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ASSESSMENT OF RENEWABLE WATER RESOURCES OF THE KAZAKHSTAN'S PART OF THE SYRDARIYA RIVER BASIN

В данной статье оценены суммарные ресурсы поверхностных вод Казахстанской части бассейна р. Сырдария на основе всей имеющейся гидрологической информации с учетом климатических изменений и антропогенных воздействий на водные объекты и их водосборы, а также, произведена оценка временных изменений и территориального распределения стока рек и суммарных водных ресурсов исследуемого региона. Приведены характеристики годового стока (норма, сток различной обеспеченности), необходимые при решении стратегических и текущих задач отраслей экономики республики. С учетом глобальных и региональных климатических изменений, антропогенных нагрузок на водные объекты и их водосборы, характеристики стока приведены в разных вариантах, в частности, для многолетнего периода, для периода, характеризующего современное гидроклиматическое условия, для предшествующего ему периода, в значительной части которого режим рек был «условно естественным».

Бұл мақалада климаттық өзгерістер мен антропогендік әсерлердің су объектілері мен олардың су жинау алаптарына әсерін есепке алынған барлық гидрологиялық мәліметтерге негізделе отырып, Қазақстан аумағындағы Сырдария өзені алабының беткі суларының жалпы ресурстары, сонымен қатар зерттеліп отырған аймақтың жалпы су ресурстарының және өзен ағындыларының аумақтық таралуы және уақытша өзгерістері бағаланды. Республиканың экономика салаларының қазіргі және стратегиялық міндеттерін шешуге қажет жылдық ағындының сипаттамалары келтірілген (қалыпты ағынды, әртүрлі қамтамасыздық жағдайындағы ағынды). Су режимінің едәуір бөлігі «шартты табиғи» болғандағы көпжылдық кезеңде және қазіргі гидроклиматтық жағдайды сипаттайтын кезең үшін, жаһандық және аймақтық климаттық өзгерістерді, су объектілері мен олардың су жинау алаптарына түсетін антропогендік әсерлерді ескере отырып, ағындының сипаттамалары әр түрлі нұсқада келтірілген.

This paper evaluated the total surface water resources of the Kazakhstan part of the basin of the river Syrdarya, based on all available hydrological data, taking into account climate change and human impacts on the water objects and their catchment areas, as well as assessed of temporal changes and the territorial distribution of river runoff and the total water resources the test region. The characteristics of the annual runoff (norm, runoff of different provision) necessary for solving the strategic and current tasks of sectors of the economy. Taking into account the global and regional climate change, anthropogenic pressures on the water objects and their catchment areas, the characteristics of runoff are available in different variants, in particular, for a multi-year period, for the period that characterizes modern hydro-climatic conditions, for prior to him period, a large part of which the regime of rivers It was "relatively natural."

Introduction. Syrdariya river, the major water-way of Central Asia, got its name after the merging of two rivers - Karadariya and Naryn, located far beyond Kazakhstan. They flow from the depths of the Tanirtau mountain system, where they receive abundant feeding from the melting snow and glaciers. Naryn is more abounding in water. Syrdariya reaches a length of almost 2900 km together with this river (Figure 1) [1-4].

Water problems and possible consequences of global climate change in the assessment of water resources are a special priority for Kazakhstan. Assessment of the current state of water resources and their forecast for the future is complicated by the fact that the river runoff is an integral characteristic of interaction of many geophysical processes and physical-geographical conditions of the basins.

Generalizations on river runoff in Kazakhstan, made on the basis of a uniform methodical framework, are related to the 50-70-ies of the last century [1]. Since then, firstly, a significant amount of additional hydrological information is accumulated, and secondly, there was a transformation of the conditions of accumulation and discharge of moisture in river basins due to the intensification of economic activity, which affected both the hydrological regime of water bodies, and the resulting volume of water resources. It was exactly in the 60-70-ies when many reservoirs were created, water-intensive industries were developed. Thirdly, climatic changes were clearly defined; they were particularly evident in the recent decades, which also had an impact on hydrological processes. It should also be noted that in connection with the collapse of the USSR, Syrdariya river became transboundary with the corresponding consequences.

