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INTERRELATION BETWEEN GLACIER SUMMER MASS BALANCE AND RUNOFF IN MOUNTAIN RIVER BASINS

ABSTRACT. Measurements of summer mass balance B_s, made over the period 1946-2016, on 56 continental glaciers, located in the basins of mountain rivers in 14 countries, were analysed for the purpose of resolving several tasks: (a) constructing physically based interrelations between river flow W_{bas} and B_s; (b) estimating the representativeness of local measurement of B_s for enhancement of hydrological computations and for control of modelled values W_{bas}; and (c) use of time series of B_s for the evaluation of norms and extrema of W_{bas}. Results of the study of the outlined problem serve as the basis for making the transition of local glaciological characteristics to the basin-wide level by using the relationship between runoff and summer balance of glaciers. It includes also analysis and conclusions on the spatial and temporal homogeneity of averaging glaciological mass balance data by the sampling method.

KEY WORDS: summer mass balance, glacier runoff, glaciers representativeness, extremes and norm, multi-year series, statistical averaging

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INTRODUCTION AND OBJECTIVE OF THE STUDY

According to the definitions in Kotlyakov (1984), Kotlyakov and Smolyarova (1990), and Cogley et al. (2011), the summer balance B_s is equal to the change in the glacier's mass starting from the time of maximum of snow accumulation to the end of the ablation period. During this interval of time, it is possible to determine the integral value of B_s as a whole for the season, or for the specific ten days/months inside the year. As a result of applying the best methods and techniques of measurements, the obtained volume of B_s characterizes output of melt water from the area of a glacier, which is necessary to calculate and forecast the river's runoff formed by the melting snow and ice.

At present, the continuous measurements B_s with the minimal number $N_{min} \geq 10$ of yearly data during 1946-2016 are available (Dyurgerov and Meier 2005; Fluctuations of Glaciers Database 2017) on a 56 continental glaciers, which distributed extremely unevenly on the Earth, see Fig. 1. Similar spatio-temporal distributions of annual mass balance B_a for 144 glaciers illustrates Fig. 3a-b, prepared by data from (Mernild et al.

2013). For this figure, we used decadal averages of B_a during 1971-2008.

The list of 56 glaciers selected for B_s analysis is given in the Table A1. In this set of data, the adopted value of N_{min} satisfies more or less to statistical requirements for correct averaging. Principally, such empirical sample have to be equal to not less than 15 years. However, following known rules of statistic leads to diminishing the size of glacier sample. In particular, at $N_{min} \geq 15$ it will consist 45 instead of 56 glaciers with long-term asynchronous data of B_s. Zemp et al. (2015) concluded, that for climate change assessments with >30 observation years, the glaciological dataset currently contains 37 reference glaciers.

There are exist opinion (Dyurgerov and Meier 2005; Zemp et al. 2009; Fluctuations of Glaciers Database 2017, and many others), that glaciers, included in WGMS mass balance network are considered a priori as reference or representative for regional/global monitoring of changes in the annual mass balance B_a and its components (winter B_w and summer B_s balances) in glacier populations. Analysis (Kotlyakov et al. 1997; Braithwaite 2009; Fountain 2009; Konovalov 2015; Zemp et al. 2009) based on the 60-years information on B_a, B_w and B_s at such reference glaciers has revealed the following properties of the WGMS network for measurements the glacier mass balance. 1) Selection of the so-called "representative/benchmark" glaciers is often basing on the principle of lowest cost for fieldwork instead of previous analyzing the spatial distribution of area, altitude-morphological and other characteristics of glaciers in the corresponding population. 2) Predominance of European data leads to distortion of global average values of annual and summer mass balances of glaciers. The amount of distortion is unknown because averaging measurements on "reference" glaciers ignores regional accumulation and ablation patterns. 3) Completeness of the series and the timing of observations is very low, due to many omissions.

