Past and Prospective Change in State of Central Asian Glaciers

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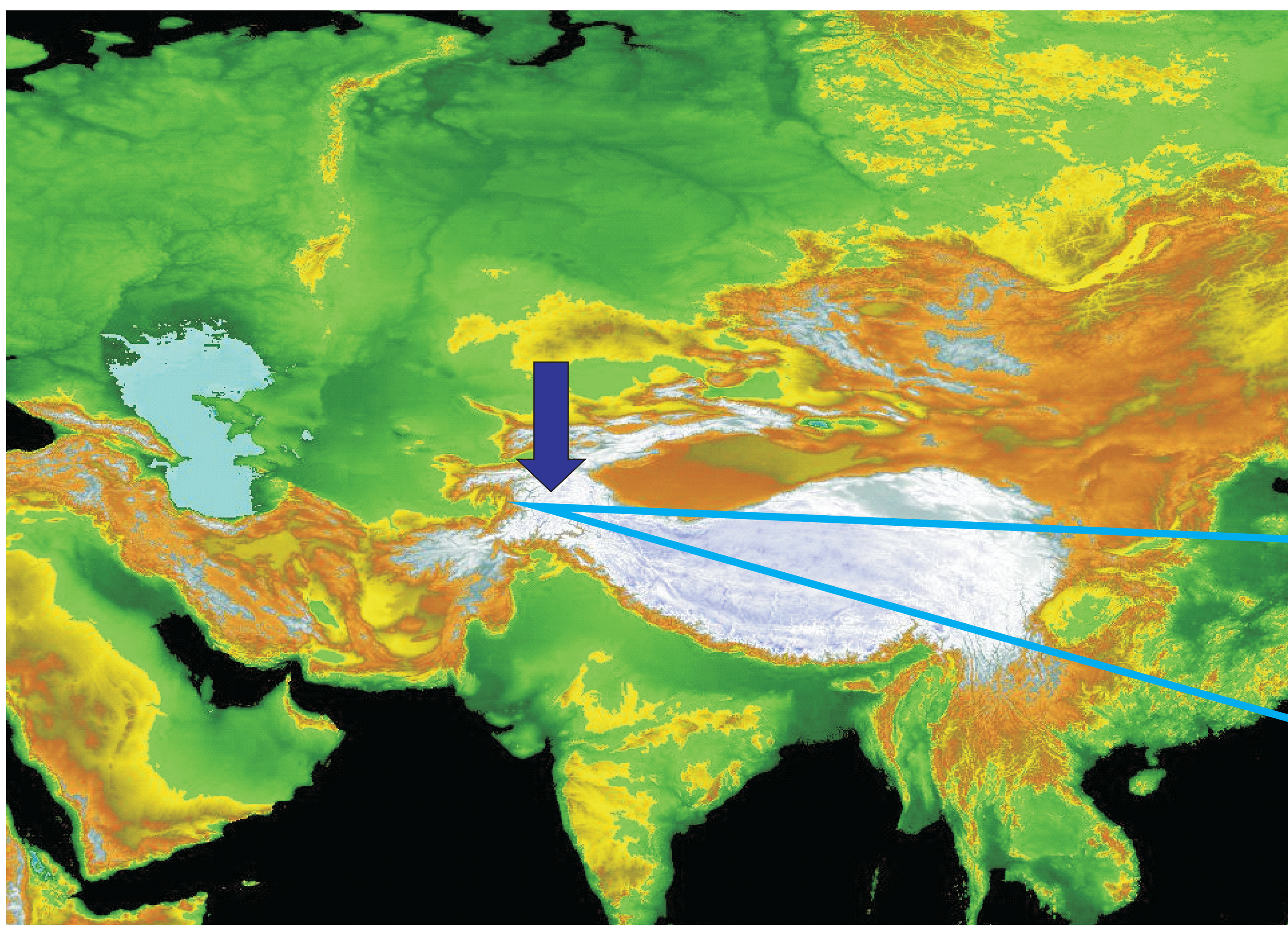
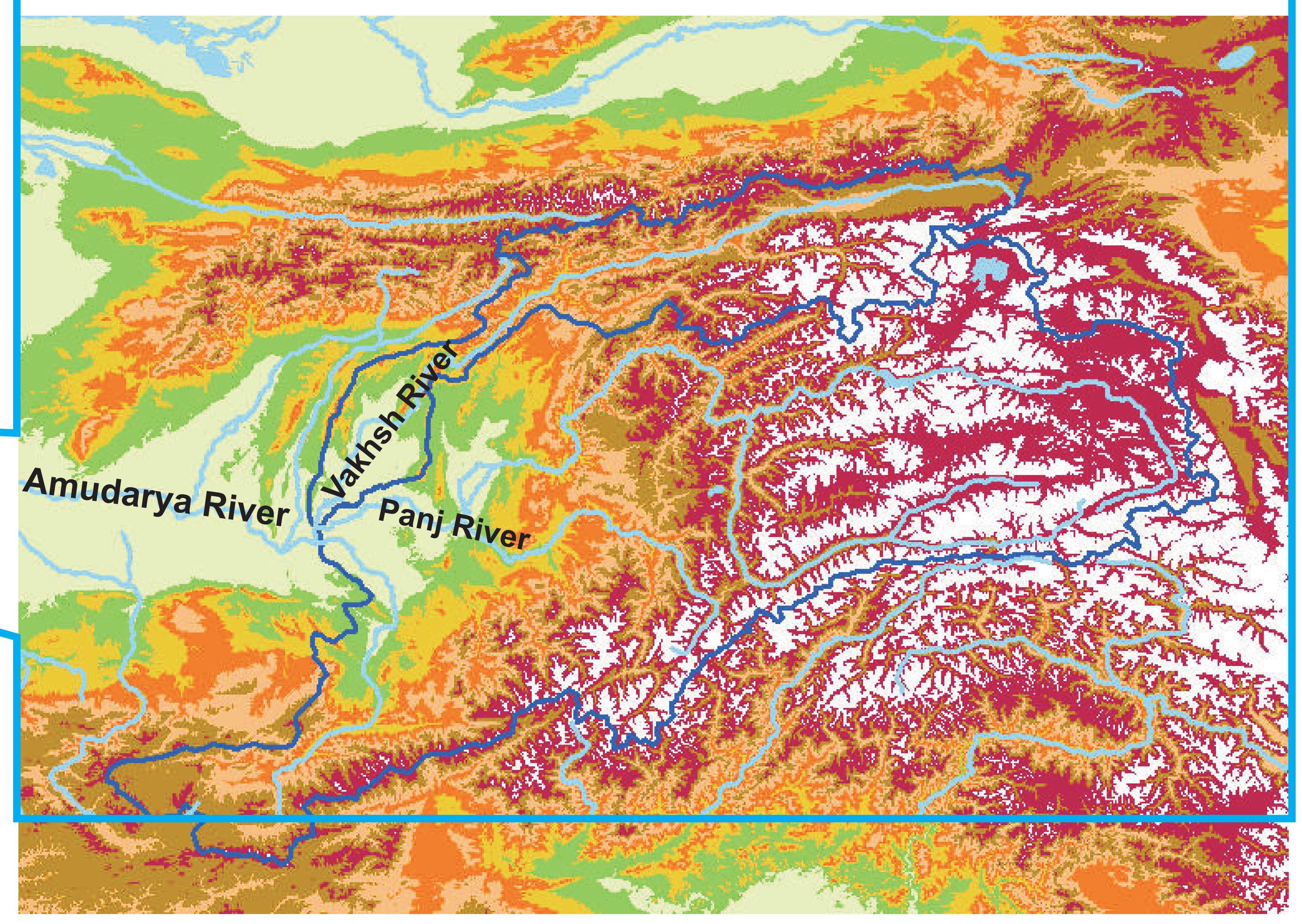


