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PRECIPITATION AS FLOW-FORMATION FACTOR IN AMUDARYA

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Abstract: In this article, different precipitation characteristics in three basins where the formation of the Amudarya River flow takes place: namely, the Surkhandarya River basin, basins of the Tajikistan rivers, basins of the northern part of Afghanistan are considered. Their role as flow-formation factor is investigated. Correlations between precipitation distribution over absolute elevation are derived, average precipitation totals are calculated for precipitation falling on these basins. Correlation between the Amudarya River flow in the Kerki cross-section and the average precipitation totals in the Surkhandarya River basin is derived, and it was used for calculation of the river flow in Kerki.

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Key words: precipitation, intrannual precipitation distribution, correlation between precipitation distribution over absolute elevation, precipitation trends, anthropogenic impact, natural losses, evaporation, infiltration, flow coefficient.

Introduction. Water resources are the limiting factor in the main fields of economy. Water demand will increase both for satisfying the needs of developing fields of economy, and for rapid population growth. Irrigated farming consumes more than 93 % of the whole water intake. That is why it is expected that in future the conflicts of interests between agriculture and other sectors of economy will arise [3].

For increasing the quality and efficiency of water consumption, of the rational distribution of water resources, attainment of acceptable agreements between the states located upstream and downstream of the river flow, preservation of ecological systems, sufficient satisfaction of demands of water users and water consumers it is necessary to investigate the water resources and their changes comprehensively taking the expected climate changes to account [3, 7, 12, 17, 19, 28].

Already in 1884 A.I. Voyeikov [15] supposed that “with other equal conditions the country will be richer in flowing water if it has abundant precipitation and less evaporation both from the soil surface and from vegetation”. All investigators of the later years approved the ideas expressed by A.I.Voyeikov. The rivers of Central Asia, including Amudarya, are not exclusion in this respect: an average long-term flow of rivers with all alimentation types depends on precipitation and evaporation [3, 16].

Due to the influence of increase of precipitation amount and decrease of the air temperature with the rise of absolute elevation in mountain areas the sharp increase of river flow is observed. There are a lot of exclusions from this regularity determined with mountain slopes orientation towards the movement of the moisture bringing air masses, their accessibility for these masses and peculiar features of synoptic processes.

The above mentioned results reveal that based on the conditions in mountain territories, the amounts of precipitation and flow are a function of a) area elevation, b) mountain slope orientation towards the movement of the moisture bringing air masses, c) their accessibility for these masses, d) peculiar features of synoptic processes.

Because of the relative homogeneity of the last three conditions it is possible to foresee the existence of relationship between precipitation amount and flow [3, 16].

Due to the arid climate of the plain areas the water capacity of Central Asian rivers outside mountainous areas does not provide for the replenishment of their flow**,** but on the contrary, the intensive water intake for irrigation and flow consumption for different types of evaporation is dramatically reduced [3, 6].

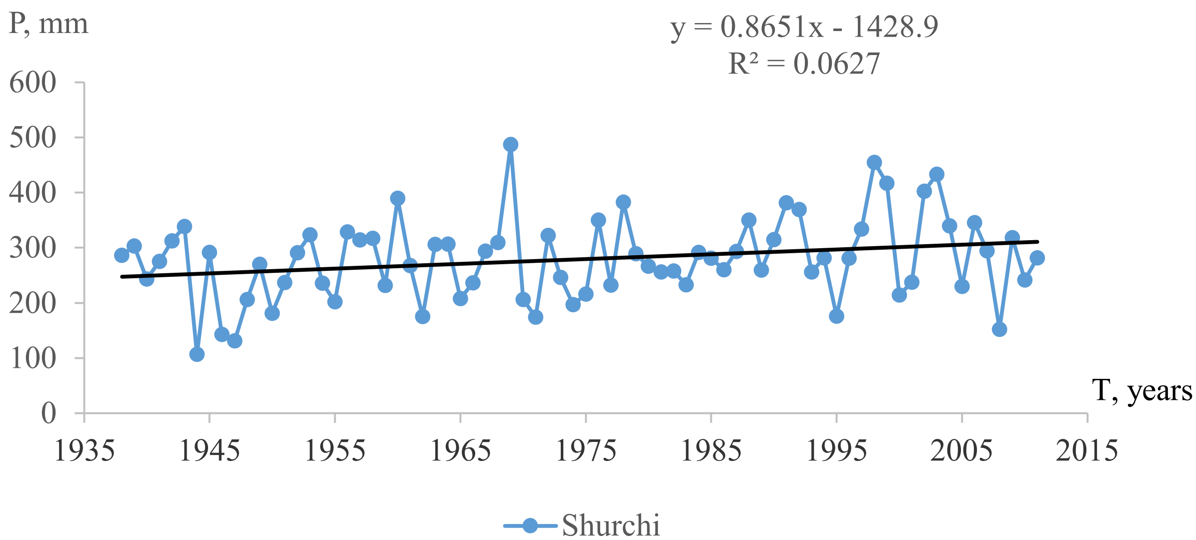
Based on this feature, we searched for correlation between changes of the Amudarja River flow in the Kerki cross-section and changes of the aforementioned climate parameters. The main focus was on precipitation over three basins: the Tajikistan river basins, the Surkhandarya River basin and river basins in the northern and north-eastern parts of Afghanistan, as precipitation on these basins are the main flow-formation factor for the Kerki hydrological cross-section, and further flow dynamics along Amudarya river length depends on the flow discharge in the Kerki cross-section.