The other problem of using initial data on B_s (Dyurgerov and Meier 2005; Fluctuations of Glaciers Database 2017) for regional/global averaging is their significant asynchrony. Table 1 illustrates the asynchrony of B_s yearly data in ten-year periods during 1946-2015.

Currently, the vast majority of glaciological publications contain climatic, physical and dynamic characteristics on the regime of individual glaciers having local spatial and temporal distribution. The peculiarity of calculations and forecasts of runoff at the scale of mountain watersheds is the necessity of estimating the annual/seasonal volume of melt water $W_{bas}=W_{snow}+W_{gl}$ formed on the total area of F_{bas} river basin, above the outlet hydrologic station. Here W_{snow} is the volume of snowmelt and W_{gl} – is glacier runoff. In models (e.g. Borovikova et al. 1972; Rets et al. 2011, 2017,2018; WaSiM Model 2015) for rivers of snow-glacial type, the catchment area presented as a set of elementary sites having known plane and altitude coordinates, parameters of exposure and slope of the surface. The total volume of water formed at all elementary sites is using to transform it into a flow hydrograph. In order to assess the quality of modeled W_{bas} we may use the initial measurements of ablation/summer mass balance. Similar assessment the modeled values of W_{bas} can be performed by comparing the measured runoff and calculated one on

Table 1. Density of WGMS network for spatial and temporal averaging of total data on B_s

Index	Ten-year time intervals						
	1946-55	1956-65	1966-75	1976-85	1986-95	1996-2005	2006-2015
M	20	109	293	337	381	304	219
M_1 %	3.4	18.5	49.7	57.1	64.6	51.5	37.1

*M – is actual number of measurements B_s for ten-years, M_1 % – is percentage of M from possible maximum $M_0 = N_{gl}$*10, where N_{gl} is total number of selected glaciers in the each decade, i.e. 56 in our case.*

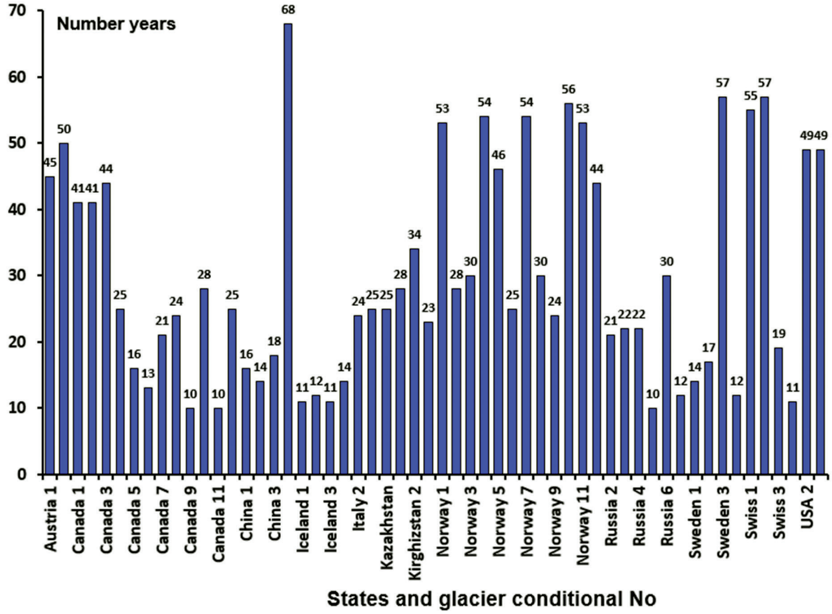

Fig. 1. Number of years with B_s data on glaciers in different states within 1946-2016. Reference on source of information see in the text

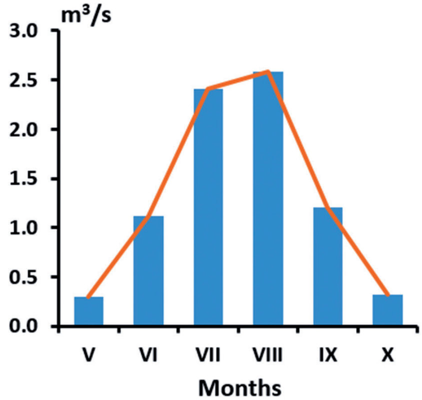

Fig. 2. Monthly runoff of Vernagtferner River in May-October. Reference on data source see in the text