Asia High Mountain Regions

Upstream of Amudarya River



Glaciers area in the Aral Sea Basin

Area of glaciers has changed essentially in this region during the last centenary. Certain information on past and future state of glaciers is presented in the Table 1. It was obtained after compiling glaciers morphometry data (Ivan'kov, 1970; USSR Glaciers Inventory, 1971-1978; Schetinnikov, 1997), processing remote sensing images from satellite LANDSAT 7 and TERRA, and by applying calculation methods (Agaltseva, Konovalov, 2005; Konovalov, Williams, 2005; Konovalov and Desinov, 2007).

Table 1 Long term change of glaciers area in the Central Asia watersheds

Basin/Region	Fgl km^2					dFgl km^2	dFgl %
	1961	1980	1991	2000	2020	1961-2000	1961-2000
Western Tienshan	171	147	133	120	107*	-51	-29.8
Matcha river	506	438	398	358	318*	-148	-29.3
Syrdarya (1)	548	450	408	367	326*	-181	-33.0
Syrdarya (2)	304	205	164	147	130*	-157	-51.6
Vakhsh river	3779	3538	3413	3243	3073*	-536	-14.2
Panj Right Tributaries	3548	2905	2780	2389	1998*	-1159	-32.7
Panj Left Tributaries	4270	3956	3799	3642	3484*	-629	-14.7
Panj river at all	7818	6861	6579	6031	5482*	-1787	-22.9
Amudarya upstream	11597	10399	9992	9273	8555*	-2324	-20.0
All basins	13126	11638	11095	10265	9435*	-2860	-21.8

Note: Syrdarya (1) – left tributaries from Aksu mouth and below, Syrdarya (2) – left tributaries between Karadarya and Aksu mouths, * – glaciers area at the mean rate of summer air temperature equaled 0.007 °C/year for 2001-2020.

Rather significant shrinkage glaciers area in the upstream of Amudarya river during 1961-2000 years corresponds well with estimations of glaciers fluctuations in the other mountain regions. Namely:

- **As reported in Vilesov and Uvarov (2001) during of 1955-1990 area and volume of glaciers in Zailiiskiy Range (Kazakhstan) diminished on 29.2% and 32.3% correspondingly;**
- **By data Tao Che et al (2003) total area of glaciers in the Pumku river basin (Tibet, China) was equaled to 1556 km^2 in 1987 but in 2001 it become less on 14.5%;**
- **According to Kuzmichenok (2006) total glaciers area in Kyrgyzstan over 1950-1960 estimated as 8100 km^2, then over 1977-1980 it diminished till 7400 km^2 and by 2000 glaciers area again reduced till 6500 km^2. Thus, shrinkage of area during of 40 years equaled to 19.8 %;**
- **The paper of Stokes et al (2006) presents information on changes in the terminus position of 113 selected glaciers in the Caucasus between 1985 and 2000. The vast majority (~94%) of the glaciers have retreated since 1985, with a mean retreat distance of 121m (8.1ma^{-1}).**
- **By using digitized glacier outlines inferred from the 1973 inventory and Landsat Thematic Mapper (TM) satellite data from 1985 to 1999, it was revealed in Paul et al (2004) that area reduction of about 930 Alpine glaciers for the period 1985 to 1999 equalled to 18%.**
- **Repeatedly inventorying Austrian glaciers revealed that their area diminished on 17.1% during 1969-1998 (http://meteo9.uibk.ac.at/IceClim/inventory.html).**
- **Shrinkage of glaciers area F_{GL} in Northern Tien-Shan for 1955-1999. By Bolch (2006)**

Characteristics	River Basins					
	Malaja-Almatinka	Bolshya-Almatinka	Levyj-Talgar	Turgen	Chon-Aksu	Chon-Kemin
F_{GL} km²	-3,4	-8,7	-24,3	-13,0	-24,0	-6,3
F_{GL} %	-37,6	-34,5	-33,6	-36,5	-38,2	-16,4

Scientific background which was used to get data in the Table 1 consists of several independent components.

1. **Adjusting of glaciers area values to the certain unified term. It was done by simple linear interpolation or extrapolation when we had at least two estimations of area.**
2. **Determination glaciers area *F* outside of known empirical temporal range. Firstly it could be done by linear extrapolation and secondly by means of equations:**

$$F_{t+1} = F_t + \frac{dF}{dt}\Delta T \quad (1) \quad \text{and} \quad \frac{dF}{dt} = f(I_{Ac}, I_{Ab}) \quad (2) \quad \text{or} \quad \frac{dF}{dt} = f(\bar{T}_S) \quad (3)$$

where T is time interval, I_{Ac} and I_{Ab} are indexes of yearly accumulation and ablation. Instead of I_{Ac} was used sum of precipitation for characteristic season and instead of I_{Ab} - mean summer air temperature $\bar{T}_s$. More detail information on getting and using equations (1-3) is contented in Konovalov and Williams (2005) and Agaltseva, Konovalov (2005).