Materials and methods. The article uses materials of hydrological and meteorological observations from weather stations in Tajikistan and Uzbekistan, as well as literary sources on atmospheric precipitation in the territories of Afghanistan. When studying the dependence of runoff on atmospheric precipitation, the methods of mathematical statistics, probability theories, geographic similarity and GIS technologies were applied when mapping the distribution of precipitation across territories.

Results and their discussion. We performed several tasks for reaching the assigned goal. First, we selected meteorological station in the above mentioned regions and calculated annual precipitation totals, as well as their temporal variations.

8 meteorological stations were selected in Surkhandarya river basin where precipitation observations were carried out for a long period of time. 8 meteorological stations were selected in Tajikistan river basins. We could not get such information for the river basins in the northern and north-eastern parts of Afghanistan.

In the result of studies over the observation stations of the Surkhandarya River basin the graphs of variations of the annual precipitation totals were created, two of which are presented in Fig.1 as an example. Variation trends are presented in Table 1.



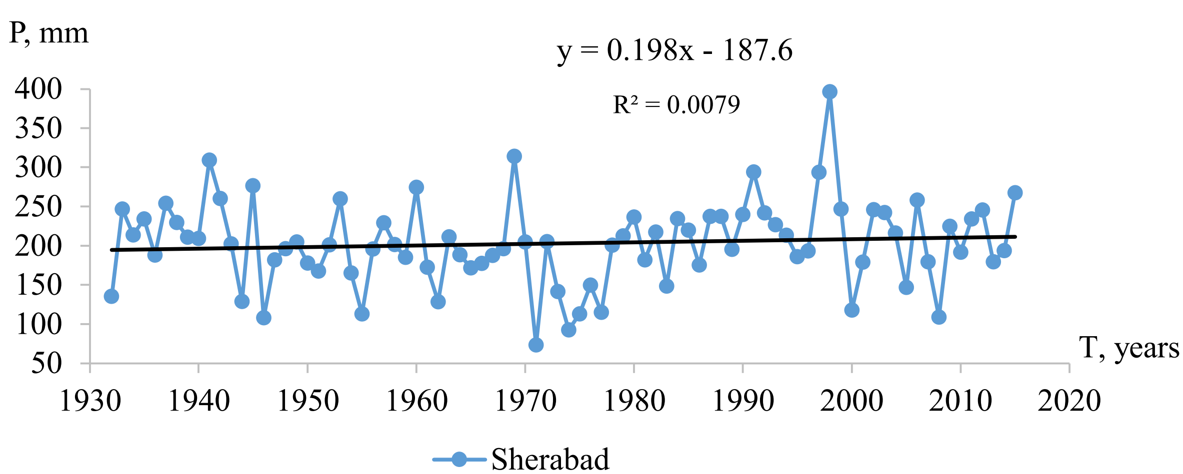


Fig. 1. Graphs of variations of the annual precipitation totals over meteorological measuring points in Surkhandarya river basin

Regarding the presented graphs and data given in Table 1, it was found out that six observation stations recorded negligible increase of the annual precipitation totals, while two of them showed their reduction.

The results of investigation of observation materials over two meteorological points in the Tajikistan river basins are given in Fig.2, and in Table 2 the equations and trends for all eight observation stations are given.

Table 1

Equations and trends of variations of the annual precipitation totals over observation points in Surkhandarya river basin

№	Name of observation station	H, km	Equation	Trend
1	Shurchi	0,45	У = 0,8651X – 1428,9	0,8651
2	Sherabad	0,42	У = 0,1485X – 90,568	0,1485
3	Denau	0,52	У = - 0,6414X + 1615,4	- 0,6414
4	Baisun	1,24	У = - 0,6922X + 1837,4	- 0,6922
5	Kinguzar	0,80	У = 2,5217X – 4511,4	2,5217
6	Dashnabad	0,77	У = 1,2938X – 1958,5	1,2938
7	Zarchob	0,69	У = 1,4221X – 2285,9	1,4221
8	Termez	0,31	У = 0,0715X + 5,0752	0,0715