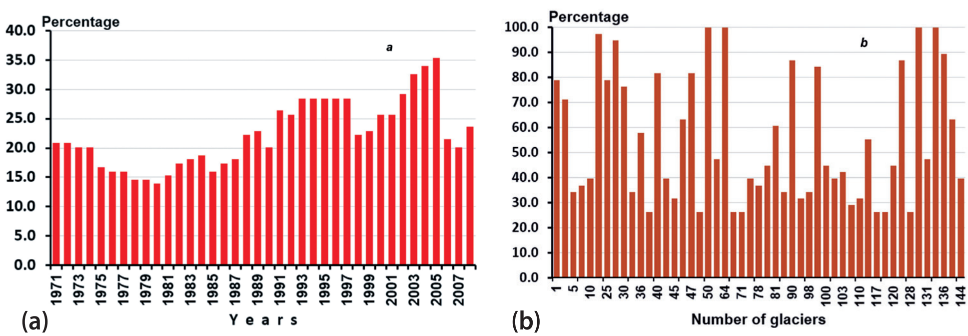

Fig. 3. Temporal distribution of B_a data (a), and spatial distribution of averaged B_a data (b) Reference on source of information for figures a-b see in the text

the basis of application the equation of the annual water balance (Konovalov 2014; Konovalov 2015; Konovalov and Pimankina 2016).

The objectives of our research are the following. a) To understand how suitable current B_s data in (Dyurgerov and Meier 2005; Fluctuations of Glaciers Database 2017) for statistically substantiated spatial and temporal averaging. It means that our assessment concerns only existence or absence of data and not of their quality. The last one characteristic needs rigorous analysis for each case, but not fulfilled yet, and one may discover not compatible data of B_s for the same glacier in different sources. (b) To study physically based relationships between W_{bas} and B_s for simplified verification of modelled values of W_{bas}. c) To use time series B_s to characterize the norms and extremes of W_{bas}. d) To verify the possibility of spatial extrapolation of B_s data, obtained on glaciers, which have been considered as representative/reference in the WGMS network.

STUDY REGION, OBJECTS AND METHODS

The regions of and subjects for the present study are continental glaciers of the Earth, contained in the system of WGMS - World Glaciers Monitoring Service (Dyurgerov and Meier 2005; Fluctuations of Glaciers Database 2017). Several glaciers suitable for our analysis are in the Table 2. Their number is mainly limited of extremely rare or inaccessible hydrological information at runoff measurement stations, have located near the glaciers with B_a, B_w and B_s data. Information on the runoff for the rivers of snow-glacial type are taken from the special glaciological editions and hydrological reference books such as the following: Glacier Aktru 1987; Bodo 2000; Dahlke et al. 2012; Glacier Djankuat 1978; Escher-Vetter and Reinwarth 1994; Kamnyanskiy 2001; Krimmel 2000; USGS Alaska Water Science Center; Vilesov and Uvarov 2001. At selecting the time interval for averaging the runoff and B_s data, took into account the interannual distribution of runoff at the hydrological stations near the glaciers. A typical example of such distribution presented in Fig. 2. Source of data is Escher-Vetter and Reinwarth (1994).

High level correlation dependences $Q=f(B_s)$, presented in the Table 2, serve as a basis for obtaining empirical functions of distribution for Q and B_s, building links between statistical probability (Prob) of flow and summer mass balance, and ultimately assessing the probability of extreme flow values.

