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A NEW APPROACH TO ESTIMATE WATER OUTPUT FROM THE MOUNTAIN GLACIERS IN ASIA

ABSTRACT. Regional data on climate, river runoff and inventory of glaciers within High Mountainous Asia were used as informational basis to elaborate new approach in computing components of the hydrological cycle (glaciers runoff, evaporation, precipitation). In order to improve and optimize the calculation methodology, 4 675 homogeneous groups of glaciers were identified in the largest Asian river basins, i.e., Amu Darya, Syr Darya, Indus, Ganges, Brahmaputra, Tarim, and others. As the classification criteria for 53 225 glaciers located there, the author consistently used 8 gradations of orientation (azimuth) and 23 gradations of area. Calculating of the hydrological regime of glaciers was performed on the example of several Asian river basins. It has been shown that in the drainless basins in Asia, the only potential factor of the glacial influence on the changes in global Ocean level is the seasonal amount of evaporation from the melted surface of perennial ice and old firn. These results and published sources were used for re-evaluation of the previous conclusions on the influence of glacier runoff on change of the Ocean level. Comparison of measured and calculated annual river runoff, which was obtained by means of modeling the components of water-balance equation, showed good correspondence between these variables.

KEY WORDS: Asian river basins, generalization, glaciers runoff, water balance, Ocean level.

INTRODUCTION

Water resources of rivers in the Asian continent constitute a significant proportion of the total volume of the global fresh water resources. According to [World Water Resources, 2003], in terms of the basin area and the average annual runoff volume for the five major rivers, Asia is the second, after South America, in a group of five continents of the Earth (Africa, Asia, Europe, North America and South America). Asia is the first in terms of renewable water resources, and its contribution to the overall global volume equals 31.6% [World Water Resources, 2003]. The total area of world inland glaciation is 287 230 km^2 [Dyurgerov, 2002] and Asia's share of this amount is 42.0%.

The majority of the contemporary issues and problems are solving by glaciologists in many countries are directly connected with the study and description the regime of glaciers, which produce in Asia essential part of river runoff. The author uses the term "regime" in its definition by [Kotlyakov and Smolyarova, 1990]. Depending on the purpose and level of generalization of the initial information, researchers describe the diurnal, intra-annual, annual, and perennial temporal variations of glaciers and parameters of their regime. At this, the objects of study are components of regime in a separate point on the glacier, the whole area of individual glaciers, and aggregation of glaciers with different hierarchy. Typically, measured components of regime are available for a very limited number of individual glaciers. Data series contained many gaps, not evenly distributed in space, and often not comparable across time and in the composition of parameters. All this greatly hampers usage of direct measurements in assessments of regime of glaciers in mountain ranges or for entire river basins. Attempts to substitute the assessments of regime for the statistical population of glaciers with observations on individual "representative" or "reference" glaciers proved fruitless, as has been rightly pointed out in [Fountain et al, 2009], primarily because of the lack of a clear definition of representativeness and for many other reasons.

In the author's opinion, estimation of runoff volume from all glaciers in the large river basins or mountain regions may use limited number of mass balance measurements (now it varies between 250–300 for the whole Earth) only for calibration of local or regional physical relationships, used in mathematical models of hydrological regime. Suggested new method to determine water output from regional populations of mountain glaciers in Asia includes the following stages.

A. Separation of the Asian large rivers, from origins to mouth, into two main groups: (a) not drained to the Ocean or closed (e.g., Amu Darya, Syr Darya, Tarim) and (b) having direct inflow to the Ocean (e.g., Indus, Ganges, Brahmaputra).

B. Regionalization of separated large watersheds into sub-basins, depending on given applied tasks and quantity of initial hydrological, glaciological, and climatological information.

C. Generalization of glaciers in sub-basins into groups with similar sets of area-altitudinal parameters, which initially were extracted from available glacier inventories and obtained after processing of satellite images.

D. Development of model of glacier runoff as a component of annual water balance of a river basin, based on generalized information (see item C) and a set of hydrometeorological data.

E. Computation of the components of water balance (precipitation, evaporation, and glacier runoff) and evaluation of their quality and consistency to the measured river runoff; estimation the influence of these components on the change of the Ocean level.

OBJECTIVES OF THE RESEARCH

Main objectives of the research presented herein are: (a) introducing statistically substantiated new concept "characteristic groups of glaciers" instead of the current concept "sample of reference glaciers"; (b) using this new concept in modeling of the water output from regional populations of glaciers in the Asian river basins; (c) re-evaluation of the glaciers' contribution to the change of the Ocean level. Our study includes the following sections. 1. Spatial generalization the parameters of glaciation. 2. Informational base for calculating hydrological regime of the total glaciers' number in the river basins. 4. Model of calculating runoff, precipitation, and evaporation in the area of glaciation. 5. Application of the elaborated model and background information for estimation of the water balance components in the several Asian river basins.

