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Estimation of glacial runoff to the Tarim River, central Tien Shan

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Abstract Regional-scale statistical relationships linking key meteorological variables (i.e. temperature, solar radiation, albedo) and physiographic variables (i.e. elevation, aspect, slope, moraine thickness) to glacier runoff were obtained from long-term data (1936–1990) and three years of expeditionary observations on the glaciers of central Tien Shan. The Pobeda-Khan Tengry glacier massif in the central Tien Shan, the West Kun Lun glaciers, and the Chogori (K-2) glacier massif in Karakorum are the major sources of water to the Tarim River basin, where 36% to 64% of total river runoff has been contributed by these glaciers. Mean annual runoff from the Pobeda-Khan Tengry glaciers was determined at 1053–1081 mm year^{-1}.

INTRODUCTION

The Tarim River basin, one of the world's largest closed drainage hydrographic systems, has no significant lakes and appears to be a large sink for atmospheric moisture. The central Tien Shan, Kun Lun, Eastern Pamir and Karakorum mountains surround the Tarim River depression and contain more than 6000 glaciers. The major tributaries of Tarim River are the Aksu, Yarkend, Hotain and Muzart rivers (Fig. 1). However, only the Aksu River holds runoff the year round; water from other tributaries flows only during the spring–summer floods. The purpose of our study was to employ physical approaches to estimate annual glacier-melt runoff from the data available for the Pobeda-Khan Tengry massif, central Tien Shan.

MEASUREMENTS AND DATA COLLECTION

The Inylchek Glacier covers all glacial zones of this massif from 2900 to 7400 m a.s.l. A detailed description of field measurements and observations is presented by Aizen *et al.* (1997). Statistical analysis of long-term average meteorological conditions in this region is based on long-term data from the Tien Shan station, located 150 km west of the glacier massif. In the summers of 1989, 1990 and 1992 we conducted observations on the Inylchek Glacier located at the centre of the Pobeda–Khan Tengry massif. We also used meteorological data from four other stations, snow surveys and precipitation sites at altitudes between 2200 and 4400 m.

METHODS OF CALCULATIONS

Topographic maps (1:25 000) and aerial photography were used for the calculation of the glacial area in the Pobeda-Khan Tengry massif that was divided into 25