3. **Recognition and digitizing glacier contours on remote sensing images and processing sets of such contours by means of known GIS software, e.g. ENVI, ArcGis, IDRISI and others.**

Since method 2 plays significant role for estimation of future glaciers area Table 2 presents some independent data on results of quality control for this method.

Table 2. Comparisons glaciers area determined by different methods

BASIN/REGION	DETERMINATIONS F_{GL} IN ~2000 YEAR KM^2		F, %
	F_{gl} $f(\bar{T}_S)$	Other estimations F_{gl} and their sources	
Oigaing river (part) - TienShan	39.6	38.8 (Batirov, Yakovlev, 2003) * 43.7 (Glazyrin, Schetinnikov; 2001a)	-3.3 -10.4
Pskem and Chatkal rivers - TienShan	119.9	107.8 (Glazyrin, Schetinnikov; 2001a)	10.1
Gissaro-Alai mountain region	1503.7	1579.0 (Glazyrin,Schetinnikov; 2001b)	-5.0
Pumku river (Tibet, China)	1356.5 (2001)	1330.0 (Tao Che et al.,2003) *	2.0
Obihingou river - Pamir	575.9	608.5 (Konovalov) *	-5.7
Kyzylsu West river - Pamir	397.3	449.7(Konovalov) *	-13.2
Yazgulem river - Pamir	214.6	200.3(Konovalov) *	6.7
Vanch river - Pamir	238.2	255.1(Konovalov) *	-7.1

Notes: 1. F_{gl} $f(\bar{T}_S)$ – results obtained according to method in Agaltseva, Konovalov (2005), 2. symbol * means, that glaciers area is determined by processing remote sensing images obtained from LANDSAT 7 and TERRA satellites. 3. F is relative difference between the considered estimations.

As one may see the relative difference between glacier areas determined from remote sensing images and computed by dependence F_{gl} $f(\bar{T}_S)$ varies from 2% till 13% that confirms reliability of the suggested method.

Modeling and computation glaciers runoff

A set of PC programs and informational base were elaborated for computation long-term series of glaciers hydrological regime by means of REGMOD model. The formula used in the REGMOD for calculation total volume of glaciers melting v_m in the moment *t*, has the form:

$$v_m(t) \quad M_c(z_{im},t)S_{im} \quad M(z_i,t)S_i \quad M(z_f,t)S_f \quad M(z_{ws},t)S_{ws} \quad M(z_{ss},t)S_{ss} \qquad (4)$$

Here M_c M $f(h_c)$ is the intensity of ice melt under the solid moraine cover (*im*), *i* is the bare ice, *f* is the old firn, *ws* is the winter snow, *ss* is the summer snow, $f(h_c)$ is the function of extinction of ice melting under the moraine cover of the thickness h_c, z - is mean weighted altitude for the S area of certain type of glacier's surface. Final results of calculation by REGMOD are seasonal volumes of total melting V_M and the ice-melt runoff W_{gl}.

Computations of V_M and W_{gl} by REGMOD model include certain methods described total melting and runoff process of glaciers. These methods are the following: (a) Statistical model (Konovalov, 1979, 1985) of glaciers aggregation presents quantitative form of regionalization of the following morphometry parameters related for quasi-homogeneous groups of glaciers within a river basin: areas of glaciers and solid moraine; distribution of area along altitude; altitudinal values of glacier beginning, end, firn boundary, upper limit of solid moraine cover; mean values of slope and azimuth of glacier surface. (b) Local and regional formulae of melting intensity of snow, bare ice and ice under moraine cover which were derived for the majority of Central Asian glacial areas. General form of those formulae is $M=M(B_k,T)$, where B_k is absorbed solar radiation, *T* is air temperature. For calculation of ice melting intensity under the moraine cover were derived (Konovalov, 1985, 2000): universal function of extinction of ice and snow melt intensity depending on moraine thickness; function of moraine thickness distribution on the glaciers surface; equation for calculation mean thickness of moraine at the termini of glaciers. (c) Method calculation data of the beginning and end of ice melt period and glaciers runoff formation based on separate modeling of seasonal snow line movement Z_{ssl} inside of glaciers area and outside of glacierized basins. (d) Model of snow line movement $Z_{ssl}(t)$ on glaciers surface during ablation period. (e) A new method was elaborated and used for computing precipitation, air temperature and humidity at the arbitrary point of glaciers area (Konovalov, 1993, 2006). (f) The method of albedo A_k computation. It includes: (i) mean values of A_k for main types of glacier surface (Konovalov,1985); (ii) conclusion on stability or small changing of A_k during of 20-30 days interval for the homogeneous surface of glacier; (iii) experimental function which describe $A_k(t)$ variability over a glacier termini depending on the ratio between the areas of solid moraine and bare ice.