Table 2. Studied glaciers and correlation between runoff Q and summer mass balance B_s

State	Glacier name	F_{bas}	F_{gl} 1	F_{gl} 2	N	R^2			
						Q_1	Q_2	Q_3	Q_4
Kyrgyzstan	Abramova	55.5	26.1	47.0	21	0.80	0.84	0.84	0.89
Austria	Vernagtferner	11.4	9.3	81.6	31	0.82	0.91	0.92	0.91
Russia	Djankuat	8.0	3.1	38.8	6	0.80	0.87	0.95	
Russia	Maly Aktru	36.0	2.5	6.9	7	0.56	0.85	0.85	
Kazakhstan	Centralny Tyuksu	21.0	2.9	13.7	22	0.36	0.22	0.31	0.22
USA	Wolverine	31.3	18.0	57.5	37	0.22	0.25	0.26	0.27
Sweden	Stor	19.6	3.1	15.9	16	0.15	0.15	0.15	0.12

Definition of symbols: R^2 is coefficient of determination; F_{bas} is area of basin above site of runoff measurement, km²; F_{gl} 1 is area of reference glacier, km²; $F_{gl}2 = F_{gl} 1/F_{bas}$ in %. Hence, value F_{gl} 2 reflects significance of reference glacier in a area of basin; N is nimber of measurement years; Q_1 is average of Q(VI-VIII) as f(B_s), Q_2 is average of Q(VI-IX) as f(B_s), Q_3 is average of Q(VI-X) as f(B_s), Q_4 is average of Q(V-X) as f(B_s), V-X are the months May throuigh October.

Calculations of probabilities Q and B_s (empirical non-exceedance $X>x_i$) were done by the method from (Alexeev 1971):

$$p_i(x_i) = \frac{m(x_i) - 0.25}{N_i + 0.5} * 100 \quad (1)$$

where $m(x_i)$ = 1, 2, ..., N_i - the sequence numbers of the values x_i after their arrangement in descending order.

Besides the determing empirical functions of distribution Q and B_s, there included selection of the most appropriate type of standard function of probability distribution (see parameter Freq B_s in the Table 3). The computer program in (Oosterbaan 1994) used for that purpose.

RESULTS AND DISCUSSION

In principle, the process of runoff formation from the glacier area and from the not glaciated surface measured on a point, located near the terminus of the glacier, includes such closely related characteristics as the intensity of melting, air temperature, solar radiation, clouds, and water vapor pressure in the air. This fact serves as a justification for the search for correlation Q=f(B_s), which turned out to be quite successful on the example of four glaciers from seven in the Table 2. Variation in the coefficient R^2 for Q = f(B_s) in the other three cases need further study, and they may be due to inaccuracies in determining the flow and/or summer balance B_s of glaciers, which was corrected (e.g. Dyurgerov and Meier 2005; Fluctuations of Glaciers Database 2017) and turned out to be not compatible in different sources of data.

Examples of subsequent use of dependencies Q = f(B_s) on the Vernagtferner and Abramova glaciers, used to obtain equations Prob=f(B_s), Freq Bs=f(B_s), Prob $Y_1 \div Y_4$=f(Prob B_s), are presented in the table 3. Here Prob is statistical probability, and Freq B_s is the equation of the chosen standard function of probability distribution.

Forcing the line of dependences Prob $Y_1 \div Y_4$ = f(Prob B_s) through the origin of the coordinate axes in order to estimate the influence of the runoff from the non-glacial part of the basin leads to a slight decrease in the determination coefficient R^2. In this case, the values of R^2 for the glaciers Abramova and Hintereisferner in the order $Y_1 \div Y_4$, as

Table 3. Formulas for calculating the distribution functions of the mass balance B_s

