The correlation between variations of climatic factors and zonal runoff of mountain rivers

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Abstract A mountain river catchment is a territory of variable absolute height, with climatic factors influencing differently the runoff coming from the different altitudinal zones (zonal runoff). In the conditions of unstable climate, hydrological forecasting calls for more detailed study of the impact made by changing climatic factors, not only on total runoff, but also on zonal runoff. The correlation of the zonal runoff with air temperature and precipitation sums is investigated, with the example of the mountain rivers of the Upper Amu Darya basin. Time series of annual total and zonal runoff and their changes during the observation period are analysed. Annual zonal runoff values are estimated using the total runoff values from gauging stations. For this, the Tikhonov regularization method is applied to solve the corresponding ill-posed inverse problem. The territory is delimited into homogeneous regions according to the different character of average annual zonal runoff dependence on height. The fluctuations of zonal runoff values, calculated for several altitudinal zones inside each of the homogeneous regions, are compared with those of air temperature and precipitation sums measured on the nearest meteorological stations to find the correlation. The zones of strong correlation of zonal runoff with climatic factors were found to have different altitude in different regions, depending on the peculiarities of their natural condition. The closest correlation is found between precipitation sums and the runoff from upper and medium altitudinal zones. The correlation with air temperature is only found in one of the homogeneous regions.

Key words zonal runoff; mountain rivers; Upper Amu Darya; ill-posed problems; Tikhonov regularization

INTRODUCTION

Climate nonstationarity is now one of the main factors influencing the changes in river flows. However, modern changes in temperature and precipitation may have different influences on the formation of mountain river runoff in different altitudinal parts of a catchment because of the altitudinal zonality typical of mountainous rivers. Runoff measured at the gauging station characterizes a resulting amount coming from different altitudinal parts of a mountain basin, where changes in climatic characteristics and their impact on local runoff may be different. For example, increase in air temperature may reduce runoff in lower parts of a catchment increasing the evaporation. On the other hand, temperature increase may cause more active glacial melting, thus increasing runoff from the upper parts of a catchment. To make a forecast of the total runoff – the so-called integral runoff measured by a gauging station – it is necessary to take into account all the processes which may act in contrasting directions. To do this, estimating zonal runoff, runoff coming from the different altitudinal zones – is proposed.

METHOD

According to M. Bolshakov (Bolshakov, 1974), a mountain river basin can be delimited into altitudinal belts, and we can assume that the specific runoff inside each of these belts does not vary by territory. Then the specific runoff calculated for all the basin area of the gauging station (integral runoff) is a sum of specific runoff values of all these altitudinal belts (zonal runoff).

$$M = \sum_{i=1}^{n} s_i m_i \qquad (1)$$

Here, M is integral runoff, i is the number of an altitudinal belt, n is the total number of the altitudinal belts, m_i is zonal runoff from the ith altitudinal belt inside the catchment, s is the relative area of the ith altitudinal belt.

Let us consider a mountainous area which we assume to be homogeneous from the point of view of natural conditions responsible for runoff formation: temperature and precipitation regime and the relief features. Then, we can assume zonal runoff values to be the same within the delimited altitudinal belts for all the rivers inside the region. Therefore, we can write equation (1) for each of the gauging stations inside this homogeneous region, and obtain the following system of linear equations:

$$M_1 = \sum_{i=1}^{n} s_{1,i} m_i$$

$$M_2 = \sum_{i=1}^{n} s_{2,i} m_i \qquad (2)$$

$$\dots$$

$$M_k = \sum_{i=1}^{k} s_{k,i} m_i$$

Or, in the matrix form,

$$Sm = M \qquad (3)$$

Here k is the number of a gauging station, S is the matrix with elements $s_{k,i}$. After solving this problem, we can obtain zonal runoff values for a homogeneous hydrological region.

However, in the process of the solution we come across a mathematical difficulty: the system (3) is ill-posed. This means that the solution may be not unique, and small errors of the initial data may result in large errors of the solution. As the measurements are always taken with some errors, in such a case we can obtain a solution of system (3) which would differ greatly from the real one. M. Bolgov was the first to use Tikhonov regularization (Tikhonov & Arsenin, 1974) to solve the problem of zonal runoff for the example of the Mongolian rivers (Bolgov & Trubetskova, 2008). The Tikhonov regularization method calls for some kind of *a priori* information. This requirement was satisfied by appointment of the errors of the right part in equation (3) which characterizes the measurements errors. In our investigation we considered it to be 10%.

We can get a reasonable solution if the region for which system (3) is written is really homogeneous. Otherwise, the values of zonal runoff are different for different rivers, and system (3) is inconsistent. This makes the correct regionalization of the territory very important.