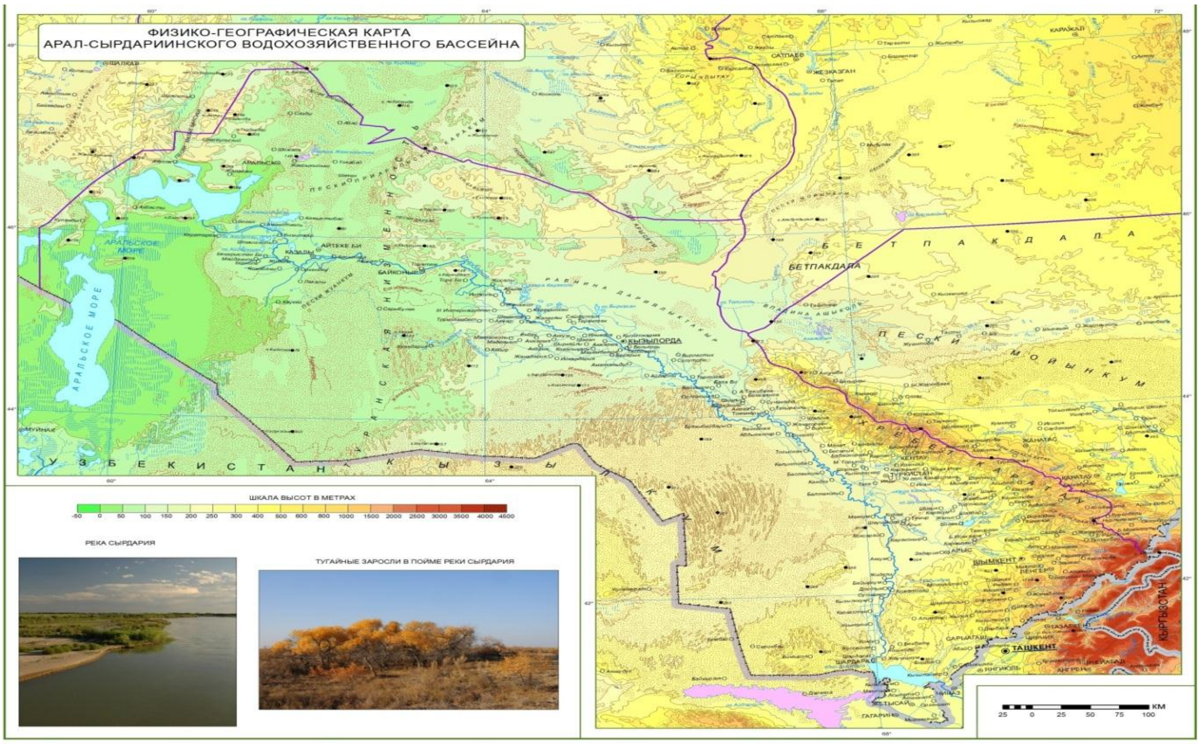


Figure 1 - Physical-geographical schematic map of the study area

As a result, there emerged an urgent task of assessing surface water resources on the basis of all the accumulated information and taking into account the ongoing climate change and anthropogenic impact on water bodies and their basins, as well as geopolitical conditions in the region.

Calculation of the rate and variability of annual runoff. The rate and variability of annual runoff of rivers and temporary watercourses of the basin were, for the first time, identified in the papers before the 70-ies of the last century [1]. These papers on the assessment of the rates of the annual river runoff of the Syrdarya river basin were based on the hydrological information of 10-15 years. 40-50 years passed since that time, and there have been fundamental changes in climatic characteristics and anthropogenic activities in the basin. This shows that there is an objective need for a new assessment of surface water resources, taking into account the mentioned changes.