MATERIAL AND METHODS

Spatial generalization of the glaciation parameters

Computational power of modern computers is enough to calculate the hydrological regime of all glaciers on the Earth as a function of climatic variables, results of cataloging, and dynamic characteristics of glaciation. The problem is that the current spatial resolution of the meteorological fields, especially in mountainous regions of Eurasia, is not sufficient to obtain the values of precipitation, solar radiation, air temperature, humidity, etc., which could be applied to the each individual glacier. Therefore, in order to get data on hydrological regime of all glaciers within large river basins, it is proposed to merge individual glaciers into quasi-homogeneous groups, according to the principle of uniformity characteristics of area, altitudinal, and morphological parameters of glaciation in each group. The input data in this case consists of morphometric parameters for all glaciers in the given population. The minimum set of input parameters includes the following: ID of the glacier, orientation (azimuth), absolute altitude of its beginning Zb, and end Ze, lower altitudinal boundary of the nourishment area Zf, geographic coordinates (Longitude, Latitude), and the total area of each glacier Fgl. This data set could be expanded.

Groups of glaciers and files of their calculated characteristics are formed using a special computer program, which performs double filtering of the initial data for glaciers in the river basin as a whole or its part: (a) first, we select a sets with the same orientation of glaciers. The number of such sets is eight for orientations N, NE, E, SE, S, SW, W, and NW. (b) then, in each of the eight sets, we identify groups of glacier with the area inside of one of the 23 intervals (see Table 1).

Determination of mean and mean-weighted on area parameters for glacier groups occurs automatically and is the final part of the second stage of data filtering. Eventually, all glaciers in the river basin or within a given mountain area are generalized maximally into 184 quasi-homogeneous groups; if in each of the eight sets are filled all 23 intervals of area. The output characteristics for each group in the case of minimum sets of input data are the following: orientation (azimuth), boundary values of the area intervals, number of glaciers that fall into each interval, weighted by the area average values of Ze, Zb, Zf, Longitude, Latitude, difference $\Delta = (Zb - Ze)/10$, and 10 values of the altitude in the range of Zb–Ze with a step Δ, area of the glacier from Ze to Zf, and the total and average area of glaciers in the ranges 1–23.

As a result of averaging, the values of the altitudinal and areal parameters for groups become more reliable, which increases quality and representativeness of glaciological calculations. An example of generalization of 6 262 glaciers in the Vakhsh and the Panj river basins (origins of the Amu Darya river) into the 1 473 groups is shown in Fig. 1 a–b. Blue squares in the figure – are individual glaciers, black triangles – are groups of glaciers. In general, the number of generalized groups and their location is associated with allotment of specific parts in the river basin: the more parts, the more groups of glaciers and, hence, we obtain a more detailed spatial distribution of the generalized parameters of glaciers.

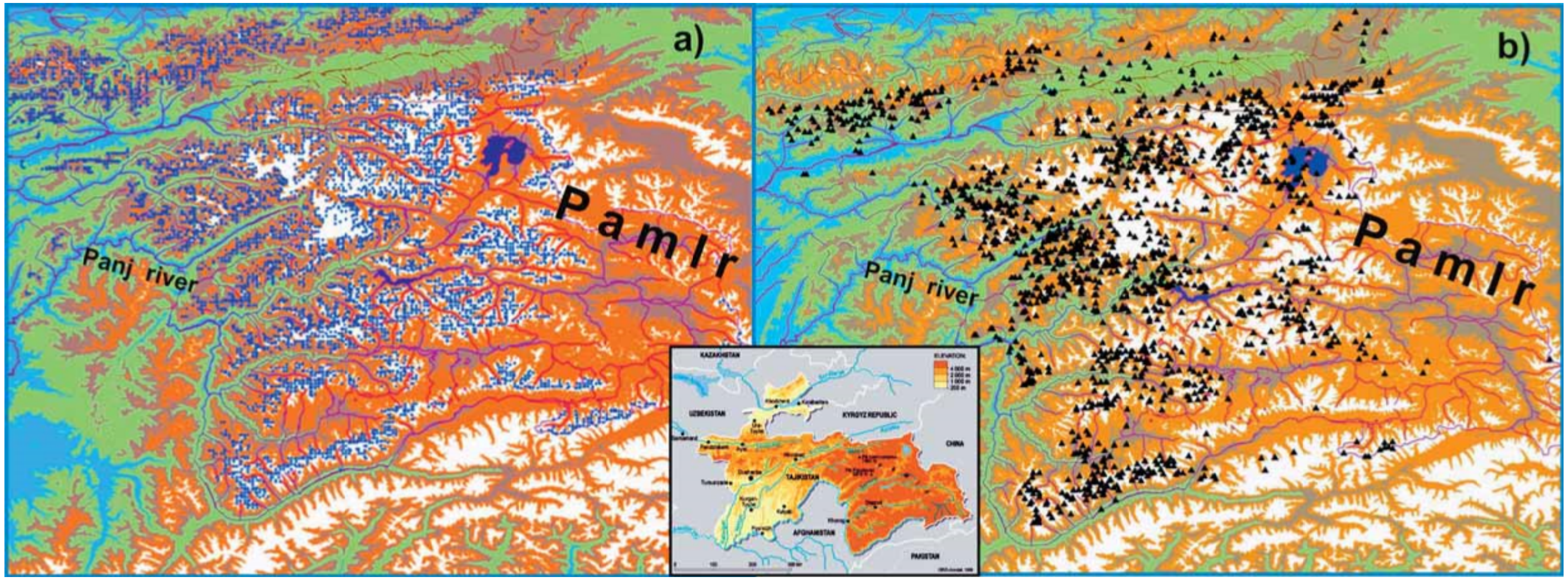
The quality of generalization of remote sensing data depends on the subjective and objective conditions of identification and digitizing glaciers on satellite images of glacial areas, as well as relates to the vertical and horizontal resolution of DEM. The negative impact of the subjective factor can be reduced by ensuring the employment of qualified experts and by using some service functions of the GOOGLE EARTH program for the purpose of identifying objects. The resolution power of the DEM SRTM3, available in the public domain, is 20 m horizontally and 16 m vertically at the 90% significance level [SRTM, 2003]. Analysis of the quality of SRTM3 has shown that application of this DEM correspond to the topographical maps of scale 1:50 000 [Jarvis et al, 2004].