Abramova Glacier			Vernagtferner Glacier		
Prob B_s / Freq B_s	Prob $Y_1 \div Y_4$= =f(Prob B_s); (Δ)	R^2	Prob B_s / Freq B_s	Prob $Y_1 \div Y_4$= f(Prob B_s) (Δ)	R^2
Prob B_s = -0.05B_s + 137.1 R^2 =0.97	Y_1 = 0.89 Prob B_s + +5.5; Δ=13.1	0.79	Prob B_s = -0.05 B_s +126.0 R^2= 0.98	Y_1 = 0.92 B_s+3.9; Δ=11.2	0.85
	Y_2 = 0.85 Prob B_s + +7.6; Δ=15.3	0.72		Y_2 = 0.93 B_s+3.5; Δ=10.6	0.86
Freq Bs = =1/{1+ +exp(A B_s+B)}	Y_3 = 0.86 Prob B_s + +6.9; Δ=14.6	0.74	Freq B_s = =1/{1+ +exp(A B_s^E+B)}	Y_3 = 0.95 B_s+2.5; Δ=9.0	0.90
A= -0.00246 B=4.6	Y_4= 0.85 Prob B_s + +7.5; Δ=15.2	0.72	E = 0.750 A= -2.29E-002 B=5.13	Y_4 = 0.94 B_s+2.9; Δ=9.6	0.89

Definition of symbols: B_s is summer mass balance, mm; Prob B_s is B_s statistical probability by formula (1), in %; Freq B_s is integral function of distribution, %; R^2 is coefficient of determination; Y_1 is equation to calculate Prob Q(Jun-Aug) as function of Prob B_s, Y_2 is equation to calculate Prob Q(Jun-Sep) as function of Prob B_s, Y_3 is equation to calculate Prob Q(Jun-Oct) as function of Prob B_s, Y_4 is equation to calculate Prob Q(May-Oct) as function of Prob B_s, Δ is RMS error of calculating Prob $Y_1 \div Y_4$, in %

in Table 3, are as follows: 0.78 (13.4), 0.70 (15.8), 0.73 (14.7), 0.70 (15.7) and 0.85 (11.3), 0.86 (10.8), 0.90 (9.1), 0.89 (9.7); the number in parentheses are the rms error of calculation Prob $Y_1 \div Y_4$, in%.

As an analogue of the glacial flow W_{gl}, it is also possible to use other known characteristics: data on the annual mass balance B_a, AAR, relationships between areas of accumulation and the entire glacier, and ELA, altitudinal boundary of equality between accumulation and ablation at the end of the ablation period. Annual information on the listed variables (except ELA) for 1971-2008 is contained in the work of Mernild et al. (2013). For glaciers in Table 3 it was not found to be useful to replace W_{gl} with B_a.

Spatial and temporal homogeneity of averaging mass balance data by sampling method

It is known, that the modern network of measurements of glacier mass balance components (B_a, B_s, B_w) includes several hundred objects (Dyurgerov and Meier 2005; Mernild et al. 2013; Zemp et al. 2015). Along with the diverse using of local time series on individual glaciers, the averaging of B_a and B_s is widely used on regional and global scales. For example, at averaging B_s over 10, 15, or 30 years during 1940-2016, in the sample remains unsynchronized spatial data only on consequently 56, 45, and 37 glaciers out of the total number of those in the WGMS network. Table 1 and Tables A1-2 present data density for decadal averaging of B_s for 56 glaciers and composition of the used sample. In addition to these, Tables 4-5 characterize the number of RGI 6 regions, where data of B_a are available for spatio-temporal averaging. After processing such information, Zemp et al. (2015) have determined decade-average B_a values for 19 regions of RGI 6 (RGI Consortium 2017).

As can be seen, the completeness and synchronicity of the time series B_a and B_s, presented in Fig. 1, 3, Tables 1, 4-5 and Tables A1-2, raise great doubts about the statistical validity of regional and global averages of B_a and B_s. Accordingly, this is reflected in the findings on the impact of these characteristics on the associated other natural processes, for example, relation to the climate change, changing the level of the ocean, etc.

Hydrological justification of the representativeness O_F B_s

Given the way in which was formed an empirical sample of 56 glaciers (see paragraph Introduction and Objectives of the

Table 4. Density of RGI 6 regions for spatial averaging of total data on B_a

Index	Ten-year time intervals						
	1941–50	1951–60	1961–70	1971–80	1981–90	1991–2000	2001–10
M	3	7	10	15	17	16	16
M_1 %	15.8	36.8	52.6	78.9	89.5	84.2	84.2

M – is actual number of RGI 6 regions, M_1 % – is percentage of M from possible maximum of RGI 6 regions, i.e. 19 in our case.