The process of regionalization has several stages. For the first approximation, the regionalization is carried out according to the traditional method for mountain hydrology: it is based on the dependency of integral runoff on height: $M = f(H_{av})$. For each of the regions obtained in such a way, system (3) is written based on the runoff measurements carried out on the gauging stations inside it. The solution of the system gives the values of zonal runoff. The altitudinal interval is taken at 600 m. The extreme upper altitudinal belts are combined into one for each of the regions, because their relative areas are too small, and their input into the integral runoff is less than the runoff norm error. Then the received solution is tested. For this, the estimated values of zonal runoff are substituted into system (3) to calculate the values of integral runoff for each gauging station inside the region. The values of integral runoff calculated in this way are compared with the measured ones. If the difference is too large for any gauging station, we make a conclusion that the corresponding river basin has conditions different from the other basins within this region. The river basin is excluded from the region, the borders of the region are changed, and the problem is solved again, for the residual gauging stations and, consequently, for the smaller area. In such a way the acute regionalization of the territory was made.

DATA

The annual runoff values measured on 85 gauging stations of small and medium rivers belonging to Amu Darya, Kashkadarya and Zerafshan basins were used. The time series have different length, varying from 10 to 76 years; the observation period for all the gauging stations ends in 1985.

We also used time series of annual precipitation sums and average air temperature obtained from four meteorological stations located within the limits of the Amu Darya River basin (Fig. 1) with the longest observation period. However, the longest time series ended in 1995. The stations are located at different heights: from 1316 m (Garm) to 1616 m (Tavil-dara).

RESULTS

Hydrological regionalization of the territory including river basins of the Upper Amu Darya, Zeravshan and Kashkadarya is carried out based on the dependence of zonal runoff values on altitude (Fig. 1). Six homogeneous regions were distinguished.

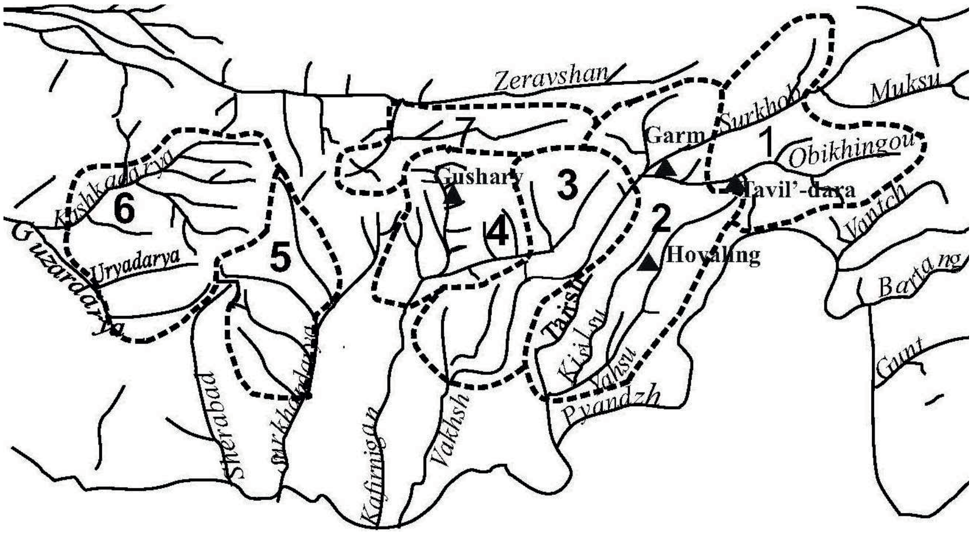

Fig. 1 Homogeneous hydrological regions of the Upper Amudarya, Zeravshan and Kashkadarya river basins. Figures are the numbers of homogeneous regions, ▲ – are meteorological stations.

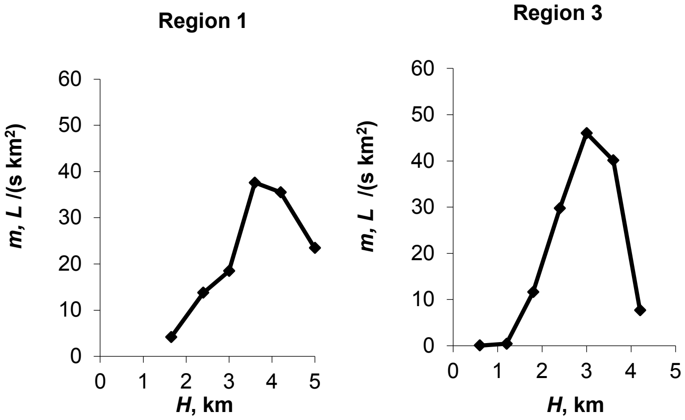

Fig. 2 Zonal runoff values *m* in different altitudinal belts for two hydrological regions of the Amu Darya basin. *H* is the average altitude of an altitudinal belt.

