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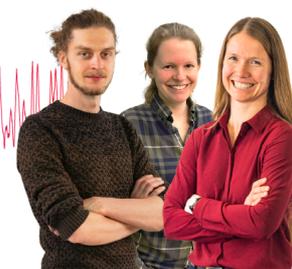
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Impact of Climate Change on Hydrological Regime and Water Resources of Zeravshan Basin Rivers

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Abstract. The work is devoted to assessing the impact of climate change on the hydrological regime and water resources of the rivers of the Zeravshan basin. Comparing the calculations performed for the selected two climatic periods, some changes in the regime of the main climatic indicators - air temperature and precipitation were revealed. The impact of these changes on the long-term fluctuations and intra-annual distribution of river flow, the timing of observation of their phases of the water regime, and maximum water discharges are estimated. Particular attention is paid to the issues of assessing the water resources of the rivers of the studied basin.

Keywords: Climate change, river runoff, long-term fluctuations, intra-annual distribution, phases of the water regime, maximum water discharges, assessment.

INTRODUCTION

The study of the hydrological regime and the assessment of rivers' water resources in the context of climate change is of current scientific, theoretical, and applied importance. The study of this problem on the example of the rivers of the Zeravshan basin is especially important because their water resources determine the current state and prospects for the development of various sectors of the economy of the five regions of Uzbekistan (Samarkand, Navoi, Jizzakh and Kashkadarya) and the Sughd region of Tajikistan.

The issues of the impact of climate change on the hydrological regime and water resources of rivers are considered in the studies of scientists from far abroad (R.M. Perkins, J. Gibson, T. Edwards, S. Birks, W. Buhay, P. Education, B. Wolfe, L. Alfieri, B. Bisselink, F. Dottori, G. Naumann, K. Wyser, Ya. Kong, Z. Pang, A. Al-Alsheikh and others). Similar studies were also carried out by scientists from the former Soviet Union and the current CIS countries (T.S. Abalyan, M.N. Bolshakov, M.I. Budyko, A.I. Voeikov, V.G. Glushkov, M.I. Lvovich, A. S. Monin, I.S. Sosedov, D.P. Sokolov, N.L. Frolova, and others). In Uzbekistan, the first studies on this problem were carried out by E.M. Oldekop, L.K. Davydov, and later by V.L. Schultz, O.P. Shcheglova, Z.V. Ovchinnikov, and others. At present, studies of the hydrological regime and water resources of rivers, taking climate change into account, are being continued by V.E. Chub, E.I. Chembarisov, and F.Kh. Khikmatov, L.M. Karandaeva, G.Kh. , S.A. Khaidarov, D.M. Turgunov and others [3, 8, 9, 13]. However, in the works of the scientists mentioned above, the issues of the hydrological regime and the quantitative assessment of the runoff of the rivers in the Zeravshan basin, as well as their changes under the conditions of climate warming, are not considered separate objects of study.

This work aims to assess the impact of changes in climate indicators on the hydrological regime and water resources of the rivers of the Zeravshan basin. To achieve this goal, the following tasks were considered and solved

in work: collection, primary processing, generalization, and systematization of materials of hydrometeorological observations; assessment of hydrometeorological knowledge of the Zeravshan river basin and selection of observation points; assessment of changes in the main climatic indicators - air temperature and precipitation in the territory of the basin under study; assessment of the impact of changes in these climatic indicators on long-term fluctuations and intra-annual distribution of river flow, on the timing of observation of the phases of the water regime and maximum water discharges; clarification of the main hydrological indicators of river flow and assessment of their water resources.

Main results and their discussion. Materials of direct hydrometeorological observations of meteorological elements and hydrological regimes of rivers in the Zeravshan river basin are very limited regarding the density of observation points and their duration. In addition, hydrometeorological observations are carried out mainly in the basin's low- and middle-mountain parts, while its high-mountain part is almost unexplored in this respect.

In the Zeravshan River basin, from the beginning of the organization of hydrometeorological observations to the present, there have been 78 hydrological and 71 meteorological observation points. Of these, 42 hydrological and 44 meteorological stations and posts are located in Uzbekistan, and the remaining 36 hydrological and 27 meteorological observation points are located in the territory of Tajikistan.