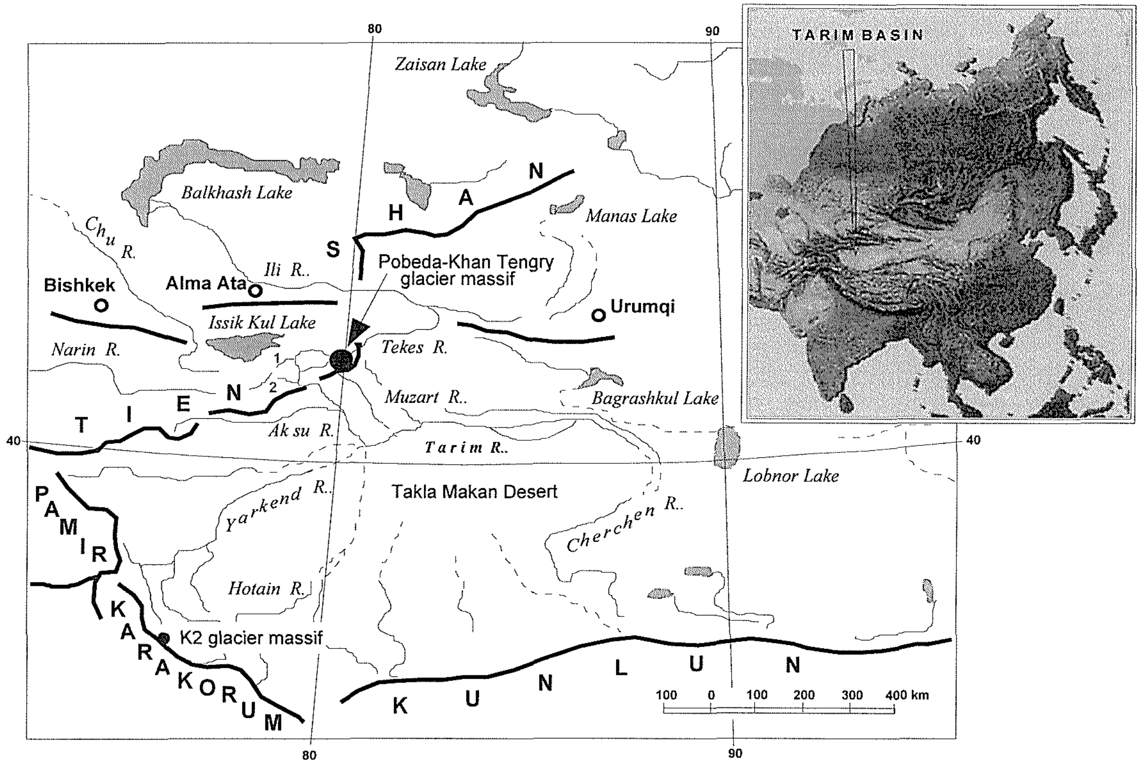

Fig. 1 Tarim River basin. 1 is Koilu River; 2 is Akshiirak River.

altitudinal zones, which, in turn, were spatially subdivided into pixels having similar topographic parameters (Fig. 2(a)). The 1178 glaciers in the Pobeda-Khan Tengry massif comprise an area of 4300 km^2. Annual runoff from glaciers, R_g (mm year^{-1}) is described as:

$$R_g = P + W \pm E - J \tag{1}$$

where P is liquid precipitation, W snow/ice melt, E evaporation or condensation, and J repeated ice formation. The volumes of precipitation P'_Σ (m^3 year^{-1}) were calculated as:

$$P'_\Sigma = 10^3 \sum_{i=1}^{n} (P_i F_i) \tag{2}$$

where P_i (mm year^{-1}) is mean precipitation in i altitudinal zone calculated on the basis of mean precipitation at Tien Shan station and altitudinal gradient of precipitation (reported below), F_i (m^2) is glacial area of the ith altitudinal zone, n is number of altitudinal zones.

Melt in the ith altitudinal zone W_i (mm year^{-1}) is calculated with equation (3). Volume of melt W'_Σ (m^3 year^{-1}) is calculated with equation (4) up to the altitude where melt occurred. Volume of melt in areas of different aspects is calculated with equations (5).