The estimation of the rate of annual runoff of rivers and temporary watercourses was carried on 172 observation stations, while in the work [1] – on 30 stations. The calculations were made in two versions: for long-term period (1912-2007) and for the contemporary period (1973-2007).

Accuracy of the estimation of the rate in this case is defined by the formula with the autocorrelation coefficient between adjacent members of the series $r < 0,5$ [5; 6]

$$\sigma_{Q_0} = (\frac{\sigma_Q}{\sqrt{n}})\sqrt{\frac{1+r}{1-r}}, \quad (1)$$

where σ_Q - mean square deviation; n – number of years of observations; r – autocorrelation coefficient between adjacent members of the series.

Thus, the errors in determining the rate of runoff for these stations range from 1,55% to 20,3% over the long-term period, and from 0,92% to 19,0% for the current period. The results of calculations on the main stations are shown in Table 1.

Table 1 - Main hydrological characteristics of the major rivers of the Syrdariya river basin

№	River-station	Long-term period (1912-2007)				Contemporary period (1973-2007)			
		Q, m^3/s	σ_Q, %	Cv	σ_{Cv}, %	Q, m^3/s	σ_Q, %	Cv	σ_{Cv}, %
1	2	3	4	5	6	7	8	9	10
1	Syrdariya river – above the estuary of Keles river	841	0,23	0,78	3,4	859	4,54	0,22	12,7
5	Syrdariya river – Tomenaryk r/w station	717	0,25	0,78	3,1	734	2,16	0,24	12,7
6	Keles river – Zhanabazar village	1,99	0,40	0,99	2,5	1,93	2,61	0,34	13,2
7	Keles river – Akzhar village (Stepnoye village)	5,80	0,32	1,02	3,2	5,60	3,92	0,28	13,3
8	Keles river – Gornyy township	4,73	0,23	1,02	4,4	4,61	9,06	0,20	34,0
9	Keles river - estuary	12,3	0,33	1,02	3,1	11,8	3,01	0,29	12,8
10	Arys river – Zhaskeshu aul	5,99	0,20	1,27	6,4	5,87	2,47	0,16	12,4
11	Arys river - Arys r/w station	45,5	0,28	1,27	4,5	44,2	2,67	0,23	12,6
12	Arys river – Shaulder village	38,4	0,29	1,27	4,4	37,2	1,79	0,24	13,0
13	Zhabagylysu river – Zhabagaly village	2,39	0,26	0,99	3,9	2,28	3,93	0,22	12,7

The stations of observation over the runoff with the duration of the series of less than 6 years dominate in the study area. The definition of the rate of annual runoff for these stations was carried out by the most developed and theoretically justified method of relations. As is known, the method is based on the assumption of the approximate equality of the module coefficients at the station with short-term observations and at the analogue-stations according to the formula [1]:

$$\overline{Q} = Q_i(\overline{Q}_a / Q_{ia}), \quad (2)$$

where Q_i and Q_{ia} - the observed values of the river runoff, respectively, at the station with short-term observations and at the analog-stations; $\overline{Q}$ and $\overline{Q_a}$ - rates of the runoff, respectively, at the estimation station and at the analog-stations.

An issue of the relative accuracy of the obtained results primarily arises, when estimating the rate by this method. In other words, the justification of the selection of the analog or the group of analogs in such cases is determined exactly by estimation accuracy. It is not possible to solve this issue theoretically without additional information. Usually, the problem is solved experimentally. Mean-square error in determining the rate of runoff according to the one-year observation data is calculated by the formula [7]:

$$\sigma_{Q_0} = \sqrt{\sum\left(\overline{y}_i - \overline{\overline{y}}\right)^2 / (n-1)}, \quad (3)$$

where $\bar{y}_i$ - the rate of runoff obtained according to the data of the i-th year of observations; $\bar{\bar{y}}$ - rate of runoff for all the years of observation.