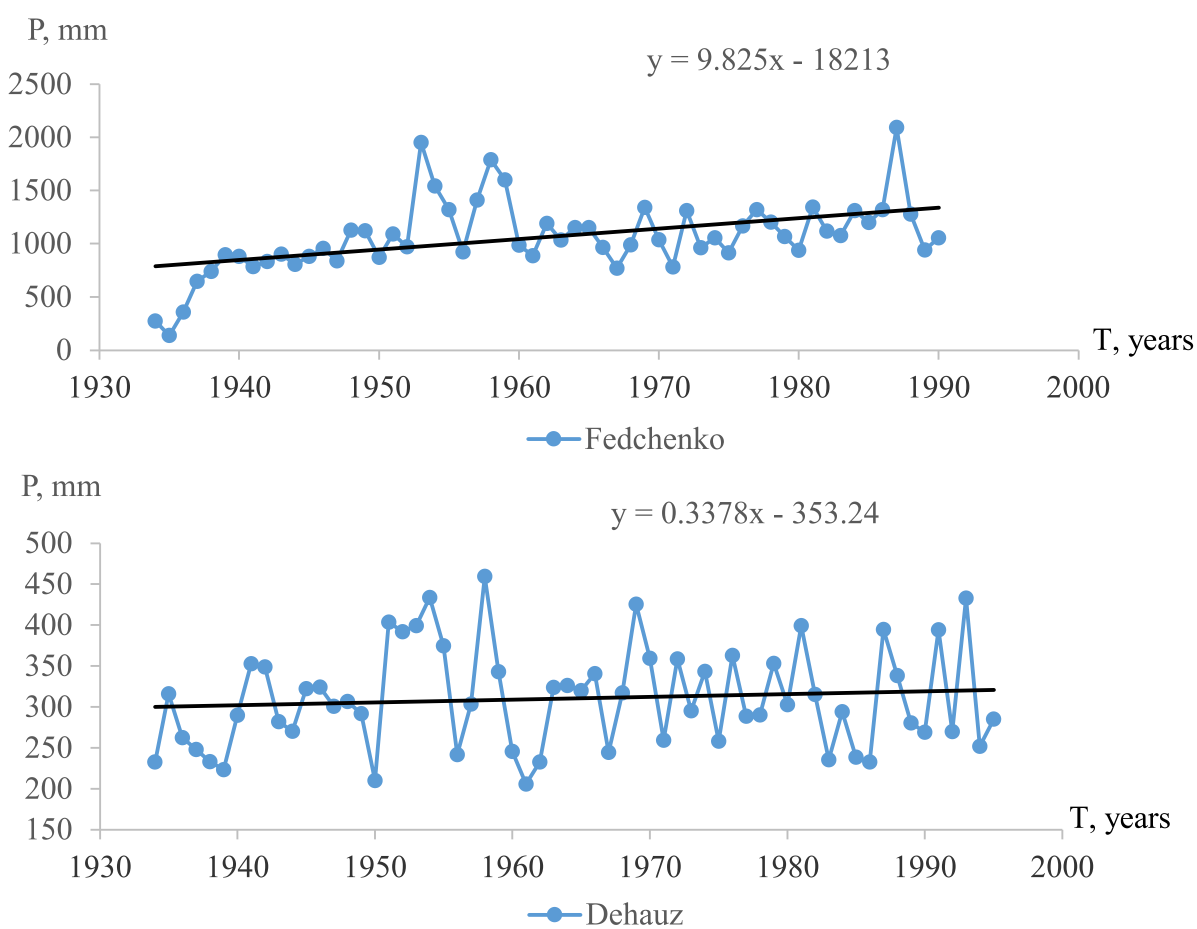


Fig. 2. Graphs of variations of the annual precipitation totals over meteorological measuring points in Tajikistan river basins

Table 2
Equations and trends of variations of the annual precipitation totals over observation points in Tajikistan river basin

№	Name of observation station	H, km	Equation	Trend
1	Fedchenko	4,17	У = 9,825X - 18213	9,825
2	Dehauz	2,50	У = 0,3378X – 353,24	0,3378
3	Anzobskiy	3,58	У = 4,9901X – 9389,4	4,9901
4	Shahristan	3,20	У = 1,4834X – 2508	1,4834
5	Irht	3,44	У = 0,3312X – 513,15	0,3312
6	Horog	2,08	У = 0,978X – 1652,4	0,978
7	Iskanderkul	2,20	У = 0,9931X – 1675,6	0,9931
8	Dgavshan	3,50	У = 0,0711X + 0,195	0,0711

The presented graphs and data given in Table 2 reveal that eight observation eight observation stations recorded negligible increase of the annual precipitation totals.

Thus, 14 precipitation observation stations in the Surkhandarya River basin and the Tajikistan river basins showed negligible increase of the annual precipitation totals during observation periods, while two of them recorded their decrease.

In all zonal parts of Afghanistan precipitation fall from November to May, and they are mainly recorded in January – May period. In other months precipitation do not fall mostly.

Precipitation distribution over the territory of country is rather uneven. In the plain and slightly hilly zones the average annual precipitation in the south and south-west is 50 – 150 mm, and in the north – 150 – 200 mm. Precipitation fall out mainly as rain, while in the moderately mountainous areas in winter months they are in a form of snow.

According to the old data, in the north of country precipitation norm is reduced gradually from Hindukush to the Amudarya River. According to corrected data it follows that the whole northern zone can be subdivided to two subzones: eastern and western ones.

In the eastern zone the gradual decrease of precipitation norm (from 500 mm up to 200 mm) is recorded. The region with precipitation norm of 200 mm and less stretches to the south from the Amudarya River. In the eastern zone the maximum precipitation norm is about 300 mm in a year. Precipitation norm is decreasing to the south and south-east [5].

Calculation of intrannual precipitation distribution presents quantitative assessment of precipitation distribution over the seasons of the year and months, as well as over decades and weeks within a month. It is usually expressed in percents or shares from the yearly value (with seasonal and monthly distribution) or the monthly (with decade or weekly distribution) precipitation totals. This provides for getting precipitation data for specific (calendar) time period.