Regionalization of the glacierized territory is one of the necessary stages in generalization

Table 1. Half-open intervals of area to identify homogeneous groups of glaciers in the eight sets of aspect

Numbers	Intervals of area in km^2							
1–8	(0; 0.1]	(0.1; 0.2]	(0.2; 0.3]	(0.3; 0.4]	(0.4; 0.5]	(0.5; 0.6]	(0.6; 0.7]	(0.7; 0.8]
9–16	(0.8; 0.9]	(0.9; 1.0]	(1.0; 1.5]	(1.5; 2.0]	(2.0; 2.5]	(2.5; 3.0]	(3.0; 4.0]	(4.0; 5.0]
17–23	(5.0; 6.0]	(6.0; 8.0]	(8.0; 10.0]	(10.0; 40.0]	(40.0; 70]	(70.0; 100]	> 100	

Note. A half-open interval means that variable x is inside of the limits a and b ($a < x \leqslant b$).



#Fig. 1.

a) Glaciation in the Vahsh and Panj river basins (origins of the Amu Darya river within the Pamir mountain region), ■ – means individual glaciers (N_{gl} = 6 262);.

b) Regionalization of glaciers in the Vahsh and Panj river basins, ▲ – means groups of glaciers (N_{gr} = 1 473).

a given aggregation of glaciers. Delineation of hydrological basins such as those in the former USSR Inventory [Vinoradov, et al, 1966] should be considered the most appropriate approach, because it allows using the water balance equation in the development and validation of hydrological and glaciological models. The same principle was used by [Shi Yafeng, et al, 2009] in structuring China's glaciation, initially for 10 hydrological territorial units and dividing them afterwards into 31, 102, 349, and 1462 separate sub-basins. Data in glacier catalogs and vector polygons of glaciers in each of these sub-basins are necessary and sufficient information in order to generalize glaciation into homogeneous groups and to determine the set of their morphometric parameters.

Characteristics of glaciers from the WGMS, Global Inventory of glaciers [WGI – World Glaciers Inventory, 2007] were used to prepare an expanded set of input data and calculation parameters for groups of glacier in the High-Mountain Asia. Brief results of this work are presented in Table 2, and detailed ones were used for comparative studies of the properties of glaciation and for calculation and prediction the glacier runoff [Agaltseva and Konovalov, 2005; Konovalov, 2006, 2007]. Location of large Asian river basins with these glacier groups illustrates Fig 2.

The spatial distribution of glacier parameters was analysed by using data for the following river basins representing a wide range of climatic conditions within the High-Mountain Asia: the Yurunkash river (`right tributary of the Tarim river), the Syr Darya river; tributaries of the Vakhsh river (Kyzylsu, Muksu, Obihingou, Surhob), the Brahmaputra river, tributaries of the Indus river (Astor, Beas, Jhelum, Ravi,

Table 2. Parameters of glaciation in the Central and High Mountain Asia

Region	River Basin	Ngl	Fgl km^2	Ngr
Asia	Vakhsh (4 basins)	2 012	3 361	500
Asia	Zeravshan	892	687	117
Asia	Panj (11 right side tributaries)	3 970	3 848	1 019
Asia	Syrdarya	3 429	2 522	148
Bhutan	Ganges tributaries	677	1 313	146
India	Indus tributaries (4 basins)	2 182	3 913	477
China	East Asia Basins	11 795	21 767	178
China	Central Asia basins	2 385	2 048	142
China	Kara Irtysh	403	289	90
China	Mekong	380	316	101
China	Ganges tributaries	13 006	18 100	173
China	Indus tributaries	2 032	1 451	134
China	Salween	2 021	1 730	145
China	Tibet	536	5 230	96
China	Yellow	121	130	56
China	Yangtze	1 324	1 893	148
Nepal	Ganges tributaries	3 252	5 322	435
Pakistan	Indus tributaries (6 basins)	2 808	7 223	570
	In total	53 225	81 144	4 675

Note. Ngl and Fgl are the number and area of glaciers by data of WGI from February 2012 and Concise Glacier Inventory of China, 2008; Ngr is the number of glacier groups generalized by the method described in this paper.

Fig. 2. High Mountain Asia river basins as objects of the research.

Sutlej, Chenab, Shayok, Shigar, Shingo), and tributaries of the Ganges river in Nepal and Bhutan. Processing was done for 27 698 glaciers with the total area of 43 981 km^2; 3 533 generalized groups were identified. By means of these data, were obtained characteristics of spatial distributions for the areal and altitudinal parameters in the glacier groups, based on the totality of glacier data in the considered region, but not on limited sample of so called "representative" glaciers.