Certainly, it is not possible to determine the standard error by the formula (3) with observational data for only one year. It is necessary to select two observation stations for that, with a rather lengthy series in homogeneous area in terms of hydrology, and one of them is conditionally taken as the station with short-term observations. Further is calculated the deviation of the rate of the estimated series calculated according to the data of individual years, from the rate determined for the entire observation period. It is clear that the accuracy of the estimate obtained in this way depends on the effectiveness of the selection of the analog-station. Therefore, the researchers select not one, but a group of analogs. The effectiveness of this method based on group analysis, is examined in the work in details [8].

Rates of runoff for 30 stations were determined by the method of relations in the Syrdariya river basin. Both weighted average altitudes, and the distance between the catchment areas have been considered in the selection of the analogs.

In order to estimate the runoff rate of the unstudied rivers and stations with disturbed regime, there was used the method of regional curves M_0=f (H_{av}), somewhat adjusted on the basis of the new results obtained in comparison with earlier generalizations.

With the help of the curves of dependence M_0=f (H_{av}), there were determined the rates of runoff for 48 stations, where the natural runoff regime was disturbed, as well as for 20 unstudied stations.

The error of the rate of annual runoff obtained by reducing the short series of observations to the long-term period on the graph of relation, consists of the errors of the average value of the long-term series of observations at the reference station on the analog-river and correlation error caused by dispersion of the points on the graph of relation [8; 9].

The error of the rate in this case is defined by the formula

$$\sigma_{Q_0} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}\ . \tag{4}$$

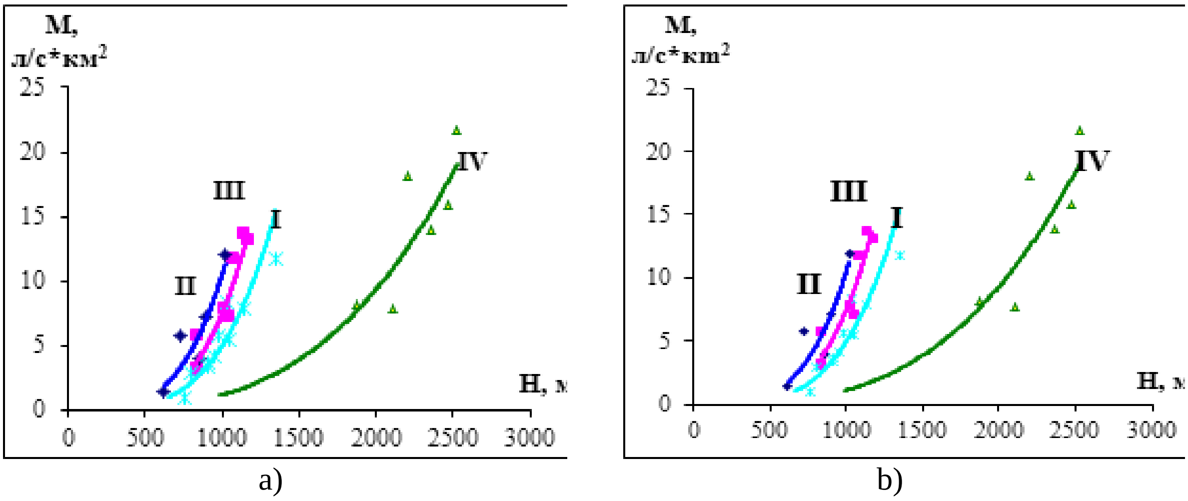
Here, σ_1 - error of the determining of the runoff rate with the short series of observations; σ_2 - error of assessment of the rate of the annual runoff of the reference stations, the data of which were used to construct a curve of dependence M_0 = f (H_{av}); σ_3 - error of the curve of dependence M_0 = f (H_{av}).

Thus, based on the data of 77 observation stations, there was obtained a series of regional dependencies M_0=f (H_{av}), characterizing the state of water content of the individual four areas of the study basin (Figure 2). Due to the adjusted data, the authors identified 4 areas, whereas 2 areas were selected in this catchment area previously in the sound generalization [1]. In addition, it should be noted that the dependencies were constructed separately for the long-term and modern periods.