$$W_i = W_{id}\, m \tag{3}$$

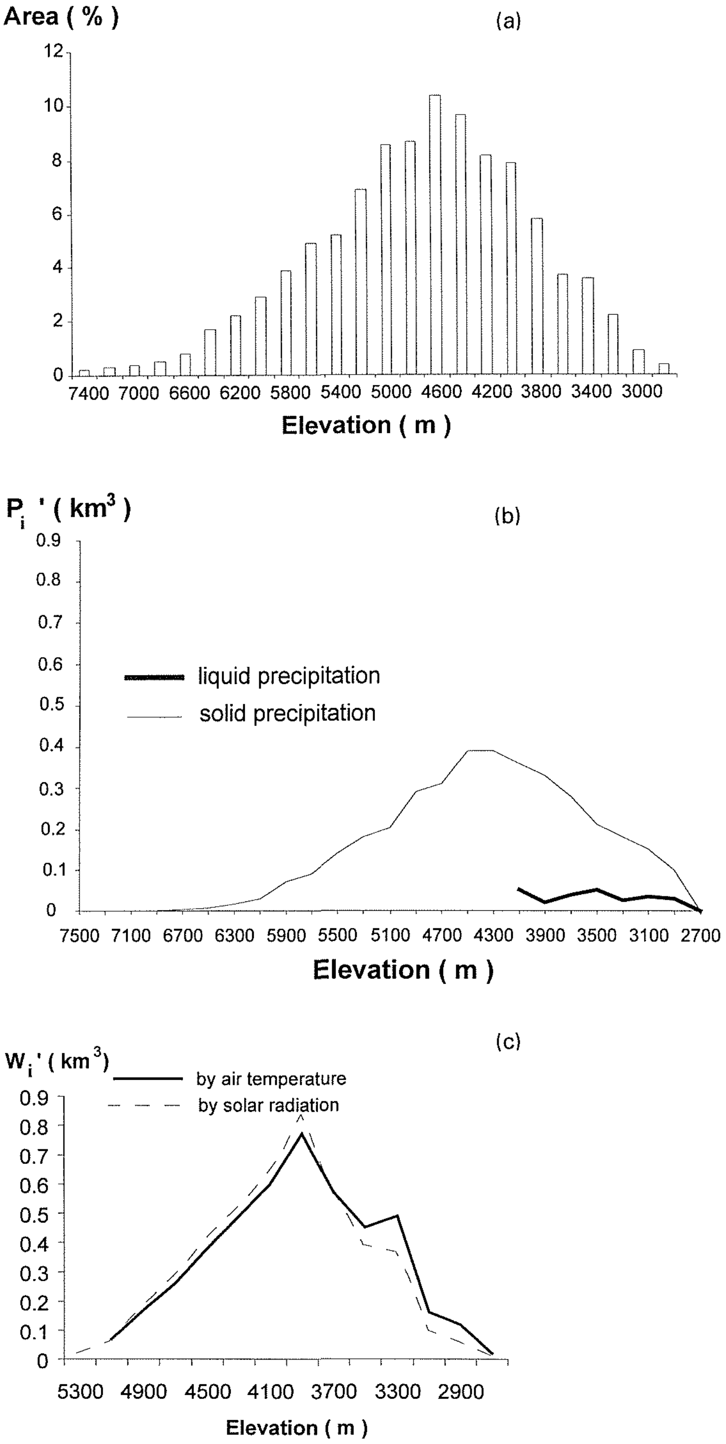

Fig. 2 (a) Percentage area *vs* elevation for the Pobeda-Khan Tengry glaciers; (b) annual volumes of liquid and total precipitation; and (c) annual volumes of glacier melt.

$$W'_{\Sigma} = 10^3 \sum_{i=1}^{n} (W_i F_i) \tag{4}$$

$$\left.\begin{aligned} W'_{\Sigma} &= \sum_{i=1}^{n} W'_i \\ W'_i &= 10^3 (W_{iN} F_{iN} + W_{iS} F_{iS} + W_{iWE} F_{iWE} + W_{ih} F_{ih}) \end{aligned}\right\} \tag{5}$$

where W_{id} (mm day^{-1}) is value of glacier melt, m is number days when melt occurred, $W_{iN,S,WE,h}$ (mm year^{-1}) is mean melt occurring on slopes of northern, southern, western and eastern aspects and on horizontal slopes within the ith altitudinal zone, $F_{iN,S,WE,h}$ (m^2) is area over the northern, southern, west–eastern aspects and horizontal surface. Surface with mean angle from 0° to 7° was taken as a horizontal.

To estimate ice melt under moraine (W_{im}) with equation (6), we used the Konovalov (1979) method (Fig. 3) where the relative intensity of melt under moraine, r_i, is a function of moraine thickness, h_i (cm), that was calculated with equation (7).

$$W_{im} = r_i \, W_i \tag{6}$$

$$h_i = [h_t \, \Delta Z - \Delta Z_i)]/(2\Delta Z) \tag{7}$$

where h_t (cm) is thickness of moraine at the tongue of the glacier (reported below); ΔZ is an altitudinal interval where moraine covers glaciers; ΔZ_i is an altitudinal interval between the ith altitudinal zone and the altitude of a glacier tongue.

The air temperature T_i (°C) and net short-wave radiation Q_{ih} (MJ m^2 day^{-1}) on the horizontal surface at the ith altitudinal zone were calculated using mean air temperature and net short-wave radiation at the Tien Shan station (at 3614 m), altitudinal gradients of air temperature and net short-wave radiation (reported below). Total solar radiation on a slope (Q_{isl}) was described by equation (8):

$$Q_{isl} = Q_{iv(N,S,E\text{-}W)} \sin(\alpha_i) + Q_{ih} \cos(\alpha_i) = Q_{ih}[K_{N,S,E\text{-}W} \sin(\alpha_i) + \cos(\alpha_i)] \tag{8}$$

where α_i is the average angle of slopes with a northern, southern or west–eastern aspect within the ith altitudinal zone, $K_{N,S,E\text{-}W}$ are coefficients of transition from the incoming solar radiation on the vertical (Q_{iv}) surface, with different aspects to the

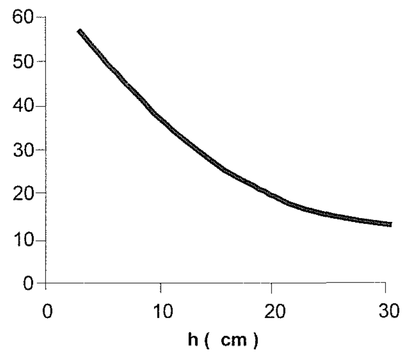

Fig. 3 Intensity of melt under moraine (r) and moraine thickness (h).

incoming solar radiation on the horizontal (Q_{ih}) surface, i.e. $Q_{iv(N,S,E\text{-}W)} = Q_{ih}\,K_{N,S,E\text{-}W}$ (Rusin, 1979).