We found that (a) for all orientations of glaciers and their area of up to 0.4 km^2, the minimum altitude (Ze) has a fairly close relationship with geographical longitude; (b) this dependence decreases linearly with the growth of area; (c) the minimum glacier altitude for all orientations and area of more than 40 km^2 has practically no relationship with geographical longitude; (d) similar dependences also revealed for the maximum glacier altitude (Zb), although with lower values of correlation coefficients; and (e) the spatial correlation of Zb and Ze with geographical latitude for all orientations and gradations of glacier area is significantly smaller than with longitude.

The distributions along longitude for average weighted values of minimal, mean, and maximal altitudes of glaciation and its area have also been obtained (Fig. 3) for the river basins of High-Mountain Asia. Distribution of altitudinal and areal parameters of glaciers are directly related to the problem of relationship between climate and glaciers, since to describe spatial distribution and calculate the climatic characteristics are also used geographic coordinates and altitude. We mean here two types of time-varying spatial distribution functions: (a) morphometric parameters of glacier groups and (b) main climate factors affecting the regime of glaciers (precipitation, air temperature) and establishing a link between these two functions of distribution.

Baseline data to study and describe regime of glaciers in river basins

Assessment of the hydrological regime of glacier groups was based on the regional and global data sources on hydrology, glacier parameters, precipitation, air temperature and humidity, clouds, and other influencing climatic factors (links to the sources of data are listed in References).

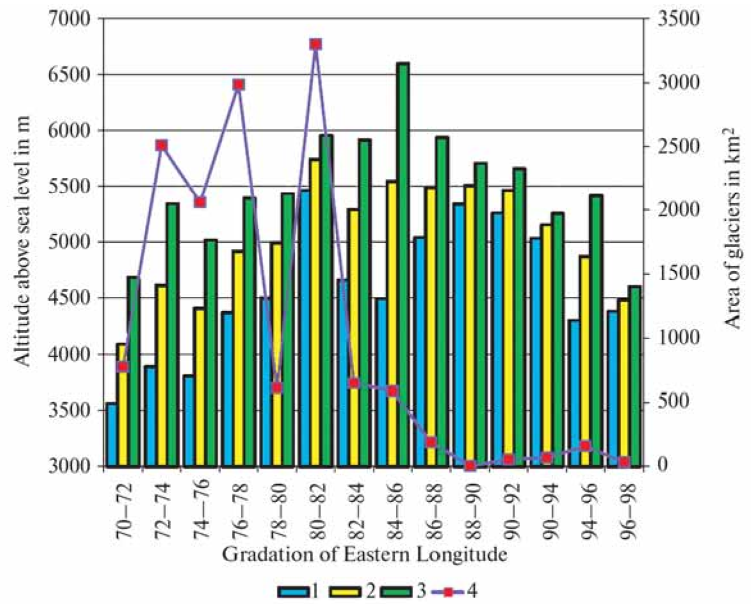


Fig. 3. Topography parameters of glaciation distributed along longitude within river basins of the High Mountain Asia. Aspects N, NE, NW are used.

1, 2, 3 – are respectively minimal, maximal, and average altitudes of glaciers' weighted by area, 4 – is area of glaciers

Meteorological data.

[Former Soviet Union Monthly Precipitation Archive, 1891–1993; GSOD (Global Summary of Day) 1929–2014; GHCN (Global Historical Climatology Network Database) v.2; CRU TS (Climate Research Unit Time Series) 3.0 1901–2006; WorldClim – Global Climate Data; Williams and Konovalov, 2007].

Regional and global data on runoff.

[GRDC (Global Runoff Data Center); Bodo, 2000]. This information includes data on runoff during the years 1881–1995 for 316 gauging stations from the archives of NCAR ds553.1 and for 2 134 gauging stations from the database of the State Hydrological Institute, Russian Federation.

Regional and global data on glaciers.

[WGI – World Glacier Inventory; GLIMS (Global Land Ice Measurements from Space); Fluctuation of Glaciers for 1959–2007; Catalog of the USSR glaciers, 1971–1978; Schetinnikov, 1997].

Preliminary assessment of the available initial data shows that their informational content and quantity is sufficient to calculate hydrological regime of glaciers in the High-Mountain Asia at the level of large river basins.

Methods of calculating runoff and evaporation in the area of glaciation

Unlike traditional studies on the specific values of heat and water-ice balance [e.g., Anderson, 1976; Cherkasov, 2004], we modeled and calculated the total runoff in the basin above a gauging site by means of independent evaluation of precipitation, evaporation, glacial runoff, and the dynamic water resources, as components of the annual river basin water balance equation. Statistical analysis of difference between calculated and measured runoff at gauging sites was used to assess the quality of calculations involving the water balance components.

The equation of the annual water balance for the river basins where runoff formed mainly due to snow and glaciers melting, has the form:

$$R = K_R(P - E + W_{gl}) + \Delta W \text{ inkm}^3, \tag{1}$$

where R is runoff, P is precipitation, Wgl is melting of perennial ice and firn resources, E is evaporation, ΔW is dynamic resources of water in the basin, K_R is coefficient transformation of the volume of water on the surface of a basin into river runoff. In equation (1) R – is a directly measured characteristic. In order to determine other components, we used different models and methods of calculation. Due to small variability of runoff during of low-flow period, its volume from January to March was accepted as estimation of ΔW value in equation (1).