When selecting reference meteorological observation points and hydrological sites, the main criteria were their distribution over the territory of the basin under study and by altitude, reliability of measurements, and duration of observations over hydrometeorological elements; the most important thing is the naturalness of the conditions for the formation of river flow.

Despite the territorial unevenness, we have chosen 20 meteorological (13 - Uzbekistan part, 7 - Tajikistan part) and 29 hydrological (11 - Uzbekistan part, 18 - Tajikistan part) observation points covered the entire range of heights, within which the runoff of the rivers of the Zeravshan basin is formed.

As is known [1, 2, 4, 5, 6, 10, 13, 15, 19, 20], air temperature and precipitation are the main meteorological factors affecting rivers' hydrological regimes and water resources. In this regard, the paper studied the issues of climate warming and the change in conditions. For this purpose, the entire calculation period (1960–2020) is divided into the first base (FBCP, 1961–1990) and current (CCP, 1991–2020) climatic periods.

The assessment of changes in climatic parameters - air temperature and precipitation was carried out using two methods: 1) according to data from individual meteorological stations (Tables 1, 2) according to the data of groups of meteorological stations (Fig. 1).

TABLE 1. Assessment of air temperature changes in high-mountainous part of Zeravshan basin

№	Weather stations	Height, H, m	Air temperature, °C			Air temperature, °C			$\Delta t_{av} = \bar{t}_n - \bar{t}_m$
			FBCP			CCP			
			max	min	aver.	max	min	aver.	
1	Anzob pass	3379	-0.7	-3.2	-1.74	1.40	-3.4	-1.24	0.50
2	Shakhristan pass	3143	1.55	-0.56	0.70	3.10	-2.3	0.86	0.16
3	Dehouse	2564	5.30	3.12	4.37	6.02	3.54	4.72	0.35
4	Madrushkat	2254	8.44	6.16	7.49	9.83	6.63	8.03	0.54
5	Iskanderkul	2204	7.61	5.33	6.62	8.01	6.02	7.07	0.45
6	Sangiston	1521	12.8	9.81	11.6	13.9	10.6	12.0	0.40
7	Panjikent	1015	13.9	10.5	12.7	14.6	12.0	13.3	0.60

Note: \bar{t}_n and \bar{t}_m are average long-term values, respectively, of the first and current climatic periods; Δt_{av} is air temperature difference, °C.

The essence of the second method lies in the fact that when it is applied, the data of all meteorological observation points operating in the study area are used simultaneously. At the same time, joint graphs of the dependence of the studied meteorological elements on height for the selected calculated climatic periods are constructed. The vertical ordinates between straight or curved lines expressing these dependencies characterize the quantitative changes in the studied meteorological elements during the considered climatic periods.

To assess the change in air temperature in the Uzbekistan part of the basin, data from 13 meteorological stations located in this territory were used (Fig. 1).

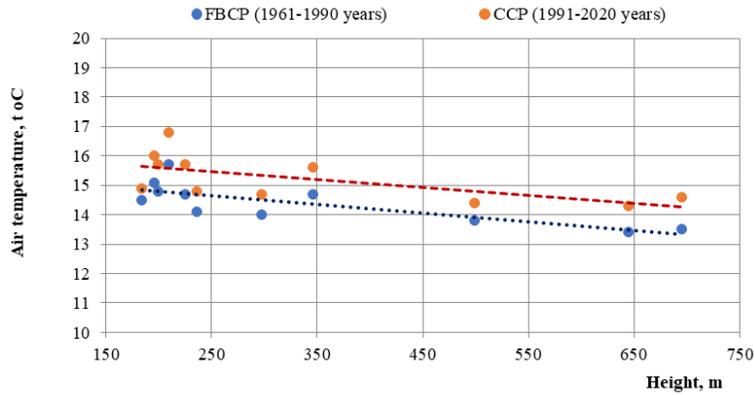


FIGURE 1. Changes in air temperature in Uzbekistan part of basin

Changes in atmospheric precipitation that fell on the high-mountain and Uzbekistan parts of the Zeravshan river basin for the considered climatic periods (FBCP and CCP) were also estimated using the above methods (Fig. 2).