Despite the diversity of individual features of the precipitation, the analyses of the long-term precipitation hydrographs in the river basins of different geographic zones and regions make it possible to determine their common or similar features that are typical for the different river groups in individual regions, and to make classification of rivers according to the sources of their alimentation and intrannual flow distribution.

Main factors determining intrannual precipitation distribution and its general quantity – are climatic ones. They define general character (background) of precipitation distribution over a year in certain geographic region.

Based on the abovementioned results, an analysis of the intrannual precipitation distribution in investigated regions was made. The analysis was made using average long-term monthly precipitation totals. The results obtained for the Surkhandarya River basin are presented in Fig.3 (as an example), and the main characteristics recorded by all observation stations points are given in Table.3.

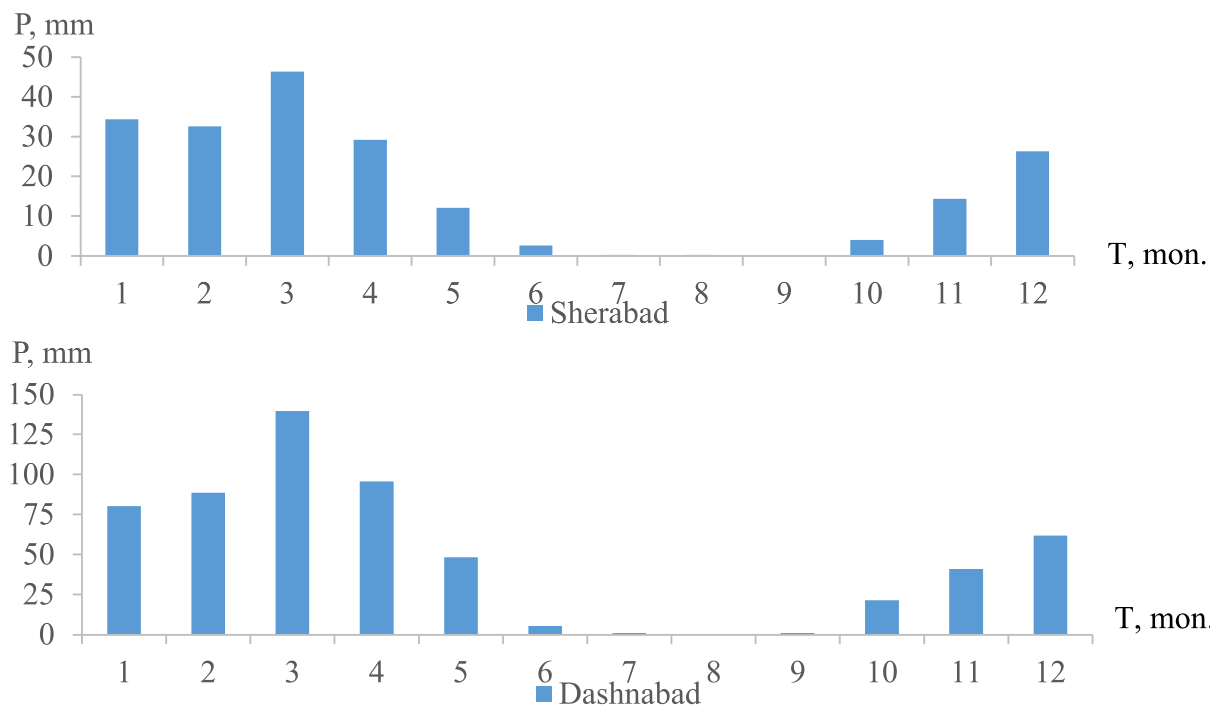


Fig. 3. Examples of the intrannual precipitation distribution at observational points in Surkhandarya river basin

Table 3 Intrannual distribution of the average long-term montly precipitation totals measured at meteorological stations of the Surkandarya River basin

№	Name of measuring station	H, km	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	Shurchi,mm	0,45	42.9	42.7	64.3	41.2	21.6	2.6	0.4	0.0	0.6	7.3	21.5	34.3	279.3
	%		15.4	15.3	23.0	14.7	7.7	0.9	0.1	0.0	0.2	2.6	7.7	12.3	100
2	Sherabad, mm	0,42	34.4	32.6	46.4	29.2	12.1	2.6	0.3	0.3	0.1	4.0	14.4	26.3	202.3
	%		17,0	16.1	22.9	14.4	5.9	1.3	0.1	0.1	0.1	2.0	7.1	13.0	100
3	Denau, mm	0,52	52.3	55.4	74.5	56.1	28.9	3.5	0.2	0.3	0.6	9.3	28.3	42.4	351.2
	%		14.8	15.8	21.2	15.9	8.2	1.0	0.1	0.1	0.2	2.7	8.1	12.1	100
4	Baisun, mm	1,24	61.6	66.1	99.7	82.0	47.8	9.9	3.4	1.6	1.4	12.6	32.3	54.7	472.4
	%		13.0	14.0	21.1	17.4	10.0	2.1	0.7	0.3	0.3	2.7	6.8	11.6	100
5	Kinguzar, mm	0,80	68	77	101	71	41	9	2	0	2	17	40	58	485
	%		14.0	15.9	20.8	14.5	8.5	1.8	0.3	0.1	0.4	3.6	8.3	11.9	100
6	Dashnabad, mm	0,77	80.2	88.7	139.6	95.6	48.3	5.4	1.0	0.3	1.1	21.4	41.1	61.8	584.5
	%		13.7	15.2	23.9	16.4	8.3	0.9	0.2	0.0	0.2	3.7	7.0	10.6	100
7	Zarchob, mm	0,69	70.7	75.8	117.3	87.9	42.0	5.5	2.3	0.1	1.2	16.9	34.4	55.2	509.3
	%		13.9	14.9	23.0	17.3	8.3	1.1	0.4	0.0	0.2	3.3	6.8	10.8	100
8	Termez, mm	0,31	23.9	22.3	33.0	23.1	9.9	1.2	0.0	0.0	0.2	2.7	10.2	18.8	145.4
	%		16.5	15.3	22.7	15.9	6.8	0.8	0.0	0.0	0.2	1.8	7.0	12.9	100