The general form of the formula for calculating volumes of precipitation, evaporation, and other variables as one-dimensional function of altitude z in the range Zmin–Zmax, is:

$$X_2 = \int_{Z\min}^{Z\max} x(z)s(z)dz, \tag{2}$$

where $x = x(z)$ is a given function of altitude, $s(z)$ is distribution of area in the altitudinal range Zmin–Zmax. Applying the generalized mean value theorem in integral calculus to the integral of the product of functions $x(z)$ and $s(z)$, we obtain:

$$X_z = x(\tilde{z}) \int_{Z\min}^{Z\max} s(z)ds, \tag{3}$$

where $F = \int_{Z\min}^{Z\max} s(z)dz$ is area in the range Zmin–Zmax.

And finally:

$$X_z = x(\tilde{z})F, \tag{4}$$

or for the mean value $\bar{x} = x(\tilde{z})$, where $\tilde{z}$ is the certain elevation in the interval Zmin–Zmax. In [Borovikova et al, 1972] have shown that when $x(z)$ is approximated by a parabola, the form of a formula to determine the average value of x in the range Zmin–Zmax is:

$$\bar{x} = x(z_0)[1 + k_2(\tilde{z} - z_0) + k_3(\tilde{z} - z_0)^2] + x(z_0)k_3\sigma_Z^2, \tag{5}$$

And for the linear version of $x(z)$:

$$\bar{x} = x(z_0)\left[1 + k_2(\tilde{z} - z_0)\right], \tag{6}$$

where the first term in the right side of (5, 6) is equal to $x(\tilde{z})$ at using given value $\tilde{z}$ for elevation z, $x(z_0)$ – is known value of $x(z)$ at the elevation z_0, k_2 and k_3 are empirical coefficients, and σ_z^2 is the variance of z in the range Zmin–Zmax. Thus, for any linear and quadratic functions $x(z)$, we have a strict equality between the average values of the dependent variable and its value at the weighted average elevation in the range Zmin–Zmax.

The physical-statistical model REGMOD for processes of accumulation and ablation of snow and ice in the glacial regions of Central Asia, as detailed in the works [Konovalov, 1985, 1994, 2006, 2007], is applied to determine Wgl.

A simplified version of the model REGMOD is based on application of the findings and conclusions in paragraphs 3.1, 3.3. Simplifications are as follows: (a) calculations of Wgl are performed only for the long-term average and extreme values of air temperature, evaporation, and precipitation in the watershed; (b) dependence of M on the average summer air temperature is used instead of melting rate M as a function of the absorbed solar radiation and air temperature; (c) morphometric parameters of glaciers are adopted invariant for the entire computing period, and (d) calculation of glacier runoff and evaporation is limited to the time interval June-August or the summer season.

In the long-term average case, according to equation (1) of water balance for the river basin, the glacial runoff forms within the area of each glacier from its end Ze to the elevation of firn boundary Zf. The author's model includes estimation of the following components of glacial runoff: melting snow, old firn, open ice, and ice under the moraine cover. Thus, the total melting of glacier is modeled as the sum of three components: M1 = M1(Ze – Zuml), M2 = M2(Zuml – Zf), M3 = M3(Zf – Zb). It is clear that in the absence of moraines, M1 = M1(Ze – Zf) and M2 = 0. Here, Zuml is the upper level of continuous distribution of the moraine cover. This important characteristic can be found from the formula (7).

$$Zuml = Ze + (Zf - Ze)\Omega \quad (7)$$

where Ω = Fmor/F(Zf). Fmor is the area of solid moraine, F(Zf) is the area of ablation zone and both of them are generalized parameters in the groups of glaciers. The sense of the expression (7) is obvious: the greater relative area of the moraine in the ablation zone, the higher level of moraine distribution in the altitudinal range Ze–Zf. Next, we determined the open ice area Fice in the range of altitudes Zuml – Zf : Fice = = F(Zf) – Fmor and the average elevation in this interval Zice = (Zuml + Zf) · 0.5. The formula for determining the average elevation from Ze to Zuml is similar: Zmor = = (Ze + Zuml) · 0.5. All altitudes: Ze, Zmor, Zuml, Zice, and Zf are averages weighted by the area, which used to determine volumes of melting in the groups of glaciers. As the estimation of Fmor is used the difference between the total and exposed areas of a glacier from the World Glaciers Inventory [WGI, 2007].

We calculated the annual precipitation and evaporation in (4) at the weighted average altitude of the catchment for the area above the measurement station of a runoff.

The working formulas to determine long term averaged volumes of glacial runoff Wgl (km^3) and evaporation Egl (km^3) in the i-th group of k-th glacial basin are as follows:

$$Wgl = Wice + Wmor \quad (8)$$

$$Wice[i, k] = M1(Zice[i, k], \varphi[i, k], \lambda[i, k]) \cdot Fice[i, k] \quad (9)$$

$$Wmor[i, k] = M2(Zmor[i, k], \varphi[i, k], \lambda[i, k]) \cdot Fmor[i, k] \quad (10)$$

$$M1(Zice[i, k], \varphi[i, k], \lambda[i, k]) = (a \cdot Ts(Zice[i, k] + c[i, k]) \cdot Nice[i, k] \quad (11)$$

