the time required for the glacier to reach the threshold state increases with increasing S_0, but decreases with increasing r_0 and r_d. Owing to the strong influences of glacier variability, the time to reach the threshold state is short in marginal humid mountains with higher variability, but comparatively long in arid inland mountains with lower variability. According to mass balance level (m), mass balance variation magnitude since the 1960s (b_n), glaciation energy (E_g), glacier area variability, etc. The glaciers in the arid region of Northwest China are divided into the following three zones.

Table 6 Runoff change for representative glacier in the current climate state

Glacier	Mountain	Geographical location	r_0 /mm	S_0 /km^2	R_0 $\times 10^8$/m^3	r_d /mm	S_d /km^2	Area shrinkage /km$^2 \cdot$a^{-1}	Time to reach threshold state/a
Xitailan	Tianshan	41°57′N;80°10′E	1415	108.15	1.530	+262	16.90	0.151	112(2 084)
Glacier No.1	Tianshan	43°07′N; 86°49′E	638	1.95	0.012	+136	0.343	0.004	86(2 050)
Laohugou Glacier No.12	Qilian	39°26′N;96°12′E	641	21.91	0.140	−75	2.90	0.008 3	349(2 305)
"July First"	Qilian	39°14′N;99°45′E	577	3.04	0.018	−21	0.115	0.001 1	105(2 061)
Shuiguanhe Glacier No.4	Qilian	37°33′N;101°45′E	1 153	1.86	0.021	+88	0.132	0.013 6	10(−)

Zone I (the active glacier zone). This zone includes the east part of the Qilian, West Tianshan and Altay as well as other marginal mountains. The various glacier activity indexes are high. Their mean values are listed in table 7.

Table 7 Glacier active zones and their runoff state

Zone number	Zone	S_0/km^2	m/m	E_g /mm·m^{-1}	b_n/m	$\Delta S/S \cdot a$ (%)	R_0 $\times 10^8$/m^3	R $\times 10^8$/m^3	Time to reach threshold state/a
I	active zone	7 088.14	1.2	≥6.0	−0.20	0.19	85.06	92.63	75(2 035)
II	less active zone	11 072.17	0.8	3.5—5.0	−0.15	0.15	88.58	99.66	105(2 065)
III	least active zone	10 170.26	0.5	≤3.0	±0.05	0.08	50.85	54.37 ~44.48	113—138 (2 073—2 098)

Zone II (the less active glacier zone). This zone includes the Heihe River, Kaxgar River, Yarkant River, and other inland rivers in Junggar and Turpan-Hami basins, etc. Their activity indexes are lower than those of zone I.

Zone III (the least active glacier zone). This zone comprises the west part of the Qilian Mountains and the Kunlun Mountains. Glaciers in this zone are characterized by low-level mass balance and alternative occurrence of positive and negative mass balance, with a lower mass balance change range, lowest glaciation energy and smallest average area variability.

4.3 Trend prediction of glacier runoff variation

Annual precipitation and summer mean temperature are two major climate factors affecting the glacier state and runoff, but their variation and range are indefinite. According to the prediction by Intergovernmental Panel on Climate Change (IPCC) (1992), the global air temperature will rise by 0.3℃ every 10 years in the next century[10]. By 2 030 or 2 050, the temperature will be 1℃ higher than at present. Because the fluctuation range of average temperature in summer (T_s) is much lower than that of a year (T_a), i.e. $T_s = 0.4 T_a$[11], the rise of average annual temperature can be converted to an increment of average temperature in summer; thereby ELA, mass balances, glacier areas and other variables of the representative glaciers and various glacier zones could be estimated. With the above parameters as variables and using the above-metioned method, we could estimate the glacier discharges and its time to reach the threshold state.

For the analyzed 5 glaciers the response time lengths of their runoff to air temperature rise are different. The huge Xitailan glacier's runoff will reach its maximum at the end of the next century when the summer mean temperature increases by 1.2℃. Afterwards, the runoff will reduce gradually with continual rise in temperature, reaching its threshold state at the beginning of the 22nd century. Similarly, the time for the runoff of Laohugou Glacier No.12 to reach the threshold state will be at least 100 years later. However, the discharge of the Shuiguanhe Glacier No.4 will decrease heavily as air temperature rises.

For all the glacier zones in the arid region of Northwest China all feature the time to reach the threshold state will shorten as temperature rises. In the active glacier zone the glacier runoff will reach the threshold state at the beginning of the next century, but it will vary considerably with glaciers of different sizes in the region. for giant valley glaciers exceeding 100 km^2, the time to reach the threshold state will be at the end of the next century. In the least active glacier zone the time for glacier runoff to reach the threshold state will be the longest.

Glaciers developed in the arid region of Northwest China all feature high altitude, lower mass balance level, and moderate variations in length and area. The time for their runoff to reach the threshold state is relatively long; even in the active glacier zone, their activity indexes are much lower than those in Alps. From this we conclude that glaciers in Northwest China are more stable than those in other regions of the world, and the influence of glacier variations on the runoff is relatively small.

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