By analyzing the attained results, the following conclusions can be made:

- Most of the precipitation falls out in the periods of January – May and November – December. The percentages of precipitation during these periods vary from 97% at Termez measuring station to 94 % at Kinguzar measuring station. Thus, precipitation distribution is the same at all eight measuring stations;

- Precipitation percentages for the periods of January – May and November – December vary from 77% to 67 % and from 20 % to 15 %, respectively;

- Regarding quantitative values, the average long-term annual precipitation totals vary from 140 mm in downstream parts of the basin up to 584 mm in the upstream parts of the basin;

- The highest precipitation values are recorded in May – April and equal to 140 – 33 mm;

- The intrannual precipitation distribution has natural character and depends on the seasonal variations of meteorological elements and on atmospheric circulations of air masses;

- The relationship between the average long-term annual precipitation totals and absolute elevation of the observation station is shown in Fig.4.

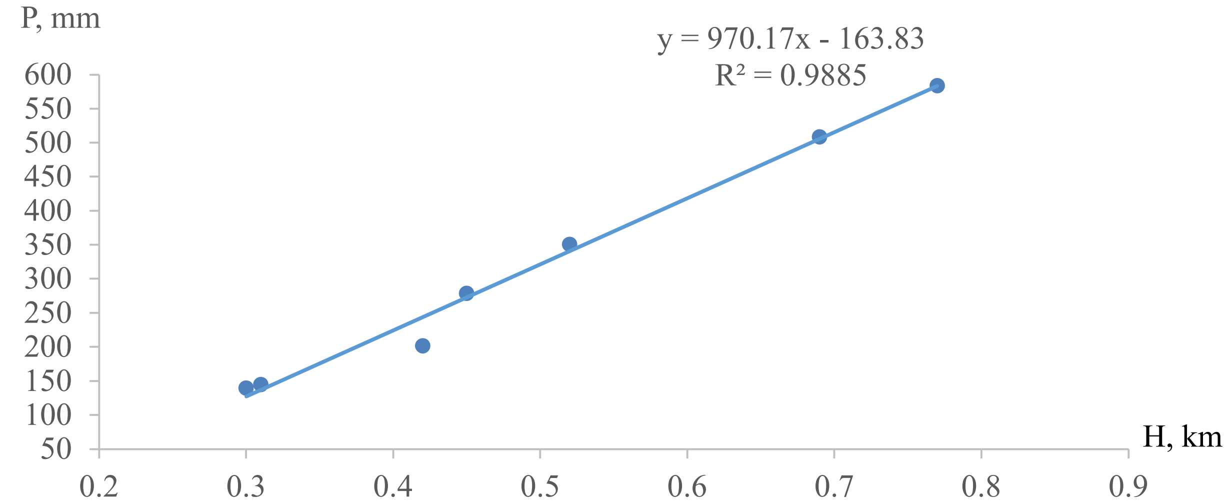


Fig. 4. Correlation between average long-term precipitation totals and absolute basin for the Surkhandarya River basin

The results obtained for the Tajikistan river basins are presented in Fig. 5 (as an example), and the main characteristics for all measuring stations are given in Table 4.