$$M2(Zmor[i, k], \varphi[i, k], \lambda[i, k]) = (a \cdot Ts(Zmor[i, k] + c[i, k]) \cdot Nice[i, k] \quad (12)$$

in (11–12) a ~ const = 0.57; c[i, k] = = 0.26 · Z[i, k] – 0.33 · φ[i, k] + 0.09 · λ[i, k] + 6.72

$$Egl[i, k] = e(Zgl[i, k]) \cdot Fab[i, k] \quad (13)$$

$$e(Zgl[i, k]) = f\{PE(Zgl[i, k]), X(Zgl[i, k]), pv(Zgl[i, k]), Ts(Zgl[i, k], \varphi[i, k], \lambda[i, k])\} \quad (14)$$

$$Ts = Ts(Z[i, k], \lambda[i, k], \varphi[i, k]); \quad (15)$$

$$X = X(Z[i, k], \lambda[i, k], \varphi[i, k]) \quad (16)$$

$$pv = pv(Z[i, k], \lambda[i, k], \varphi[i, k]) \quad (17)$$

here, M1 and M2 are the layers (in mm) of melting open (bare) ice and ice under moraine for Nice = 92–Nsnow days without precipitation during summer (June–August) in points Zice([i, k], φ[i, k], λ[i, k]) and Zmor([i, k], φ[i, k], λ[i, k]) with the coordinates φ – latitude, λ – longitude; Nsnow is the number of days with snow deposition, including the duration of its melting; β(Hc(Zmor[i, k]) is the attenuation function of melting ice under solid moraine of depth Hc at an altitude Zmor[i, k]; Zgl[i, k] is the weighted average elevation of the ablation zone; Fab is the area of ablation; Ts is the average air temperature during a summer; pv is the average partial pressure of water vapor in the air for summer at the same point, where the layers of melting M1 and M2 were determined; Zgl is the average elevation of the glacier; Egl[i, k] is the volume of summer evaporation from glacier area Fab[i, k]; e(Zgl[i, k]) is evaporation rate; PE is the largest possible value of evaporation under given conditions of moisture; X is the seasonal precipitation.

Spatial extrapolation of the temperature Ts and the water vapor pressure pv play a key role in simplified method of calculation Wgl and Egl. Depending on the availability of input data, calculation Ts(Z[i, k], φ[i, k], λ[i, k]) can be done in several ways.

1) A local linear extrapolation of the data $Ts(Z_0, \varphi_0, \lambda_0)$ at a basic weather station for the determination of Wgl and Egl:

$$Ts(Z[i,k], \varphi[i,k], \lambda[i,k]) = Ts(Z_0, \varphi_0, \lambda_0)[1 + k_1(Z - Z_0) + k_2(\varphi - \varphi_0) + k_3(\lambda - \lambda_0)] \quad (18)$$

2) A regional extrapolation and averaging of data from several weather stations. Application of the second method is expedient in the absence of local data on air temperature:

3) $$Ts(Z[i,k], \varphi[i,k], \lambda[i,k]) = K_T - \gamma \cdot Z \quad (19)$$

here, K_T, $k_1 - k_3$ are empirical parameters, γ is the vertical lapse rate of air temperature. The same approaches are acceptable for spatial extrapolation of the water vapor pressure pv.

The model of water output from a glacier area should also describe different conditions of runoff formation in the ablation and accumulation subareas. For this purpose may be used equation (20), which was obtained in [Konovalov, 1985] for the most typical features of runoff formation in ablation (Ab) and accumulation (Ac) subareas on the Asian glaciers

$$Wgl = Vm(Ab) + (Vm(Ac) - Vm(Ab)/3.5) \quad (20)$$

here Vm(Ab) and Vm(Ac) – are correspondingly the volumes of annual surficial ablation within Ab and Ac subareas of a glacier, diacritic symbol over Vm means long term averaging. Equation (20) is valid until Vm(Ac) > Vm(Ab)/3.5.

APPLICATION OF THE ELABORATED METHOD

Table 3 presents the averaged results of calculation of all components in the right side of equation (1) for 1961–1990 as an example in the Brahmaputra, Vakhsh, Zeravshan, Sokh, Isfairam, Akbura, and Pskem River basins. It is important that these basins have different total and glaciers area. Quality assessment of calculated precipitation, evaporation, and glaciers runoff was obtained by substituting values of P, E, and Wgl in the equation (1) and comparing right and left sides of the annual water balance equation. In Table 3, we see that the difference between measured Rm and calculated Rc river runoff is rather small. This is a confirmation of the fact that the model and methods used in our research are of sufficiently good quality and could be applied in the Asian river basins for determining components in the right side of equation (1). However, it is true only if there is sufficient and reliable input information for equations (4–20); the most important are the data on precipitation. As it is well known, the unresolved uncertainty in estimation of areal precipitation is the main obstacle in applying climate models of different scales. Negative difference dR in Table 3 between the measured and calculated values of river runoff is explained well by water intake for irrigation and hydropower water reservoirs above the used gorging site. In the considered river basins according to AQUASTAT: http://www.fao.org/nr/water/aquastat/, which is FAO's global water information system, water intake for irrigation varies from 2–3% to 10–15% of the annual river runoff. Besides, there is the Papanskoe irrigation water reservoir with area of 7.1 km^2 and capacity of 260 mln m^3 located in the Akbura river basin above the Tuleken gorging site (gs). From the same information system and in [Rahaman & Varis, 2009] we see that similar irrigation water reservoirs located in the transboundary Brahmaputra river basin distort the natural regime of runoff above the Pandu gs.