Detailing the regional dependencies M_0=f (H_{av}), in this work is exhaustive in the present state of knowledge of the problem and quite accurately describes the state of water content of the individual regions of the basin. The curves of dependence M_0=f (H_{av}) in this case are constructed separately for the long-term and modern periods.

The curve of dependence I characterizes the runoff regime of the basins of the rivers of the western part of the south-western slopes of the Karatau ridge. The dependence covers the average altitudes of the catchment areas from 760 to 1350 m. The standard deviation of the points from the curves was 22,0 and 20,6%, maximum – 28 and 33,7% respectively, for the long-term and modern periods.

The curve of dependence II characterizes the runoff regime of the average catchment areas within the altitudes from 620 to 1020 m of the southern part of the south-western slopes of the Karatau ridge (basins of the rivers Bogen, Kattabogen, Almaly, Shayan, Aktas, Arystandy). Previously [1], the area was characterized by a common curve of dependence together with the catchments areas of the south-western slope of the Karatau ridge. The standard deviation of the points from the curve M_0=f (H_{av}) was 26,3% for long-term period and 33,3% for the modern period, maximum –42,9 and 46,0 %, respectively



I – river basins of the western part of the south-western slopes of the Karatau ridge; II – river basins of the southern part of the south-western slopes of the Karatau ridge; III – river basins of the south-western slopes of the Boraldaitau ridge; IV – river basins of the north-western slopes of the Karzhantau ridge

Figure 2 - Dependencies of the annual runoff rate: a – for long-term period (1912-2007), b – for the modern period (1973-2007) and from the weighted average altitude of the catchment areas of the rivers of the Syrdariya river basin.

Curve of dependence III covers the average altitudes of the river basins of the south-western slopes of Boraldaitau ridge from 840 to 1140 m. Standard deviation of the points from the curves constructed during two estimation periods (long-term and modern), 20,3 and 17,5 %.

Curve of dependence IV characterizes the runoff regime of the basins of the rivers of the north-western slopes of the Karzhantau ridge at average altitudes from 1870 to 2530 m. In the work [1], the area was characterized by the common curve of dependence together with the catchment areas of the south-western slope of the Boraldaitau ridge. Standard deviation of the points from the curves was 18,6 and 20,1 %, the maximum – 33,9 and 46,4 % respectively, for the long-term and modern periods.

The curves of dependence $M_0=f\ (H_{av})$, obtained for the four regions of the Kazakhstan's part of the Syrdariya river basin, were used to determine the rate of runoff for 48 stations, where the natural regime of runoff was disturbed. Also, on the basis of regional curves, the rates of the annual runoff of 20 unstudied stations were determined.

The accuracy of the determination of the rate in this case consists of the sums of errors of the rates of the stations, the data of which were used for the construction of the curve and the error of the method.

The variability of annual runoff of the rivers of the region was determined by two different calculation periods. The relative characteristic of variability – the coefficient of variation (C_v) for the observation stations fairly lengthy actual or reconstructed series, is determined by the method of the moments:

$$C_v = \frac{\sigma_Q}{\overline{Q}} = \sqrt{\frac{\Sigma(K-1)^2}{n}}, \tag{5}$$

where σ_Q - the standard deviation of annual runoff, m^3/s; Q_0 – long-term average value of the annual runoff, m^3/s; K – modular coefficient; n – the number of the runoff series.

The values of the coefficient of variation in the observation stations range from 0,15-0,33 (closing stations of major rivers) to 0,45-1,93 (small rivers).

The error of the coefficient of variations σ_{C_v} when C_s=2C_v is estimated by the formula of Kritsky-Menkel:

$$\sigma_{C_v} = \frac{C_v}{n+4C_v^2}\sqrt{\frac{n(1+C_v^2)}{2}(1+\frac{3C_v r^2}{1+r})} \ . \tag{6}$$

When $C_s \neq 2C_v$, the formula of A.V. Rozhdestvenskiy, obtained on the basis of statistical modeling, was used:

$$\sigma_{\overline{\overline{C_v}}} = \frac{E_{C_v \overline{\overline{C_v}}}\overline{\overline{C_v}}}{\sqrt{n}} \ . \tag{7}$$

The values of the coefficient $E_{C_v \overline{\overline{C_v}}}$, which depends on the values of r, C_s/C_v, n, are given in the paper of Rozhdestvenskiy A.V. [7].