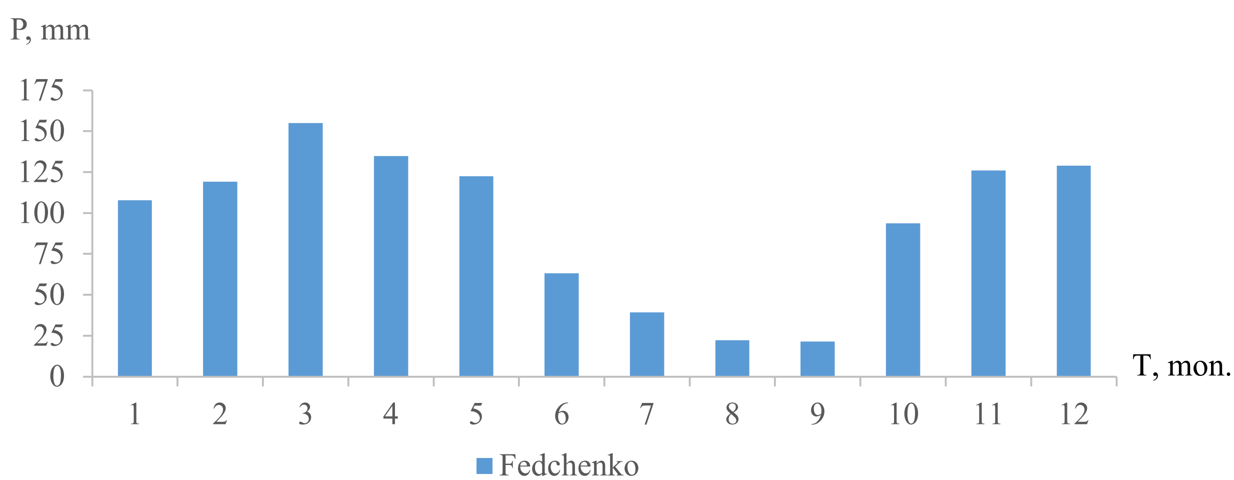


Fig. 5. Examples of the intrannual precipitation distribution at observational stations in the Tajikistan river basins

Table 4

Intrannual distribution of the average long-term monthly precipitation totals measured at meteorological stations of the Tajikistan river basins

№	Name of measuring station	H, km	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	Fedchenko, mm	4,17	100	108	139	121	113	63	39	21	21	88	115	119	1047
	%		9.6	10.3	13.2	11.6	10.8	6.0	3.7	2.0	2.0	8.4	10.9	11.4	100
2	Dehauz, mm	2,50	9.9	12.9	30.6	49.7	54.2	38.5	27.3	13.5	10.8	21.8	16.1	12.6	297.9
	%		3.3	4.3	10.3	16.7	18.2	12.9	9.1	4.5	3.6	7.3	5.4	4.2	100
3	Anzob, mm	3,58	35.6	35.7	54.1	56.0	63.4	34.1	23.3	11.2	8.4	25.7	32.1	36.4	416.1
	%		8.6	8.6	13.0	13.4	15.2	8.2	5.6	2.7	2.0	6.2	7.7	8.7	100
4	Shahristan, mm	3,20	22.6	28.9	50.6	65.7	69.2	44.9	29.0	12.9	9.6	24.0	25.2	23.4	406.1
	%		5.6	7.1	12.5	16.2	17.0	11.1	7.1	3.2	2.4	5.9	6.2	5.8	100
5	Irht, mm	3,44	13.3	14.5	22.0	21.4	18.0	9.2	6.0	5.9	2.5	5.8	7.2	11.8	137.7
	%		9.7	10.6	16.0	15.5	13.0	6.7	4.3	4.3	1.8	4.2	5.3	8.6	100
6	Horog, mm	2,08	30.4	39.2	52.5	45.7	27.0	6.9	2.8	0.4	0.9	15.4	18.1	30.3	269.8
	%		11.3	14.5	19.5	16.9	10.0	2.6	1.0	0.2	0.3	5.7	6.7	11.2	100
7	Iskanderkul, mm	2,20	15.9	21.5	45.2	56.7	42.9	18.3	10.7	5.9	3.8	16.6	14.6	18.9	270.9
	%		5.9	7.9	16.7	20.9	15.8	6.8	3.9	2.2	1.4	6.1	5.4	7.0	100
8	Dgavshan, mm	3,50	11.4	15.6	21.9	23.9	21.0	8.1	4.6	3.9	1.9	6.0	7.6	13.9	139.9
	%		8.1	11.2	15.6	17.1	15.0	5.8	3.3	2.8	1.4	4.3	5.4	10.0	100

After an analysis of the obtained results, the following conclusions can be made:

- Most of the precipitation during a year falls out in the periods of January – June and October – December. The percentages of precipitation during this period vary from 98,5 % at the Khorog measuring station to 87 % at the Shakhristan mountain pass. It is necessary to mention that intrannual precipitation distribution over the Tajikistan river basins is more even than in the basin of the Surkhandarya River. In the Tajikistan river basins precipitation falls out the whole year round;
- The percentages of precipitation for the periods of January – June and October – December vary from 75% to 62 % and from 31 % to 17 %, respectively;
- Regarding quantitative values, the average long-term annual precipitation totals vary from 138 mm at the Khorog measuring station to 1047 mm at the Fedchenko measuring station which is determined by the differences in physical and geographic conditions;
- The highest precipitation values are recorded in March – April and range from 140 mm at the Fedchenko measuring station to 21 mm at the Irht measuring station;
- The intrannual precipitation distribution has natural character and depends on the seasonal variations of meteorological elements and on atmospheric circulations of air masses;
- Regarding quantitative values, in the Tajikistan river basins a lag of precipitation totals with respect to absolute elevation is recorded and compared with the Surkhandarya River basin. For example, at the Irht measuring station (elevation of 3,44 km) precipitation total is 138 mm, which corresponds to the precipitation total at the Termez measuring station (elevation of 0,31 km);
- Similar to the Surkhandarya River basin, in the Tajikistan river basins the relationship between the average long-term annual precipitation totals and absolute elevation of observation station is recorded. Unfortunately, we could not get observation materials for the stations of the Tajikistan river basins located in the low mountain areas. The graph of correlation between precipitation totals and absolute elevation of the locality is presented in Fig.6.