Table 3. Annual water balance for some Asian river basins (mean values for 1961–1990)

River	gs	Long	Lat	Alt,	Fbas	Fgl	Rm	R(I–III)	P	E	Wgl	Rc	dR	dR	E/P	η
		grad, E	grad, N	m a.s.l.	km^2	km^3	%									
Brahmaputra	Pandu	72.52	40.24	3 384	405 000	14 113	574	40	719	162	41	639	–65	–11.3	22.5	0.80
Vakhsh	Komsomolabad	71.68	39.17	3 600	29 500	3 824	18.85	1.37	26.3	11.1	3.21	19.81	–0.96	–5.1	42.2	0.72
Zeravshan	Dupuli	67.48	39.29	3 100	10 200	674	4.84	0.30	11.1	4.73	0.34	4.95	–0.11	–2.3	42.7	0.42
Sokh	Sarykanda	71.13	39.95	3 030	2 480	252	1.38	0.08	2.0	1.11	0.33	1.51	–0.13	–9.4	56.2	0.70
Isfairam	Uchkorgon	72.05	40.11	3 240	2 200	102	0.66	0.09	1.3	0.84	0.13	0.69	–0.03	–4.5	64.1	0.50
Akbura	Tuleken	72.52	40.24	3 030	2 430	114	0.63	0.06	1.5	0.99	0.19	0.73	–0.10	–15.9	67.8	0.43
Pskem	Mullola	70.20	41.77	2 690	2 540	125	2.52	0.20	3.2	0.84	0.22	2.75	–0.23	–9.1	26.7	0.80

Note. gs – gorging site, Long, Lat – correspondingly geographical coordinates in decimal degrees, Alt – altitude above sea level, Fbas – basin area above gs, Fgl – glacier area in the basin, Rm –annual river runoff, measured at the gs, R(I–III) –volume of river runoff during January–March at the gs, P – annual sum of precipitation in the basin, E – total sum of evaporation, Wgl – annual glacier runoff, Rc – annual river runoff calculated aby the equation (1), dR – difference between Rm and Rc, η = Rm/P – runoff coefficient.

GLACIER RUNOFF AND THE OCEAN LEVEL

All continental glaciers, ice caps, and ice sheets should be hydrologically differentiated as: (1) marine-terminated, (2) not marine-terminated but having connection to the World Ocean through the river flow, and (3) not marine-terminated and located in closed river basins (not drained to the World Ocean). Simple and rather informative parameter of glaciers contribution to the level of World Ocean could be volume of inflow Vin being determined by formula Vin = μWgl. The coefficient μ is a full analog of coefficient runoff η in formula Rm = ηP (see Table 3), which shows that only certain part of precipitation P could be transformed into river flow. This is well-known and used without exception in hydrological calculations and no explanation exists why all contemporary determinations of Vin (e.g., IPCC 5-th Report) do not include coefficient μ. According to the three types of hydrological differences, which are identified above and depending on the distance between river mouth and location of glaciers, may be applied the next approximate values of coefficient μ: (1) 0.9–1.0; (2) 0.3–0.6; (3) 0.0–0.1. Surely, the spatial distribution of μ has to be studied. Since the coefficient μ was not included in the estimations of past, current, and future contribution of glaciers runoff to the level of World Ocean contained in the IPCC 5-th Report [IPCC, Climate Change 2013] and many other relevant publications, these results have to be revised only on this reason.

The other even more important reason is quality and representativeness of direct measurements of annual mass balance for very limited and random samples of so-called "typical" glaciers, which are used for global estimation of change the World Ocean Level under influence of glacier runoff. The representativeness of such "typical" glaciers regarding to the relevant general population is not proved. Besides, usage of the limited number of data on "typical" or "reference" glaciers for broad regional or global synthesis inevitably leads to uncertainty in these conclusions. For example, our processing of data in the Supplementary to Bahr et al [2009] revealed that average, maximal, and minimal completeness (in %) of mass balance measurements by years was as follows: for Asia and Caucasus, 28.4, 45.2, and 2.4 (42 glaciers during 1957–2000); for Europe, 26.8, 52.0, and 2.0 (100 glaciers during 1946–2003); and for America` 27.8, 50.7, and 1.5 (69 glaciers during 1953–2004). Thus, during of long-term period only around 30%, on average, of not synchronized and essentially unevenly distributed mass balance data were available and used for global conclusions. In, Bahr, et al. [2009], Dyurgerov [2010], IPCC 5-th report [2013], and in other publications, it is believed that all the glaciers provide drainage to the Ocean, though, for example, in Eurasia, the number, area and volume of glaciers' not drained basins is 57%, 56% and 62% of the total glaciation, respectively. Also, published calculations (e.g., IPCC 5-th report [2013]) lack independent verification by means of water balance equation of the influence of glacial runoff on the Ocean level.