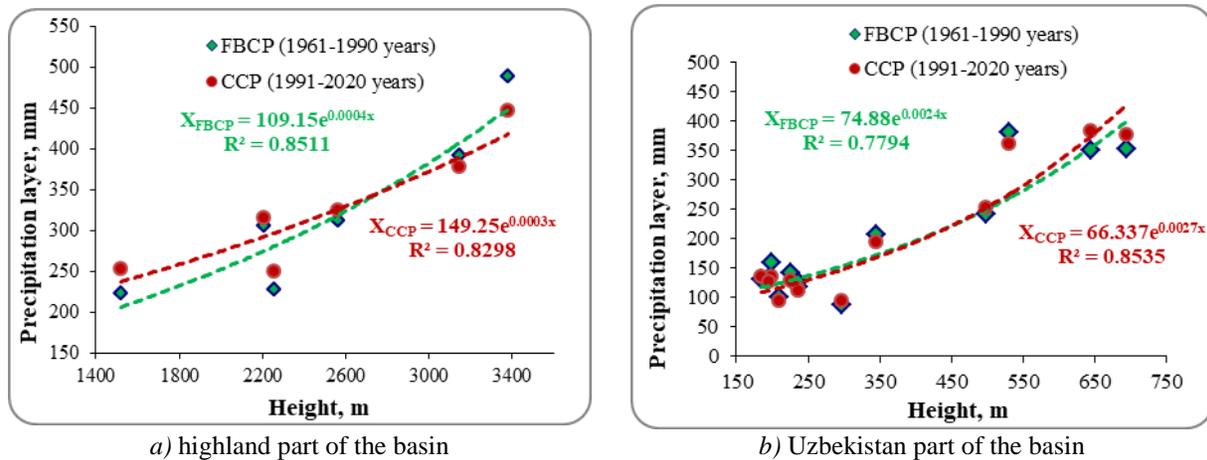


FIGURE 2. Changes in atmospheric precipitation in Zeravshan River basin

In the current climatic period (CCP), at high-mountain meteorological stations, such as the Anzob Pass and the Shakhristan Pass, located in the upper part of the Zeravshan basin, there is a slight decrease in the amount of precipitation. On the contrary, all meteorological stations located below them increase their values (Fig. 2, a). In the Uzbekistan part of the basin, the values of atmospheric precipitation at meteorological stations located at altitudes of more than 500 m are higher in the CCP than in the FBCP, and, on the contrary, at lower meteorological points, their values decrease (Fig. 2, b). These results are compared with the data of V.E. Chub (2001, 2007), and their correspondence is shown.

The issues of long-term runoff fluctuations are considered in the example of the Zeravshan River based on data from the hydrological posts Dupuli, Ziyavitdin, Navoi, and Khazar located along its length (Fig. 3).