ESTIMATIONS OF PRECIPITATION AND GLACIER MELT

The altitudinal distribution of precipitation (Fig. 4) was calculated on the basis of long-term meteorological data from five meteorological stations located at points between 1600 and 3500 m, six snow courses and 13 precipitation gauges located between 2200 and 4400 m. To estimate the annual quantity of precipitation above 4400 m we used the data from a stratigraphic and isotopic (^{3}H-tritium) analysis of ice cores (Aizen *et al.*, 1997). Solid and liquid precipitation was calculated by the Aizen & Aizen (1997) method based on air temperature. The long-term mean volume of total precipitation was estimated to be 3.37×10^9 m^3 (780 mm) including liquid volume of precipitation of 0.51×10^9 m^3 (118 mm) (Fig. 2(b)).

Ice, firn and snowmelt, W_{id} (mm day^{-1}) is calculated in two ways: based on solar radiation data (equation (9)) and based on air temperature (T_i) associated with different weather patterns (equations (10–11)). Equations (9–11) are based on expeditionary measurements (Aizen *et al.*, 1997).

$$W_{id} = 1.59 \times 10^{-3}\,[23.9\,Q_i\,(1 - A_i/100)]^{1.68} \qquad r = 0.73 \tag{9}$$

$$W_{idw} = 12.1 + 12.5\,T_i \qquad T_i \geq -0.9°\text{C} \qquad r = 0.71 \tag{10}$$

$$W_{idc} = 40.0 + 4.6\,T_i \qquad T_i < -0.9°\text{C} \tag{11}$$

where Q_i (MJ m^{-2} day^{-1}) is short-wave radiation, A_i (%) is albedo, W_{idw} and W_{idc} (mm day^{-1}) are values of melt during warm-and cold-weather patterns.

According to expeditionary data and aerial photography, moraine covers the Pobeda-Khan Tengry glaciers up to 3200 m. The average thickness of moraine at the Inylchek Glacier tongue was measured at more than 300 points and determined to be

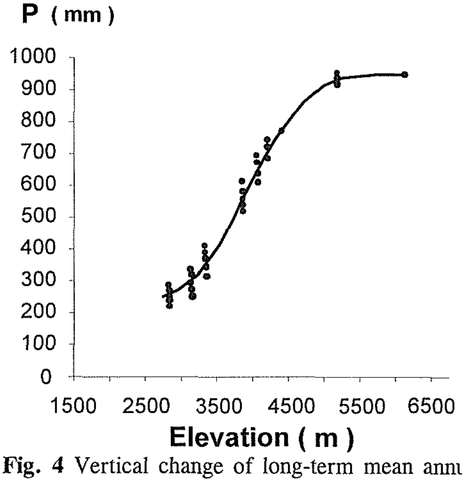

Fig. 4 Vertical change of long-term mean annual precipitation (P) in the Inylchek valley.

20 cm on average. Moraine thickness and means of relative intensity of ice melt (equations (6) and (7)) were taken into account in the assessment of glacier melt (Tables 1 and 2).

Significant correlation (r = 0.84) was found between mean daily air temperatures at the Tien Shan station (3614 m), and at 4150 m on the Inylchek Glacier. Hence, the reference point in calculations of air temperature distribution over the glaciers was 4150 m. The altitudinal gradient of air temperature over the glacial surface based on expeditionary data was found to be 0.0036°C m^{-1} (Aizen *et al.*, 1997). The air temperature difference between the Tien Shan station and 4150 m

Table 1 Estimation of mean ice, firn and snowmelt based on air temperature from the Pobeda-Khan Tengry glaciers.