Values of the average annual runoff were calculated using average annual values of the specific integral runoff. The examples of the received dependences of zonal runoff on altitude are shown in Fig. 2 for the two regions located within the Amu Darya basin. We found some features of the zonal runoff dependence on height common for all the delimited regions. In the lowest parts of mountain rivers basins, mostly at the heights where a river exits from mountains to a plain, the zonal runoff values are very low, often close to zero. Then, higher, the runoff values grow with a height up to altitudes 3–3.5 km; at greater heights the runoff decreases.

Four regions were chosen to analyse the correlation between the zonal runoff values and the climatic features (numbered 1–4). These regions belong to the Upper Amu Darya basin, the gauging stations inside them have the longest runoff time series. For these regions, values of zonal runoff for each year were estimated. Correlation was investigated between the zonal runoff values and climatic characteristics such as air temperature and annual precipitation sums measured on meteorological stations inside each of the regions or close to their borders. Correlation coefficients are in Tables 1, 2. As the regions are located at different heights, the upper and the lower altitudinal belts for zonal runoff calculation may be different in different regions.

Table 1 Correlation coefficients R between zonal runoff values and annual average temperature on the nearest meteorological station.

Altitudinal belt, km Region	0.3–0.9	0.9–1.5	1.5–2.1	2.1–2.7	2.7–3.3	3.3–3.9	3.9–4.5	Higher than 4.5
1		–0.71		0.35	0.11	– 0.49	0.78	0.68
2	0.07	–0.51	–0.34	–0.13	0.14	0.14		
3		–0.20	–0.06	–0.08	–0.20	–0.29		
4		–0.20	–0.35	–0.57	–0.15	–0.08	–0.11	

Table 2 Correlation coefficients R between zonal runoff values and annual precipitation sums on the nearest meteorological station.

Altitudinal belt, km Region	0.3–0.9	0.9–1.5	1.5–2.1	2.1–2.7	2.7–3.3	3.3–3.9	3.9–4.5	Higher than 4.5
1		0.20		0.32	0.50	0.94	– 0.62	0.01
2	– 0.31	0.79	0.81	0.45	0.11	– 0.17		
3		0.40	0.74	0.78	0.77	0.47		
4		0.12	0.87	0.86	0.79	0.60	0.38	

The correlation between the zonal runoff and the air temperature was only found for one region (Region 1). In the lower altitudinal belt the correlation is negative, correlation coefficient equals to –0.71. In the belt higher than 3.9 km the correlation is positive.

The correlation between zonal runoff and annual precipitation sums is found for all the four investigated regions, but in different altitudinal belts. In Region 1 close positive correlation were found for the altudinal belt 3.3–3.9 km, the correlation coefficient was 0.94. In Regions 2, 3 and 4 a high correlation was found in the middle parts of the catchments.

DISCUSSION

The investigators studied altitudinal peculiarities of the mountain rivers' runoff by analysing the specific runoff estimated on gauging stations located at different absolute heights. One can obtain a dependence of the specific runoff on an average catchment height and thus make a conclusion about changes of water content with altitude. This approach is also the basis for a method of mountain territory regionalization: rivers with the same kind of dependence form a homogeneous region. But the main problem of mountain hydrology is a lack of gauging stations: most of them are located no higher than 2 km, and their catchments have an average height of no more than 3.6 km. Consequently, such a method does not give information about the upper parts of catchments, some of them reaching 7 km in Central Asia. The method of zonal runoff gives this information.

The discovered common features in the changes of zonal runoff values with height for all of the regions can be explained in such a way. Small values of the specific runoff in the lower parts of mountain river basins are caused by high evaporation in the arid territory of Central Asia. The other reason for this effect is the runoff losses in loose talus deposits. Heights of about 3–3.5 km, where the decreasing of zonal runoff is found, correspond to the firn line level. Low temperatures and termination of surface melting at altitudes higher than the firn line are the reason for the runoff extinction here. The zone between the firn line and the glacier tongues has the best condition for runoff formation, having the optimal balance of heat and moisture (Bolshakov, 1974).