The impact of glaciation on the volume of annual or seasonal runoff is inversely proportional to the distance from origins to mouth of the rivers. For example, relative contribution of glacial runoff in the mouths of the major Siberian rivers Ob, Yenisei, Lena, and Indigirka equals to, respectively: 0.6–0.7%, 0.03%, 0.02%, and 0.75% of the annual river runoff. According to calculations made by Krenke [1982], the norm of runoff from melting of the long-term resources of ice and firn of all glaciers within of the former Soviet Union was 24.1 km^3. Of this amount, the Ocean has received 14.58 km^3 (60.5%) and 9.52 km^3 was left in drainless basins.

Even at the maximum overestimation of the global glacial runoff made by Meier and Dyurgerov [2007], its average annual volume for 1961–2003 amounted to only 1.8–1.9% of the annual inflow to the Ocean from continental rivers of the Earth. Obviously, in such proportions of these components of the hydrological cycle and a very low long-term variability of the annual river runoff, it does not make sense to consider the contribution of the glacier component in the change of the Ocean level, as rightly noted by Malinin [2009]. Undoubtedly, the actual water output from all continental glaciers is at least half of the value proposed by Meier and Dyurgerov [2007].

Our statistical processing of data in World Water Balance [1974] showed that the coefficient of correlation between the Ocean level and the annual inflow there from rivers in Europe and Eurasia varies from –0.30 to 0.09 and the coefficient of variation for inflow of the same rivers changes from 0.04 to 0.20. At the same time, the coefficient of variation of the Ocean level was 2.23, which is much greater than the variability of the annual river runoff in Europe and Eurasia.

Thus, glacial runoff, which forms in different types of river basins, influences the Ocean level to a much lower degree than is described previously in the 5-th IPCC report [IPCC. Climate Change, 2013], Dyurgerov and Meier, [2007], Bahr, et al. [2009], and Dyurgerov [2010].

DISCUSSION

Rather than using the concept of "typical" or "reference" glaciers, our method, described in our research takes into account the peculiarities of the spatial distribution of all glaciers in a large river basin and can serve as a basis for essential improving of future glaciological and hydrological calculations. In this method, the quality of generalization for glacier parameters is not related to the subjective decisions of researchers and depends only on the completeness and reliability of the data sources. An extensive set of parameters obtained for the characteristic groups of glaciers is a sufficient basis for a comparative analysis of morphometry of glaciers and modeling components of hydrological cycle.

Here is necessary to emphasize that a broad application of the suggested method to measure, model, and calculate all components of equation (1) depends strongly on availability to operate at the regional scale with representative and reliable data on runoff, precipitation, air temperature, vapor pressure in the air, and area-altitudinal parameters of glacier. For example, measurements of river runoff should relate to rather large area of a glacierized watershed and should not be distorted by irrigational water intake.

Calculations by formulas (15–17) reflecting the dependence of precipitation, air temperature, and water vapor in the air on the altitude and geographic coordinates will be successful if original meteorological data cover or approach the range of altitudes where the glaciers are located. The number of meteorological stations is very limited in the upper watersheds of the rivers in the territory of the Himalayas, the Hindu Kush, and the Tibet. In this situation, in order to obtain formulas (15–17), we should use information from the regional and global climate databases: APHRODITE [Yatagai et al, 2012], CRU [CRU Datasets – CRU TS Time-Series, 1901–2009], GPCC: http://gpcc.dwd.de, UDEL [Willmott and Matsuura, 1995], WORLDCLIM:http://www.worldclim.org/current and others. If several empirical formulas for the same function are obtained, we may choose the most suitable expression for minimizing the difference between the measured and calculated runoff according to equation (1).

CONCLUSIONS

Determination of glaciers runoff is required for meso- and macro-trend analysis of the evolution of glaciation, in the study of similarities and differences of glacial complexes, and in solving problems related to water use, runoff forecasts, and sustainable development of mountain areas at the river basin scale. Specifics of the considered problem lies in the fact that the components of the annual water balance for the whole glacial areas can only be obtained by computational methods. This places high demands on the initial information, validity and spatial applicability of main applied decisions in mathematical modeling of runoff in glacierized basins. This statement agrees well with the conclusion made in [Cryosphere Theme Report, 2007] that updated methodology for estimating mass balance of glaciers should be based on meteorological data, in synergy with remote sensing data, to give a more comprehensive picture of mass balance in various climate zones and globally.

Assessments of the components of the water balance should be seen as a stage in a multifaceted system of description and prediction the long-term regime of rivers fed by snow and ice melting.

The methods used in our research to calculate the annual amount of precipitation, evaporation, glacier runoff, and dynamic water reserves are sufficiently reliable and suitable for other basins in the Central Asia with a similar type of runoff formation, as these methods provide quality of calculated river runoff, which is comparable with its measurements.

Application of generalized areal and altitudinal parameters for groups of glaciers has improved spatial extrapolation the climatic factors of runoff and has allowed comparison of parameters of hydrological regime of glaciers in different river basins.

This paper suggests a new method on regionalization of glacier populations and presents examples of its application in the Asian river basins. It demonstrates a new potential for the objective description of the spatial distribution of the areal-altitudinal parameters of glaciers and for usage of this information in statistically substantiated glaciological and hydrological models and computations.

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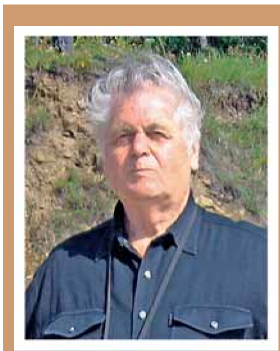

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