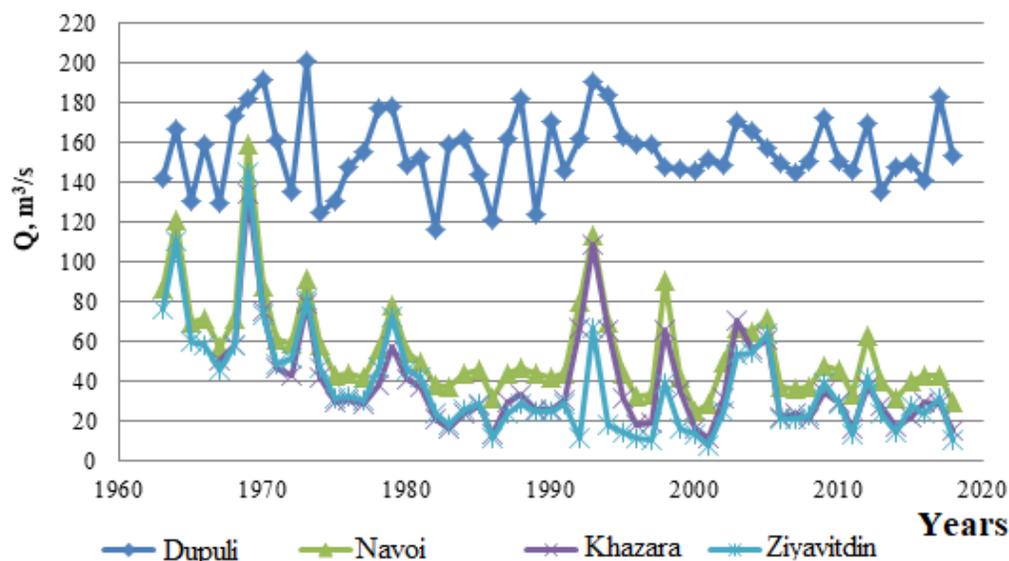


FIGURE 3. Graphs of long-term fluctuations of average annual water discharges of Zeravshan River

An analysis of the calculation results showed that the Dupuli hydrological station, 1973, is characterized by high water (201.0 m³/s). Taking into account the flow of the Magiandarya (Sudzhina), the average annual water flow that entered the Ravatkhodzha hydroelectric complex this year amounted to 209.6 m³ / s, or the annual flow volume was equal to 6.611•10⁹ m³. Of this volume of water, only 43.7% reaches the Ziyavitdin gauging station, and 37.7% reaches Navoi. It should be noted that due to the flow of collector drainage and groundwater into the channel of the Zeravshan River, a slight increase (up to 38.8%) in the volume of runoff is observed at the Khazar hydrological station, located below the Navoi gauging station. In dry years, such as 1982, both absolute and relative values of annual runoff recorded at stations downstream of the Zeravshan River were even less. In general, the paper shows that starting from the Ravatkhodzha water distribution facility to the lowest Khazar post, there is an increase in anthropogenic impact on the water regime of the Zeravshan River [10, 15].

The analysis of interannual fluctuations of the average annual water discharges of 11 rivers of the Middle Zeravshan for a 60-year period (1961-2020) was made. In 9 out of 11 cases, the fluctuation trend equations had a positive sign; in the remaining two cases, they had a negative sign. The largest increases in average annual water discharges over the specified calculation period were observed in Amankutansay ($\Delta Q=0.352$ m³/s), Kuksaraysay ($\Delta Q=0.27$ m³/s), Maidansay ($\Delta Q=0.324$ m³/s) and Beglyarsay ($\Delta Q=0.304$ m³/s). A decrease in the values of average annual water discharges was observed in Tusunsay ($\Delta Q=-0.103$ m³/s) and Aktepasay ($\Delta Q=-0.041$ m³/s).

The coefficients of variation (Cv) of the annual water discharges of the rivers of the Middle Zeravshan for different calculation periods are calculated and compared with the results of previous researchers. The results of calculations performed for PBKP (1961-1990) showed that their highest values, like those of V.E. Chub, corresponded to Tegirmansay (Cv=1.18) and Kuksaraysay (Cv=1.02). The values of variation coefficients calculated for Amankutansay, Akdaryasay, and Sazagansay are relatively small and fluctuate within 0.457÷0.515, which are close to the results of V.E. Chub [14, 15, 19, 20].

The intra-annual distribution of the annual river runoff by months and seasons of the year for the selected two calculated climatic periods (FBCP, CCP) was studied. Comparison of the calculation results made it possible to evaluate their quantitative changes (Fig. 5).