Flow chart of REGMOD model for calculation long term regime of total glaciers melting and runoff

REGMOD

Input of information on glacier groups and initial climate data

Permanent or changeable during long term time interval

Different for years and groups
a) Zmax, b) Air temperature,
c) Precipitation,
d) Total cloudiness

Regionally averaged - *Time dependent*: Mean values of albedo, Different empirical coefficients

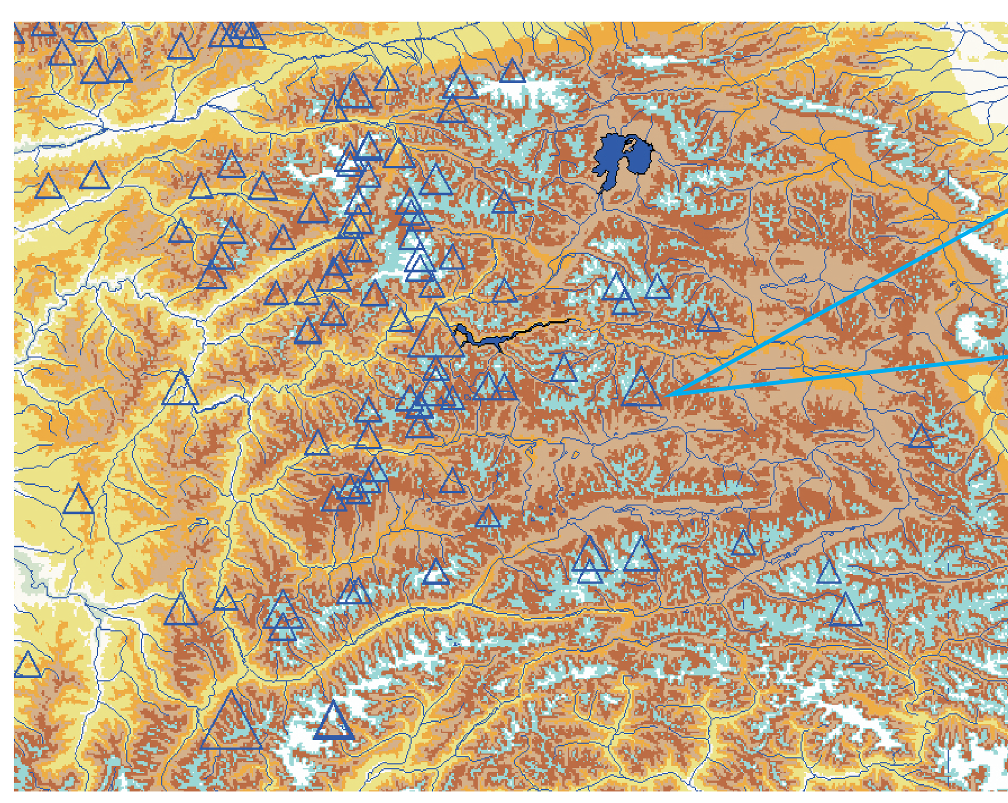
Calculation dates of beginning and end of ice melt period for glacier groups

Calculation components of total melting and mass balance for glacier groups

OUTPUT results:

n.1 Altitudes of $Z_{SSL}(t)$ during of October-September; n.2 Distribution of snow water equivalent from min Z_E till max Z_b altitudes starting from October till *DSI* at the highest Z_E; n.3 *DSI* and *DEI* dates at the ten characteristic altitudes inside of Z_b – Z_E interval; n.4 Layers of seasonal snow maximum accumulation at the ten characteristic altitudes inside of Z_b – Z_E interval; n.5 Layers of snow melted at the ten characteristic altitudes inside of Z_b – Z_E interval, during of May-October; n.6 Layers of ice melted at the eight characteristic altitudes inside of interval Z_b - Z_{max}, during of May-October; n.7 V_M and *Wgl* volumes for the different months of May-October and for this season as a whole.