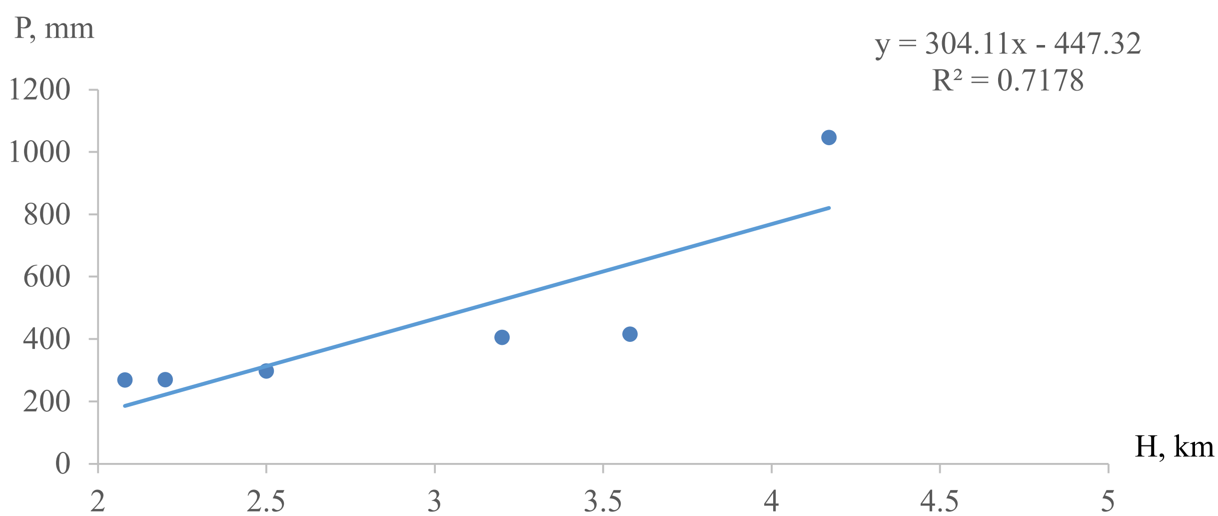


Fig. 6. Correlation between average long-term precipitation totals and absolute elevation values for the Tajikistan river basins

As there are no results of precipitation observations for the Afghanistan river basins, we used fragmentary data presented in [5]. Figs. 7 and 8 the intrannual precipitation distribution in the north-eastern and north-western zones of Afghanistan is shown. The graphs are executed in relative quantities $\eta = \frac{P_m}{P_{sm}}$, where η is the relation of precipitation layer P_m in a given month to the average monthly value of P_{sm} ($P_{sm} = \frac{P_g}{12}$ - is the typical average monthly value; the quotient of division of the typical yearly P_g is 12 months).

In the north-eastern zone (Fig.7) precipitation in March quantitatively prevails over precipitation falling in other months. The amount of precipitation gradually decreases until July (almost reaching zero) with complete termination in August. Afterwards, the layer of monthly precipitation increases and stabilizes within the range of 0,7 – 0,8 of the average monthly precipitation in November – December.

In the north-western zone (Fig.8) the character of the intrannual distribution of precipitation is similar to that in the preceding zone, with the exception that from June up to September there is no precipitation, while during autumn – winter period their gradual increase is recorded from September to January.

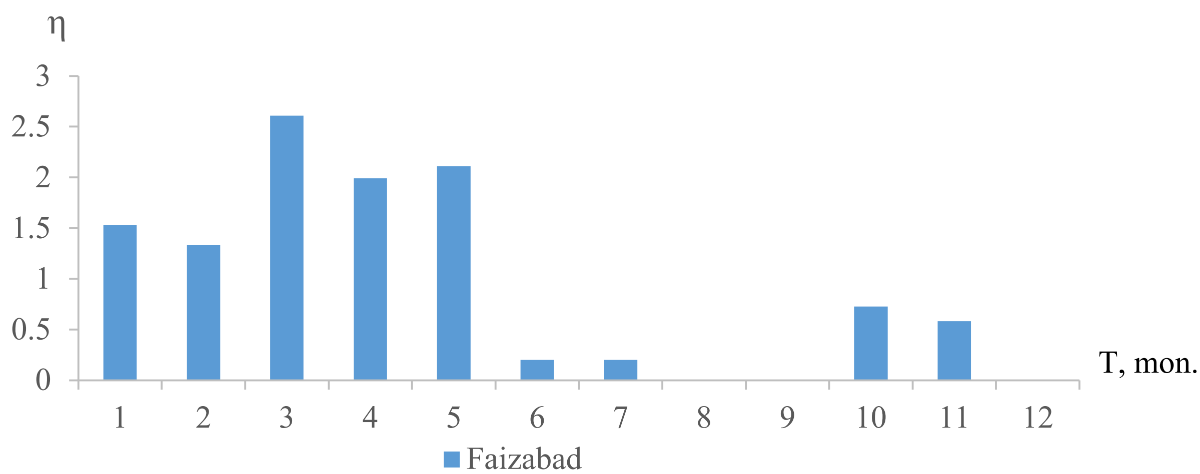
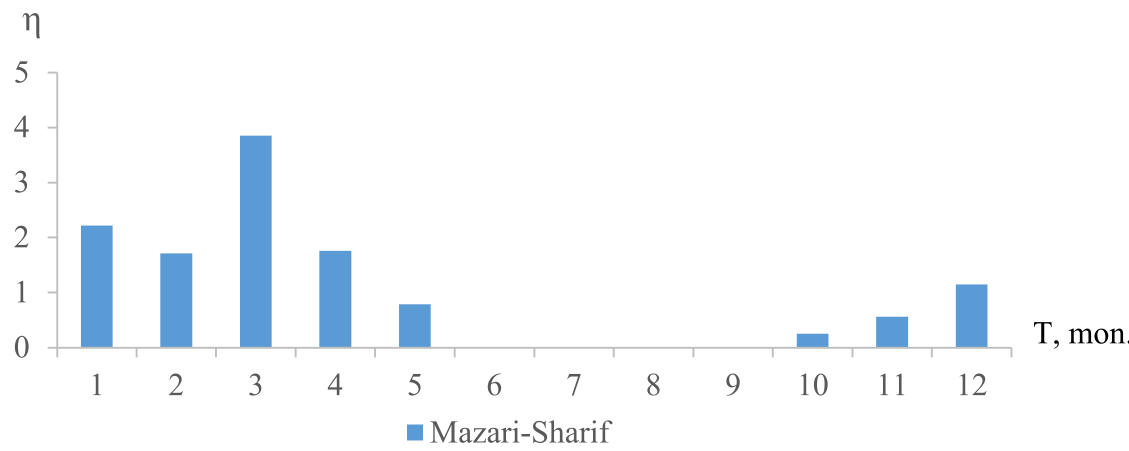