One should take into account that in our study we used the runoff time series ending in 1985 and climatic time series ending in 1995 because of severe difficulties with the hydro-meteorological information in the area under investigation. By 1995, significant trends in climatic characteristics had not been recorded either in air temperature fluctuations, or in precipitation for the period up to the beginning of 1990. Figures 3 and 4 illustrate the variations of climatic characteristics measured on the meteorological stations used in our investigation.

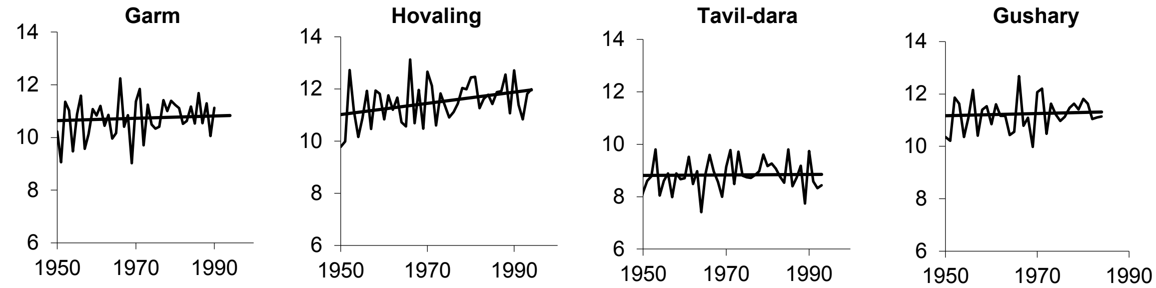

Fig. 3 Annual air temperature *t* (°C) on the meteorological stations of the Upper Amu Darya.

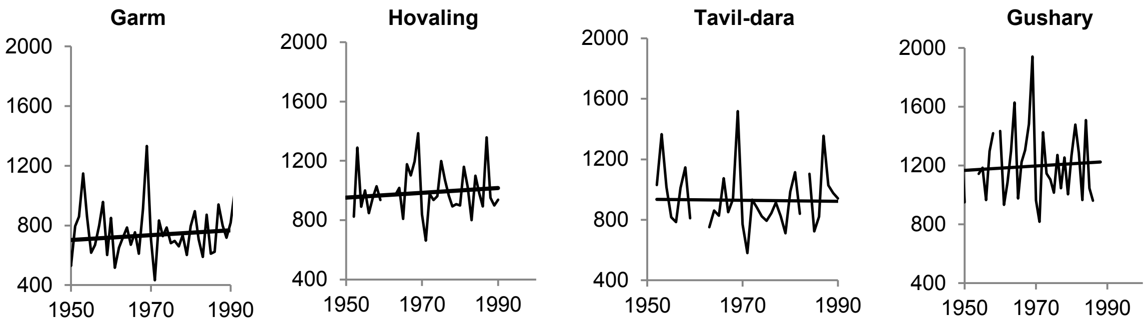

Fig. 4 Annual precipitation sums on the meteorological stations of the Upper Amu Darya.

For the period 1950–1995 air temperature only demonstrates a marked increase in one of the meteorological stations (Hovaling). For three other stations there are no significant changes. As for the annual precipitation sums, we found some growth on three stations, but it is rather weak. However, in the future air temperature is expected to increase (Agaltseva *et al.*, 2010), and in the conditions of changing climate it is important to understand which of the climatic factors can influence zonal runoff at different altitudes.

We found that air temperature itself does not influence runoff greatly: its changes only correlate with zonal runoff in one region in the higher and the lower parts of its catchment, making a small contribution to total runoff value. The precipitation sum variations are the factor influencing a stronger correlation.

The investigation showed that for different homogeneous regions this influence is not the same. This effect can be caused by the difference in natural conditions of the regions. Region 1 includes high-altitude rivers originating in the northern part of Western Pamir, with average catchment heights exceeding 3 km. In the southwest the region is shaded from the main humid air currents by the Darvaz ridge, with a height of about 3 km. Because of this, at heights below 3 km the snow storage is less than that in Regions 2, 3, 4 at the same altitudes. Higher zonal runoff value increases significantly (Fig. 2), and strong correlation with precipitation sums is obvious. Regions 2, 3, and 4 are located just on the route of humid air flows, mountain ridges of the Pamiro-Alay system contributing to the increase of the precipitation by the upward air movements on their slopes. Precipitation is therefore the principal factor of the runoff formation here, and the zonal runoff values vary in compliance with it.

CONCLUSIONS

Calculating zonal runoff values gave the opportunity to get more detailed information on the water content of different altitudinal belts of mountain river catchments and their possible future changes due to climatic changes. Although presently air temperature is the climatic characteristic undergoing the most significant changes, variations of the precipitation sums are more important for estimations of future zonal runoff.

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