Example of regionalization glaciers integrity



Location of quasihomogeneous glacier groups (Δ) within Pamir and Gissaro-Alai mountain regions.

Total number of selected groups there is 144. Criteria for selection are: main boundary of watersheds, general exposition of slopes, types of glacier, climate conditions.

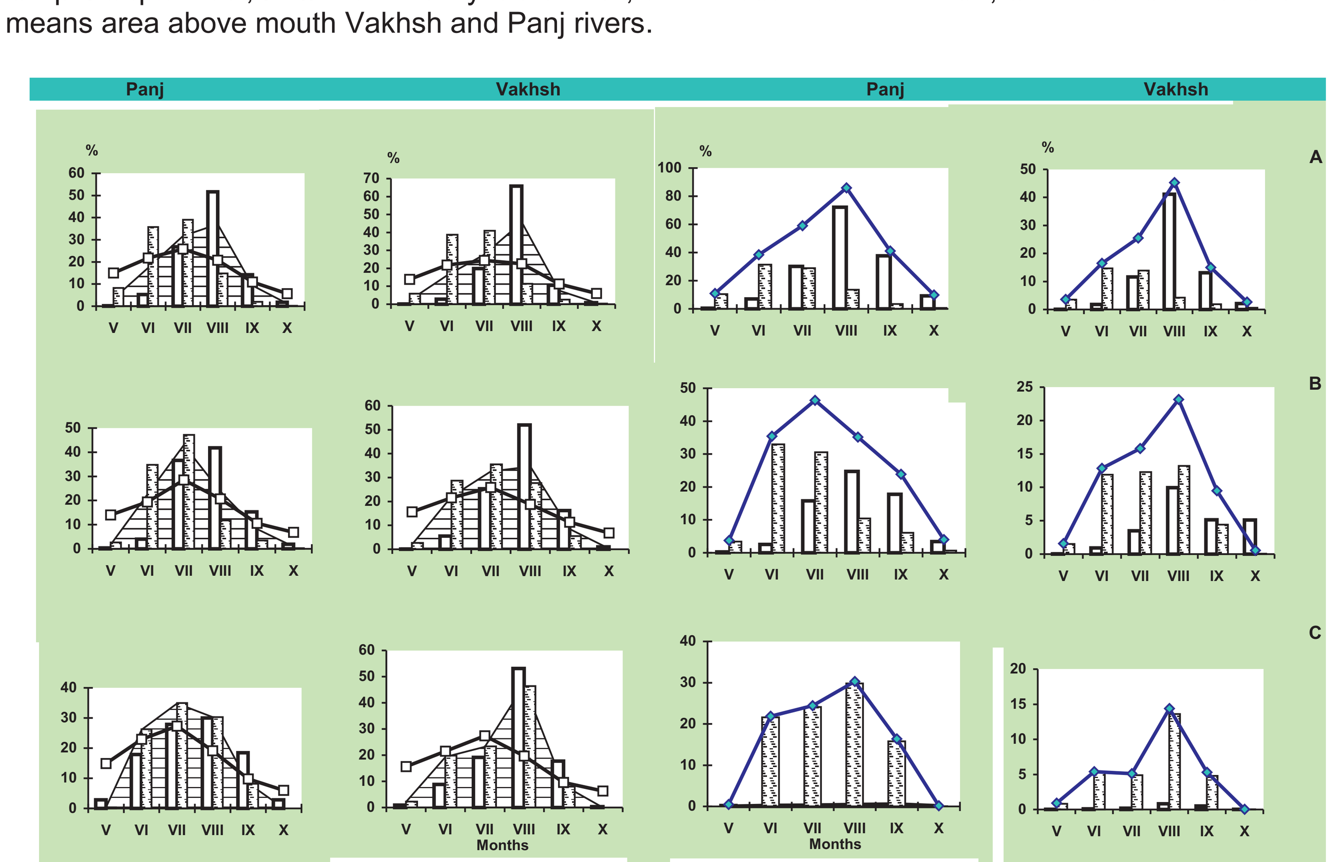
The set of generalized mophometry parameters for each group include: total area of glacier, area of solid moraine, distribution of area along altitude, altitudes of beginning, end and firn line, highest point of solid moraine, mean depth of solid moraine on the end of glacier. All altitudinal data are weighted on area.