As a result of reducing of the series of runoff to the long-term one, the errors of the coefficient of variation were 7,8 - 24,7 % for long-term period and 7,8 - 38,6 % for the modern period.

Results of the estimations of the coefficient of variation for the main stations are given in Table 1, main hydrological characteristics for total 172 hydrological stations were obtained in the study basin.

As a result of the calculations done, values of annual runoff rates and their variability were obtained. More detailed information on the assessment of the rate and variability is presented in [10].

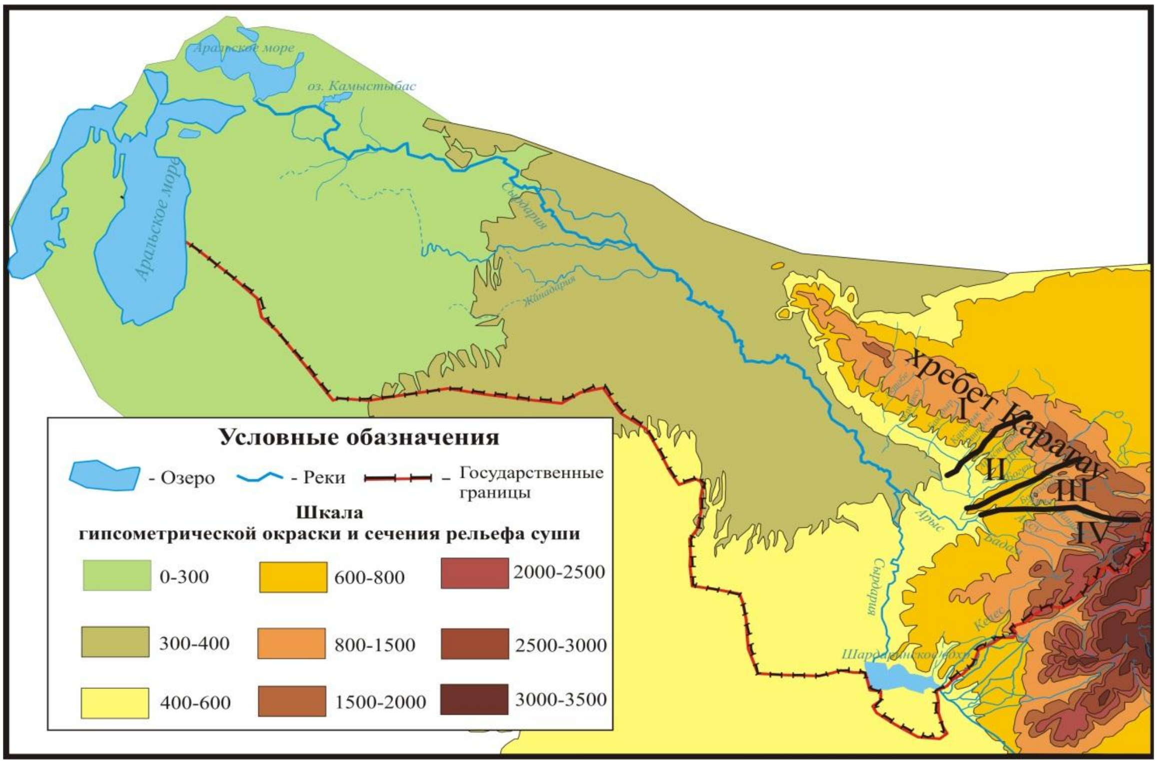
Patterns of spatial distribution of river runoff. Spatial changes of such dynamic natural process as the river runoff, in the conditions of variety of orography and landscapes are very complicated. As it is known, the Earth's surface is characterized by zonal distribution of natural climatic components. One of the most common and major physical and geographical patterns of mountain areas is their altitude-zonal system distribution.