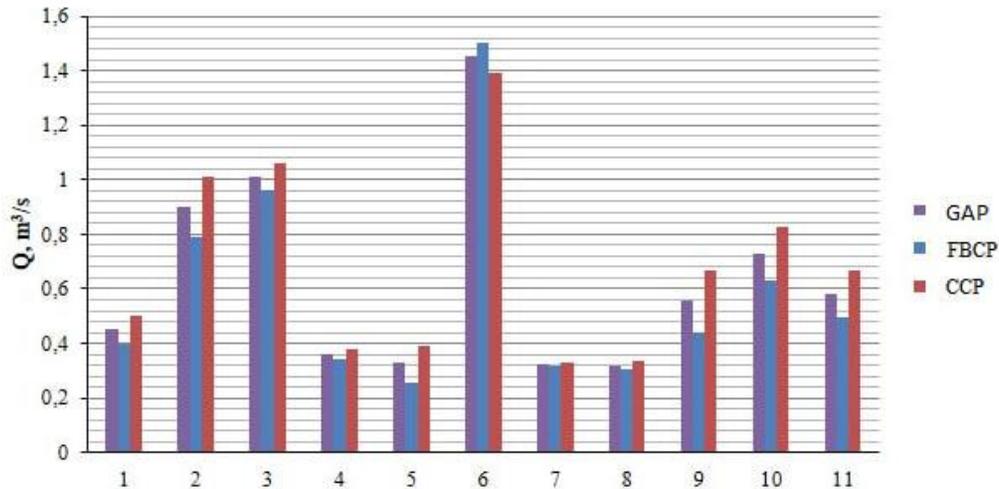


FIGURE 4. Quantitative changes in average long-term water discharges of rivers of Middle Zeravshan: 1 is Urgutsay-Urgut city, 2 is Amankutansay - Amankutan, 3 is Akdaryasay - Agalik, 4 is Sazagansay - Sazagan, 5 is Tegirmansay - Sagishman, 6 is Tusunsay-estuary, 7 is Aktepasay - Ocha, 8 is Karagachsay - Mavlon, 9 is Maidansay - Olmata, 10 is Kuksaraisay - at the exit from the mountains, 11 is Begliarsay - Yangi Akchob, GRP - general reference period (1961-2020).

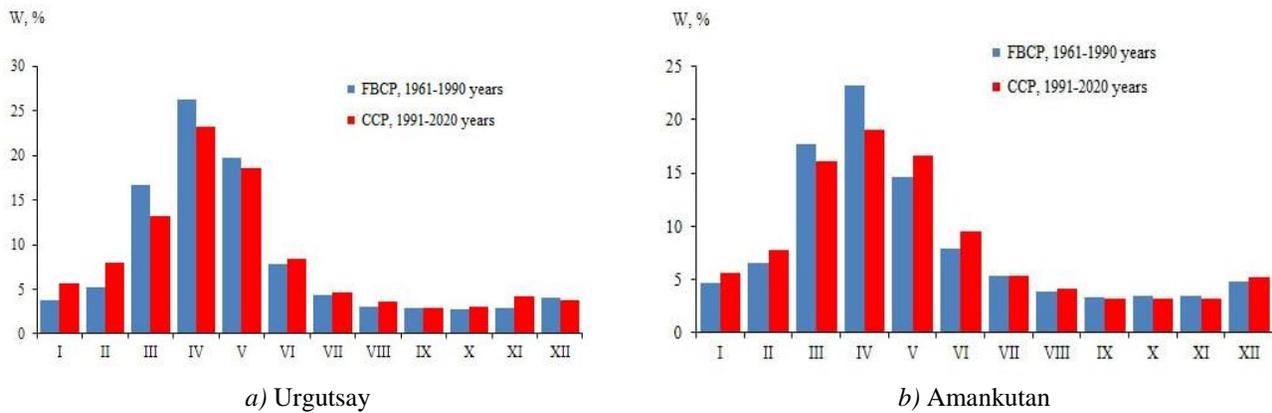


FIGURE 5. Relative changes in intra-annual distribution of river runoff by months

It was revealed that in Urgutsay in the TKP, the volume of its runoff during the flood period (March-May) decreased relative to the PBKP; at the same time, in all months of the low-water period (except December), the runoff increased. A similar situation is observed in Amankutansai. Changes in the intra-annual distribution of river runoff by seasons were also revealed. For example, the volume of spring runoff in Urgutsay was $7.63 \cdot 10^6 \text{ m}^3$ (63.3%) in the FBCP, and CCP- $7.15 \cdot 10^6 \text{ m}^3$ (55.5%), i.e. it decreased. This pattern is repeated in Amankutansai.