Combined analysis of long-term variability of the Amudarya, Syrdarya and other rivers flow components during of May-October showed that relative contributions of glacial runoff and total melting increase in low flow years and decrease in high flow ones. This peculiarity of glacial runoff is highly important for water supply of agriculture and hydropower in the Central Asian states because it provides natural regulation of intra-seasonal distribution of runoff. Anyone can see from the presented information that in the years with significant melting of glaciers the rate of river's flow in the April-September season is mainly provided by runoff from the alpine areas.

Contribution of glaciers total melting into river runoff during 1961-1990 for different seasons

River – gorging site	Fbas	Fgl	V_m/Wb for (IV-IX), %			statistics		V_m/Wb for (I-XII), %			statistics	
	km^2		min	mean	max	Cv	Cs/Cv	min	mean	max	Cv	Cs/Cv
Zeravshan-Dupuli	10200	530	15.0	28.5	43.5	0.24	0.36	13.0	24.4	37.5	0.24	0.53
Naryn-Naryn	10500	954	9.0	26.2	54.1	0.43	1.37	7.3	19.8	46.7	0.47	1.82
Vakhsh-Komsomolabad	29500	3413	9.7	23.6	38.6	0.31	0.98	8.7	20.9	35.6	0.31	0.90
Panj-Nizhniy Panj	158412	6579	13.4	34.6	56.8	0.30	-1.12	10.1	26.2	44.2	0.31	-0.74
Amudarya-upstream*	187912	9992	13.3	30.4	50.0	0.29	-0.32	10.2	23.4	39.6	0.30	0.01

Notes: Fbas – area of basin above gorging site, Fgl – area of glaciers by 1991, determined by V.G. Konovalov, except of Naryn basin where data of USSR Glaciers Inventory (~1960 year) were used, V_m/W_b – relative contribution of total meting within glaciers area into the river runoff for the proper time interval, IV-IX – is April-September, I-XII – is January-December, Cv – is coefficient variation, Cs – coefficient of skewness, * - means area above mouth Vakhsh and Panj rivers.



Inter-annual distribution of total runoff and components of total glacier melting in years, different by the water yield (A – high water, B – average, C – low water) for the Vakhsh and Pyandzh river basins, W_b, is total river runoff, V_m, is total melting of glaciers, W_{sn}, is runoff from melting of a seasonal snow on glaciers, W_{gl}, is runoff produced from melting of ice and old firn. Left pair of graphs present percentages of V_m, W_{sn}, W_{gl}, and W_b to their sums for May-October. Right pair of graphs present percentages of V_m, W_{sn}, W_{gl}, and W_b to the total river runoff for May-October. Graphs on line "A" are related for high flow years, "B" – for average flow years, "C" – for low flow years.

Conclusions.

1. **At the first time long term variability of glaciers area during 1861-2000 was estimated at several temporal cuts. These data should be considered as rather reliable because percentage results based on using large scale maps, air-photo survey, and remote sensing images for monitoring glaciers change equaled by years: 1961 – 100%, 1980 – 66%, 2000 – 74%. The other determinations of glaciers area in the Table 1 were calculated by author.**
2. **Data on glaciers shrinkage presented in the Table 1 coordinate well with other known similar information in mountain regions of Asia and Europe.**
3. **Extreme and average contributions of total melting volumes in glaciers area to the annual and seasonal runoff in the Aral Sea Basin stress vital role of glaciers water resources there.**
4. **Projected value of glaciers area by 2020 was obtained by linear extrapolation of dF/dt during 1991-2000 and it turned out larger in comparison the same one but after using trend equation for 1961-2000 years.**
5. **Statistical distribution of total melting values is essentially asymmetrical and differs from binomial curve at $C_S=2C_V$.**