Two major hydrologically homogeneous areas can be distinguished in the Kazakhstan's part of the Syrdariya river basin: catchment areas of the rivers of the south-western slopes of the Karatau ridge and catchment areas of the rivers of the south-western slopes of the Boraldaitau ridge and the north-western slopes of the Karzhantau ridge. As it is known, allocation of homogeneous areas in the mountainous catchments is rather relative and depends on the hydrological study. Based on the analysis and calculations of data of 77 stations of observations, the study territory is divided into 4 districts (Figure 3), which are well characterized by common features of runoff distribution on the territory of the Syrdariya river basin.

Spatial patterns of the distribution of runoff of rivers in the region are to a large extent related to the azonal factors - mountain elevations. Geographic zonality of the increase in favorable conditions for the formation of water from south to north is completely disturbed.

The runoff for all areas gradually increases with altitude of the terrain, peaking at the most elevated catchment areas and at the same time to the west, where there are the most favorable conditions for the formation of runoff. The runoff of the rivers in the region naturally decreases from east to west of the Karatau ridge.

The rivers of the north-western slopes of the Karzhantau ridge are characterized by maximum water content in the region; the rivers of the southern part of the south-western slopes of the Karatau ridge are characterized by the least water content. The catchment areas of the rivers of the western part of the south-western slopes of the Karatau ridge and south-western slopes of the Boraldaitau ridge have larger surface water resources, than the catchment areas of the rivers of the southern part of the south-western slopes of the Karatau ridge.



I – the basins of the rivers of the western part of the south-western slopes of the Karatau ridge;
II – the basins of the rivers of the southern part of the south-western slopes of the Karatau ridge;
III - the basins of the rivers of the south-western slopes of the Boraldaitau ridge;
IV – the basins of the rivers of the north-western slopes of the Karzhantau ridge

Figure 3 - Scheme of the regionalization of the Syrdariya river basin by the nature of dependence of the runoff modulus on the weighted average altitude

River water resources. The major part of water resources of the Kazakhstan's part of the Syrdariya river basin is focused in the upper reaches of the catchment areas of the Arys, Keles, Shayan, Bogen rivers. The resources of the lowest north-western part of the Karatau ridge are insignificant and are mostly lost at the outlet from the mountains, not reaching the channel of Syrdariya river. The discharges of water of various probability of rivers and temporary watercourses were calculated to assess the surface water resources of the study basin [13,14].

The permanent watercourses defining the surface water resources in the study basin in the territory of Kazakhstan originate in the mountainous areas of the north-western slopes of the Karzhantau ridge, south-western slopes of the Karatau and Boraldaitau ridges. Small rivers of the south-western slopes of the Karatau ridge, entirely used for irrigation, do not reach Syrdariya river.

Assessment of water resources of the basin (Y km^3) through the indicators of the runoff of its individual rivers was carried out by the method of linear equations of the runoff [11,12].

The coefficients k_1, k_2 ... k_n, taking into account the fact that these stations usually close not the entire catchment area, are included into the rate of runoff at the stations of major rivers of the territories (Y_1, Y_2 ... Y_n)

$$Y=3,154\times 10^{-2}(k_1Y_1 + k_2Y_2 + \ldots\ldots + k_nY_n) \quad (8)$$

It is recommended to use one of the following examples when determining the coefficients of linear equations: the interpolation of the river runoff rate along its length, the estimation of the runoff rate from the unrecorded territory on the map of isolines, the estimation of the runoff rate of this territory by the method of hydrological analogy.

According to present estimates, the surface water resources in the Kazakhstan's part of the Aral-Syrdariya basin make up 3,28 km^3 (Table 2).

Table 2 – Water resources of the Aral-Syrdariya basin for the long-term period (1912-2007), km^3/year.