When 65-80% of the annual runoff of the Zeravshan River passes, high water is observed in April-September, and on small rivers and sayas of the Middle Zeravshan, it occurs in March-May; their reasons are indicated. This issue was analyzed using the example of the Zeravshan River based on the materials of the Dupuli hydrological station (Fig. 6).

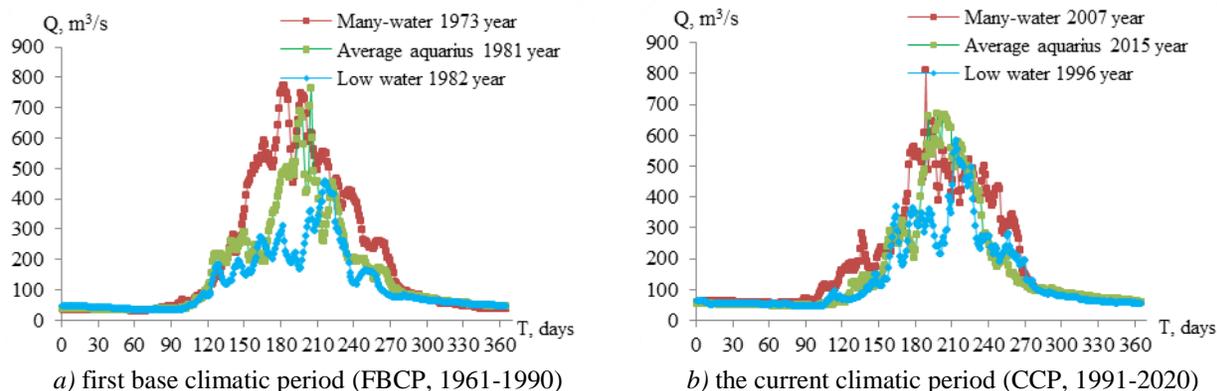


FIGURE 6. Hydrographs of extreme water years observed on Zeravshan (Dupuli) River in different climatic periods

Floods on the rivers of the high-mountainous part of the Zeravshan basin can be observed during the intensive melting of snow cover and glaciers due to a sharp increase in air temperature or heavy rainfall. Small rivers and sairs of the Middle Zeravshan are characterized by autumn and early spring floods. Suppose the Zeravshan River is characterized by autumn-winter low water and on its small tributaries, which are formed on the territory of Uzbekistan. In that case, there is a long summer-autumn-winter low water [4, 15].

In the paper, the issues of shifting the dates of the beginning, end, and total duration of the flood period and the maximum water discharges are considered in the example of the Zeravshan (Dupuli) River. For this purpose, the general series of hydrological observations is divided into the following three calculation periods: 1) conditional natural climatic period (CNCP, 1931-1960); 2) the first basic climatic period (FBCP, 1961-1990); 3) the current climatic period (CCP, 1991-2020). For each calculation period, the average daily water discharges over many years were calculated, and, on their basis, joint annual hydrographs were constructed, with the help of which the main changes in flood elements were determined (Fig. 7).