Elevation (m)	Warm weather pattern: T_{3614} = 10°C T_{4150} = 5.1°C m = 2 days		T_{3614} = 5°C T_{4150} = 0.1°C m = 27 days		Cold weather pattern: T_{3614} = 0°C T_{4150} = –4.9°C m = 47.5 days		T_{3614} = –2.5°C T_{4150} = –7.4°C m = 14 days		T_{3614} = –5°C T_{4150}=–9.9°C m = 1.5 days		W_i (mm year^{-1})	h_i (cm)	r_i	W_{im} (mm year^{-1})	W'_i (×10^9 m^3 year^{-1})
	T_i	W_i	T_i	W_i	T_i	W_i	T_i	W_i	T_i	W_i					
2700	10.3	705	5.3	2122	0.3	1846	–2.2	420	–4.7	28	5120	18.3	0.24	1229	0.02
2900	9.6	660	4.6	1879	–0.4	1698	–2.9	373	–5.4	23	4633	15.0	0.31	1436	0.12
3100	8.9	615	3.9	1636	–1.1	1551	–3.6	327	–6.1	18	4146	11.7	0.39	1617	0.16
3300	8.2	570	3.2	1393	–1.8	1403	–4.3	281	–6.8	13	3660			3660	0.40
3500	7.4	525	2.4	1150	–2.6	1256	–5.1	234	–7.6	8	3173			3173	0.45
3700	6.7	480	1.7	907	–3.3	1109	–5.8	188	–8.3	3	2686			2686	0.57
3900	6.0	435	1.0	664	–4.0	961	–6.5	141	–9.0		2202			2202	0.77
4100	5.3	390	0.3	421	–4.7	814	–7.2	95	–9.7		1720			1720	0.60
4300	4.6	345	–0.4	178	–5.4	666	–7.9	49			1238			1238	0.49
4500	3.8	300	–1.2		–6.2	519	–8.7	2			822			822	0.38
4700	3.1	255			–6.9	372	–9.4				627			627	0.26
4900	2.4	210			–7.6	224					435			435	0.17
5100	1.7	165			–8.3	77					242			242	0.07
$W_{i\Sigma}'$															**4.55**

Table 2 Estimation of mean ice, firn, snowmelt based on solar radiation data from the Pobeda-Khan Tengry glaciers.

	K (sin(α_i) + cos(α_i)): Q_{isl} (MJ m^2 day^{-1})							Albedo	W_{im} (mm year^{-1})				W_i × 10^9 m^3 year^{-1})				W_i' (×10^9 m^3 year^{-1})
K	0.19	0.36	0.44														
H (m)	N	S	WE	h	N	S	WE		h	N	S	WE	h	N	S	WE	
2700				14.2				0.08	546				0.01				0.01
2900				14.7				0.08	748				0.06				0.06
3100				15.2				0.08	945				0.14				0.10
3300			1.046	15.7			16.4	0.08	2694			2905	0.21			0.07	0.29
3500	1.017		1.046	16.2	16.5		17.0	0.10	2736	2815		2951	0.35	0.02		0.02	0.39
3700	1.017		1.052	16.7	17.0		17.6	0.14	2668	2744		2905	0.51	0.02		0.03	0.57
3900	1.018	1.053	1.057	17.2	17.5	18.1	18.2	0.23	2328	2399	2539	2555	0.62	0.04	0.03	0.14	0.83
4100	1.018	1.053	1.061	17.7	18.0	18.7	18.8	0.37	1743	1796	1901	1926	0.35	0.06	0.07	0.15	0.63
4300	1.018	1.055	1.077	18.5	18.8	19.5	19.9	0.50	1265	1303	1384	1433	0.27	0.07	0.06	0.13	0.52
4500	1.015	1.060	1.091	19.3	19.5	20.4	21.0	0.62	857	878	945	992	0.21	0.05	0.04	0.10	0.41
4700	1.015	1.060	1.092	20.1	20.4	21.3	21.9	0.69	652	668	719	755	0.08	0.08	0.05	0.07	0.29
4900	1.014	1.061	1.088	20.9	21.1	22.1	22.7	0.77	421	431	465	486	0.04	0.06	0.04	0.05	0.18
5100	1.007	1.054	1.072	21.7	21.8	22.8	23.2	0.86	195	197	213	219	0.01	0.02	0.02	0.01	0.06
5300	0.991	1.049	1.072	22.5	22.2	23.6	24.1	0.93	65	64	70	73	0.00	0.01	0.01	0.00	0.02
W_{Σ}'																	**4.43**

on Inylchek Glacier was determined to be 4.9°C.