Water resources	Water resources of the RK			
	Average annual	Probability, %		
		25	75	95
Keles river basin	0,39	0,47	0,30	0,21
Basins of the rivers of the western part of the south-western slopes of the Karatau ridge	0,42	0,53	0,28	0,17
Basins of the rivers of the southern part of the south-western slopes of the Karatau ridge	0,26	0,32	0,19	0,12
Basins of the rivers of the south-western slopes of the Boraldaitau ridge	0,79	0,97	0,58	0,38
Basins of the rivers of the north-western slopes of the Karzhantau ridge	1,41	1,59	1,22	0,97
Total	**3,28**	**3,88**	**2,57**	**1,85**

About 91% of the resources of the basin are formed on Syrdariya and Keles rivers, of them 89% come from the Republic of Uzbekistan. However, the actual inflow from the territory of Uzbekistan in recent years is 18,4 km^3. Surface water resources for other rivers are distributed as follows: the basins of the rivers of the western part of the south-western slopes of the Karatau ridge – 1,4 %, the basins of the rivers of the southern part of the south-western slopes of the Karatau ridge – 0,9 %, the basins of the rivers of the south-western slopes of the Boraldaitau ridge – 2,6 %, the basins of the rivers of the north-western slopes of the Karzhantau ridge – 5 %.

Transboundary location of the Syrdariya river basin is the reason of the importance of water allocation disputes between neighboring Republic of Uzbekistan and Kazakhstan. The water resources calculations obtained in the present research show that 26,5 km^3 of water are formed in the catchment area outside the RK, but the actual runoff at the border in recent years is 18,4 km^3. The inflow to the RK through the channels of Zakh, Khanym, which bring their waters to the Keles river basin – 0,39 km^3 per year (1,0 km^3/year according to the agreement). Water resources formed in the basin in the territory of the Republic of Kazakhstan – 3,28 km^3 per year. Total actual water resources - 21,6 km^3 per year.

Conclusions. The rate and variability of annual river runoff of the Kazakhstan's part of the Syrdariya river basin are assessed. The rate of annual runoff was determined by the most developed and theoretically justified method of relations. The calculations were made in two versions: for the long-term period (since the beginning of instrumental measurements from 1912 to 2007) and for the modern period (from 1973 to 2007).

The mean-square error of the determination of the rate of annual runoff according to the observations of one year is calculated by the A.V. Rozhdestvenskiy's formula in assessing the rate using this method.

In order to estimate the runoff rate of the unstudied rivers and stations with disturbed regime, there was used the method of regional curves $M_0 = f\,(H_{av})$, somewhat adjusted on the basis of the new results obtained in comparison with earlier generalizations.

With the help of the curves of dependence $M_0 = f\,(H_{av})$, there were determined the rates of runoff for 48 stations, where the natural runoff regime was disturbed, as well as for 20 unstudied stations.

The error of the rate of annual runoff obtained by reducing the short series of observations to the long-term period on the graph of relation consists of the errors of the average value of the long-term series of observations at the reference station on the analog-river and correlation error caused by dispersion of the points on the graph of relation.

It became possible to identify 4 areas after the adjustment of the rates of runoff at the hydrological stations, while 2 areas were identified in this catchment area earlier in the sound generalization of the Surface water resources in the USSR.

The values of variability of annual runoff at the observation stations range from 0,15-0,33 (closing stations of major rivers) to 0,45-1,93 (small rivers).

The spatial distribution patterns of river runoff are analyzed. In general, the water content of the region is reduced from north to south, according to the pattern of geographical zonality, as well as from west to east, depending on the reach of moisture-bearing western air masses. At the same time, the high-altitude, typical of mountain areas, zoning, or the so-called high-altitude zonality, is fully manifested.

Assessment of water resources of the basin (W km^3) through the indicators of the runoff of its individual rivers was carried out by the method of linear equations of the runoff.

According to the research results, surface water resources in the territories of the Kazakhstan's part of the Aral-Syrdariya basin for long-term period (from 1912 to 2007) amount to 3,28 km^3/year.

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