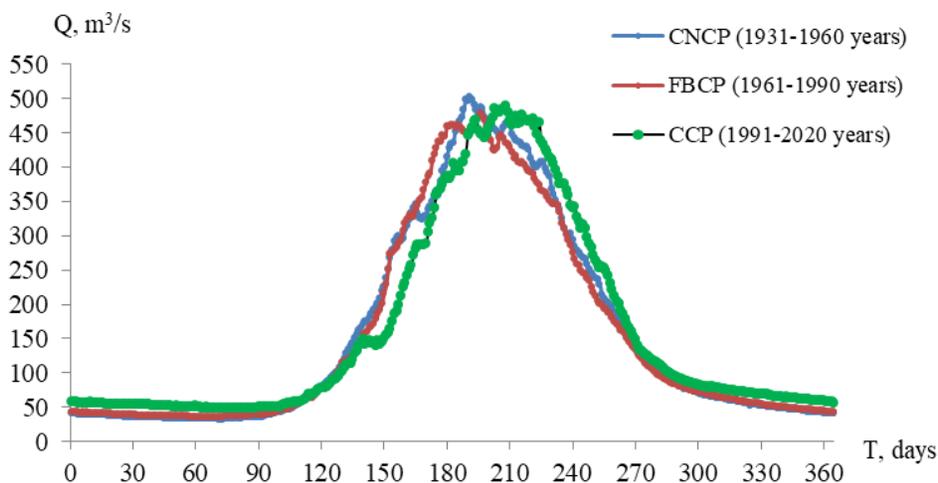


FIGURE 7. Hydrographs of Zeravshan (Dupuli) River for different climatic periods

The analysis of joint hydrographs was made, and the following was revealed: 1) in all three climatic periods, the dates of the beginning of the flood period almost coincide; however, the dates of their end in the TST are shifted a week later; 2) as a result of this shift, the duration of the flood in the TCH increased by one week; 3) if you do not take into account some small shifts during the rise and fall, the hydrographs of the UECP and PBKP almost coincide; 4) there is a shift of the TCH hydrograph to the right side relative to the hydrographs, on average 10-12 days, and when it declines, 8-10 days; 5) hydrographs of the UECP and PBKP show that the values of their runoff during the low water period coincide completely; 6) an increase in the low-water runoff is observed in the TCH, i.e.,

spring-winter period by 20-25% relative to the two previous settlement periods [4, 5, 8].

It is known that one of the most important tasks of hydrological calculations is the determination of the maximum water discharges. This is because hundreds and thousands of bridge crossings, outlets, hydraulic dams, power lines over them, and others have to be designed on rivers. Typically, the maximum flow of water is observed during periods of high water or high water. The analysis of the average dates of the passage of the maximum water discharges during the flood period according to the calculated climatic periods was carried out. Quantitative changes in the maximum water discharges during the flood period and shifts in the timing of their passage were revealed (Table 2).

TABLE 2. Maximum water discharges of flood period and shifts in timing of their passage

Indicators	Estimated climatic periods			Difference	
	CNCP (1931-1960 y.)	FBCP (1961-1990 y.)	CCP (1991-2020 y.)	between CNCP and FBCP	between FBCP and CCP
Q_{max} , m3/s	503	478	489	-25	+11
date	09.07	14.07	26.07	5 days	12 days

The water resources of the rivers of the Zeravshan basin were assessed. For this purpose, the water resources of the rivers formed in its mountainous part were initially assessed. According to the calculation results, the sum of the average long-term water discharges formed in the high-mountainous part of the Zeravshan river basin and entering Uzbekistan is 163 m3/s, and the average long-term runoff is 5.141 km3. Of this amount of runoff, the Zeravshan (Dupuli) River accounts for 95.1%, and the Magiandarya River for 4.9% (Table 3).

TABLE 3. Average long-term runoff values of rivers in Zeravshan basin

Parts of the pool	F, km ²	H _{av} , m	\bar{Q} , m3/s	W, 10 ⁹ m ³	M, l/s·km ²	h, mm	
Alpine part	1	10200	3100	155	4.889	15.2	479
	2	1110	2660	7.95	0.251	7.2	226
Runoff indicators		11310	3057	163	5.141	14.4	454
Mid- and low- mountain part	3/11	1888	-	7.01	0.221	3.7	117
Runoff indicators	4/19	695	-	2.19	0.069	3.2	99
General flow rates		2583	-	9.2	0.290	3.6	112
		13893	-	172,2	5.431	12.4	391

Note: 1 is Zeravshan - Cape Dupuli; 2 is Magiandarya - p. Sujin; 3 is hydrometrically studied rivers, the denominator - their number; 4 is hydrometrically unexplored rivers, the denominator - their number; F is the catchment area; H_{ave} - hav is the average weighted watershed height; \bar{Q} is average long-term water consumption; W is the flow volume; M is the sink module; h is the runoff layer.