Table 5. Density of decades for temporal averaging of B_a at 19 regions of RGI 6

Index	Numbers of RGI 6 regions																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M	6	2	7	2	6	2	5	3	5	7	4	3	4	2	4	7	5	4	6
M_1 %	86	29	100	29	86	29	71	43	71	100	57	43	57	29	57	100	71	57	86

M – is actual number of decades in RGI 6 regions, M_1 % – is percentage of M from possible maximum of decades with B_a data in RGI 6 regions, i.e. 7 in our case.

research), it is evident that such a scanty sample cannot be representative regarding population of 215,547 (RGI Consortium 2017) continental glaciers on Earth. However, an estimate of the spatial representativeness of the summer mass balance measured on individual glaciers is of interest for the rationalization of methods for calculating and forecasting the flow of rivers fed by snow and ice melt.

The solution of this problem, obtained with the example of river basins in the Pamir-Alai and Central Caucasus (see Table 6), is based on an assessment of the effect of using local measurements of B_s as one of the main or additional arguments in the equations of multiple linear regression for calculation of the runoff for June-September and June-August. In this case we adopted model of river runoff W_{bas}, as a regression function of precipitation P and air temperature T, i.e. $W_{bas}=f(P, T)$, where both arguments cover the certain characteristic intervals of time. In this combination of independent variables the seasonal air temperature is considered as the index of the thawed component of the river flow. The regression analysis also includes calculating, by means of Alekseev's method (1971), the relative contributions δ of independent variables T, P, and B_s for describing W_{bas} variance for VI-VIII, VI-IX, and IV-IX (June-August, June-September, and April-September) seasons. The expression in order to estimate δ for the independent variable no 1 has the general form:

$$\delta_1 = r_{01}^2 / (r_{01}^2 + r_{02}^2 + r_{03}^2) \quad (2)$$

where r_{01}^2 – is the square of paired correlation between the given function, labelled as 0, and independent variable no 1. And so on for the next variable in the numerator of (2) and the rest of the parameters δ.

Multi-year mass balance measurements, available on the Abramova and Dzhankuat reference glaciers (Dyurgerov and Meier 2005; Fluctuations of Glaciers Database 2017; Kamnyanskiy 2001), were used for modeling seasonal runoff W_{bas} in river basins of the Pamir-Alai and Central Caucasus, respectively. Local measurements of B_s on these glaciers might be considered representative at the basin scale, if it is true that B_s as an additional independent variable provides an increase in the coefficient of multiple linear correlation for equation $W_{bas}=f(P, T)$. And also, if B_s can be used instead of T in the equation $W_{bas}=f(P, T)$ for a certain basin.

After performing numerical experiments it is found out, that only in one catchment (the Akbura River) of six in the Pamir-Alai, the empirical equations $W_{bas}=f(P, T)$ for calculating the river runoff for IV-IX, VI-IX and

Table 6. Glaciation in some watersheds of Pamir-Alai (P-A) and Central Caucasus (CC)

River basin	Outlet point	F_{bas}, km²	$\delta F_{gl}=F_{gl}/F_{bas}$, %	R1/R2
Isfara (P-A)	Tashkurgan	1560	8.3	0.78/0.73
Sokh (P-A)	Sarykanda	2480	10.2	0.91/0.79
Shahimardan (P-A)	Djidalik	1180	4.0	0.70/0.69
Isfayram-1 (P-A)	Uchkorgon	2200	4.6	0.72/0.56
Isfayram-2 (P-A)	Lyangar	697	14.6	0.76/0.60
Akbura (P-A)	Papan	2200	5.0	0.82/0.83
Baksan-1 (CC)	Zayukovo	2100	6.7	0.61/0.39
Baksan-2 (CC)	Tegenekly	210	27.1	0.58/0.73

R1 – coefficient of correlation for equation $W_{bas}=f(P, T)$, R2 – the same parameter after using Bs instead of T in equation for W_{bas}

VI-VIII included data of the summer mass balance B_s on the Abramova glacier, located outside the Akbura basin. Here we used the next time averaging for the independent variables P, T, measured at meteorological stations: P(X-IV), T(VI-VIII).