According to expeditionary observations at 4150 m, the daily mean air temperature was determined to be -0.9°C, above which the glacier melt was estimated by equation (10) as for warm-weather patterns. The days with an air temperature below -0.9°C were considered to show cold-weather patterns: and calculations of melt occurred with equation (11). The long-term mean air temperatures and number of days with these air temperatures at the Tien Shan station were obtained from the *Reference Book* (1990). An estimation of ice, firn and snowmelt based on air temperature data is shown in Fig. 2(c) and Table 1. The long-term mean of total annual ice, firn and snowmelt from the Pobeda-Khan Tengry glaciers is about $4.55 \times 10^9 \text{m}^3$ (1053 mm).

We used solar radiation data (equation (9)) to check these estimations of annual glacier melt. The correlation (r = 0.76) between mean daily total solar radiation at the Tien Shan station and at 4150 m on the Inylchek Glacier was found to be significant. Hence, the reference point in calculations of incoming total radiation over the glaciers was 4150 m. The difference in total incoming radiation between the Tien Shan station and 4150 m on the Inylchek Glacier was determined at 6.4 MJ m^2 day^{-1}. The long-term mean of total solar radiation at Tien Shan station is 24.2 MJ m^2 day^{-1} (*Reference Book*, 1990). This corresponds to 17.8 MJ m^2 day^{-1} of mean total radiation at 4150 m on the glacier. The mean solar radiation gradients over glaciers were obtained from expeditionary observation. During summer its mean was found to be 0.004 MJ m^{-2} day^{-1} m^{-1} for altitudes above 4100 m and 0.003 MJ m^{-2} day^{-1} m^{-1} for altitudes from 2800 to 4100 m.

We took topographic factors in glacier melt calculation, i.e. elevation, angle and aspect of the slopes (equation (8)) into account. Empirical characteristics of albedo were used for interpretation of satellite images. A comparison was made using the synchronous albedo surveys for certain points on the Inylchek Glacier during summer expeditionary measurements. Melt was considered to occur for 92 days.

Estimation of firn, ice and snowmelt on the basis of solar radiation data for the Pobeda-Khan Tengry glaciers is presented in Fig. 2(c) and Table 2, and the long-term mean of glacier melt was estimated at about 4.43×10^9 m^3 (1025 mm). The relative errors of glacier melt calculated as the difference in estimations of two considered methods were closed and determined to be about 2.6% of total melt.

ESTIMATIONS OF GLACIER RIVER RUNOFF

Evaporative losses are compensated by condensation gains for the Tien Shan glaciers (Aizen *et al.*, 1997). Based on expeditionary data, the mean annual value of refrozen meltwater for the Pobeda-Khan Tengry glaciers equalled $0.39 \times 10^9 \text{m}^3$ (90 mm of the water equivalent related to total glacial area) (Aizen *et. al.*, 1997). Thus, the value of annual glacier runoff calculated in equation (1) is 4.55–4.67 × 10^9 m^3 (1053–1081 mm).

The runoff from the Pobeda-Khan Tengry glaciers enters the Tarim River basin coming into mainly the Aksu and the Muzart rivers and some small river heads (Fig. 1, Table 2). Only 2% of the Pobeda-Khan Tengry glacier runoff reaches the

Table 3 Annual glacier runoff estimations in the Tarim River basin.

River	R_g (km^3 year^{-1})	R (km^3 year^{-1})	f (%)
Aksu (gauge Aksu)	2.324–2.44	6.47†	35.9–37.8
Muzart	1.67*		63.7*
Heads	0.580*		56.8*
Tekes (former USSR territory)	0.121*		
Akshiirak	0.238*		
Koilu	0.168*		
Yarkend			51.4†
Tarim	5.5*		46.7*

* Adapted from Dikih (1993).
† adapted from Kuznezov (1968).

Tekes River, the Balkhash hydrographic system. To estimate the share, f, of glacier runoff in the whole (R) Aksu River we used equation (12) (Table 3). The glacier runoff, R_g, of the Aksu River is composed of glacier runoff from Pobeda-Khan Tengry (without Tekes River glacier runoff) and Akshiirak massifs (i.e. Koilu and Akshiirak river glacier runoff).

$$f_{\text{Aksu}} = (R_{g\text{Pobeda-Khan Tengry}} + R_{g\text{Koilu, Akshiirak}} - R_{g\text{Tekes}} - R_{g\text{ Muzart, Heads}})/R_{\text{Aksu}} \qquad (12)$$

The glacier runoff contributes 36%–38% to the total runoff of the Aksu River. According to Dikih (1993) and Kuznezov (1968) estimations, the total share of glacier runoff from other tributaries of the Tarim River varied from 47% to 64% (Table 3).

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