The water resources of the rivers of the Middle Zeravshan were assessed by dividing them into hydrometrically studied (221.1·106 m³) and hydrometrically unexplored (69.1·106 m³) rivers. Their sum, i.e., the average long-term runoff of the rivers of the Middle Zeravshan, is 290·106 m³. Generally, the total average long-term runoff of the rivers in the Zeravshan basin is 5.431·109 m³.

CONCLUSIONS

1. An assessment of changes in air temperature and precipitation in the Zeravshan River basin was assessed. Materials of 20 meteorological (13-Uzbekistan part, 7-Tajikistan part) and 29 hydrological (11-Uzbekistan part, 18-Tajikistan part) observation points were used. The general calculation period (1960-2020) is divided into the first base (PBKP, 1961-1990) and current (TKP, 1991-2020) climatic periods;

2. Assessment of changes in climatic parameters (temperature, precipitation) was carried out using two methods: 1) according to data from individual meteorological stations; 2) according to the data of groups of meteorological stations. An increase in air temperature was revealed both in the high-mountainous part (according to the 1st method by 0.43 0C, and according to the 2nd method by 0.40 0C) and in the territory of the Middle Zeravshan (according to the 1st method by 2-method at 0.88 0C);

3. The increase in the layer of atmospheric precipitation according to the 1st method for the high-mountainous part averaged 7.4 mm, and for the Middle Zeravshan, a decrease of 2.1 mm was revealed. The results of assessing the change in atmospheric precipitation by the 2-method showed that in the high-mountainous part of the basin at high altitudes in the TST, precipitation decreases. In contrast, at its relatively low altitudes, on the contrary, it increases. A similar picture is observed in the Middle Zeravshan;

4. The issues of long-term runoff fluctuations are considered in the example of the Zeravshan River based on data from the hydrological posts Dupuli, Ziyavitdin, Navoi, and Khazar located along its length. It is shown that the data from the Dupuli gauging station characterizes the natural regime of fluctuations in the runoff of the Zeravshan River. Starting from the water distribution facility of Ravatkhodzha to the lowest post of Khazar, an increased anthropogenic impact on its water regime is observed;

5. The calculated values of the coefficients of variation of the average annual water discharges of the rivers of the Middle Zeravshan are compared with the results of previous researchers. The calculations performed for PBKP showed that their highest values, like those of V.E. Chub, corresponded to Tegirmansay ($C_v=1.18$) and Kuksaraysay ($C_v=1.02$). The C_v values calculated for Amankutansay, Akdaryasay, and Sazagansay are relatively small and fluctuate within $0.457\div 0.515$;

6. The intra-annual distribution of the annual river runoff by months and seasons of the year for the selected two calculated climatic periods (PBKP, TKP) was studied. It was revealed that in Urgutsay in the TKP, the volume of runoff during the flood period (March-May) decreased relative to the PBKP; at the same time, in all months of the low water period (except December), the runoff increased;

7. The issues of shifting the dates of the beginning, end, and total duration of the flood period, as well as changes in the value of maximum water discharges, are considered in the example of the Zeravshan (Dupuli) river. The analysis of joint hydrographs showed that in the calculated climatic periods, the beginning dates of the flood almost coincide; however, the dates of their end in the TCH shifted a week later. The hydrographs of the UECP and PBKP almost coincide; however, there is a shift of the TKP hydrograph to the right side relative to them, on average 10-12 days;

8. The water resources of the rivers of the Zeravshan basin have been assessed. Calculations showed that the sum of average long-term water discharges formed in the high-mountainous part of the Zeravshan river basin and entering Uzbekistan is 163 m³/s, and the average long-term runoff is 5.141 km³.

9. The water resources of the rivers of the Middle Zeravshan were assessed by dividing them into hydrometrically studied ($221.1\cdot 10^6$ m³) and hydrometrically unexplored ($69.1\cdot 10^6$ m³) rivers. Their sum, i.e., the average long-term runoff of the rivers of the Middle Zeravshan, is $290\cdot 10^6$ m³.

10. The total average long-term runoff of rivers in the Zeravshan basin is $5.431\cdot 10^9$ m³.

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