As it seen from the Table 7, measurements of B_s on the Abramova glacier we may consider as basin-wide representative for calculating of seasonal runoff in the neighboring Akbura watershed by equation Wbas=f(P, T, B_s).

For estimating basin-wide applicability of the B_s frequency distributions obtained on the Abramova reference glacier (see Table 3), we used again W_{bas} data for the six Pamir-Alay river basins. After correlation analysis as of all basins, the highest R^2 coefficient between frequensies of W_{bas} and B_s for VI-IX and VI-VIII was in the Sokh river basin. There, the empirical equation for computing cumulative frequency distribution of Wbas(VI-VIII) by the corresponding of B_s data at the Abramova Glacier has coefficient of correlation, equal to 0.66. After that, for transition from the obtained frequency distribution value to the runoff data we should use equation W_{bas}(VI-VIII) =f(Freq W_{bas}(VI-VIII)), obtained earlier for the Sokh river basin. Consequently, this analysis also confirms limited basin-wide applicability of the B_s frequency distributions obtained on the Abramova reference glacier.

CONCLUSION

1. Research of the outlined problem, illustrated by the Tables 1-7 and Appendix A, (available at https://ges.rgo.ru) serves as the basis for the practically important transition from the local to the regional level of glaciological asessments by means of using the relationship between runoff and summer balance of glaciers. In this case, as repeatedly shown, the contribution of B_s in the formation of the river flow and, accordingly, the correlation Q=f(B_s) become weaker as the relative area of the glaciation decreases above the site of runoff measurement. However, it is still possible to use parameters (mean, extremums, coefficient of variation, etc.) of empirical functions of spatial and temporal distributions of B_s and Prob B_s, regardless of flow data and data from the World Glaciers Monitoring Service. The possible source of getting wide spread information about B_s is its determination (Davaze et al. 2018) as a function of the surface albedo of a glacier, measured by remote sensing at the end of ablation season.

2. The investigation has shown that the correlation coefficient between the total summer mass balance, characterizing the glacier's water output, and the river runoff W_{bas} at the hydrological outlet site for the time intervals: June-August, June-September, June-October, and May-October varies in a wide range: from 0.97 to 0.39 (Table 1). Study and understanding of this is still insufficient.

3. The hydrological representativeness of a glacier is a new characteristic, of practical importance for basin-wide tasks of hydrology and glaciology. For its evaluation, we propose to replace the seasonal air temperatures with the summer mass balance of glaciers B_s or to include B_s in the multi-

Table 7. Parameters of equations for calculating seasonal runoff W_{bas} in the Akbura river basin

Months	Mean W_{bas}, m³/s	Equation for calculating W_{bas}	R^2	rmse	δ P	δ T	δ B_s
IV-IX	32.4	18.1-0.012B_s+5.77T+0.035P	0.70	3.0	0.41	0.21	0.38
VI-IX	38.7	23.8-0.016B_s+7.30T+0.038P	0.67	3.9	0.35	0.17	0.48
VI-VIII	44.3	27.2-0.012B_s+8.95T+0.044P	0.67	4.8	0.33	0.16	0.51

Definition of symbols: R^2 – coefficient of deternination; rmse – root mean square error of calculated W_{bas} in m³/s; δ P, δ T, δ B_s – are consequntly relative contributions of precipitation P, air temeperature T, and B_s for describing W_{bas} variance.

ple regression equations for calculating the runoff of rivers fed by melting of snow and ice. This method can be recommended for at least of some glaciers in the existing network of the WGMS (World Glacier Monitoring Service).

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