Fig. 7. Intrannual distribution of precipitation (in relative quantities) over the north-eastern zone of Afghanistan [5]

As it was mentioned before, because of fragmentary data of precipitation observations and short data series the derivation of relationship between precipitation and elevation is not possible.

Further we calculated average annual precipitation amount recorded in the Amudarya River basin. It is accepted in hydrology that precipitation in the river basin (with the exception of losses for evaporation, infiltration, transpiration, etc.) forms the river flow in the outlet of the basin. From this assumption one of the main formula of the flow characteristics is as follows – flow coefficient which shows the amount of precipitation that falls in the river basin, forms a flow or $\eta = \frac{Y}{X}$. The logical conclusion of this formula is that, with other equal conditions being equal there should be definite correlation between the flow and precipitation



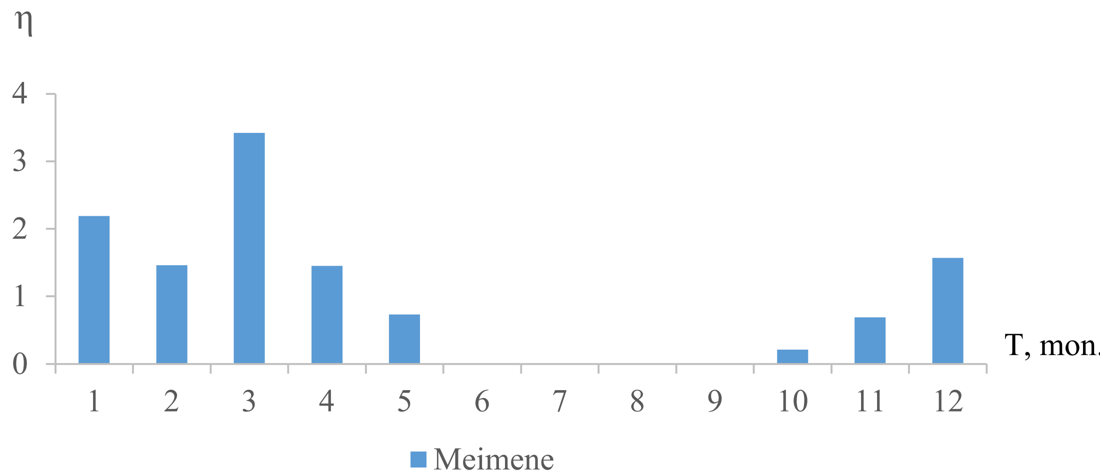


Fig. 8. Intrannual distribution of precipitation (in relative quantities) over the north-western zone of Afghanistan [2]

Based on the assumption mentioned above, we were faced with the problem of calculation of the average amount of precipitation in the three studied basins: the Surkhandarya River basin, basins of Tajikistan and basins of the northern zone of Afghanistan.

Calculation of the average amount of precipitation in the river basin is performed by several commonly used methods. For this purpose we used two methods: a) method of arithmetic average and b) method of isohyets.

Method of the arithmetic average. For 8 stations of the Surkhandarya River basin (Table 1) and stations of the Tajikistan basins (table 2) yearly precipitation totals were calculated for every year of observations, and from them the average values were calculated. From the resulted data the graphs of variations of the average yearly precipitation totals for the observation period were constructed (Figs. 9 and 10). An analysis of graphs demonstrates that the changes in precipitation values and their negligible variations during observation period are determined by the natural causes: yearly, seasonal variations of meteorological elements and by circulation of the atmospheric air masses

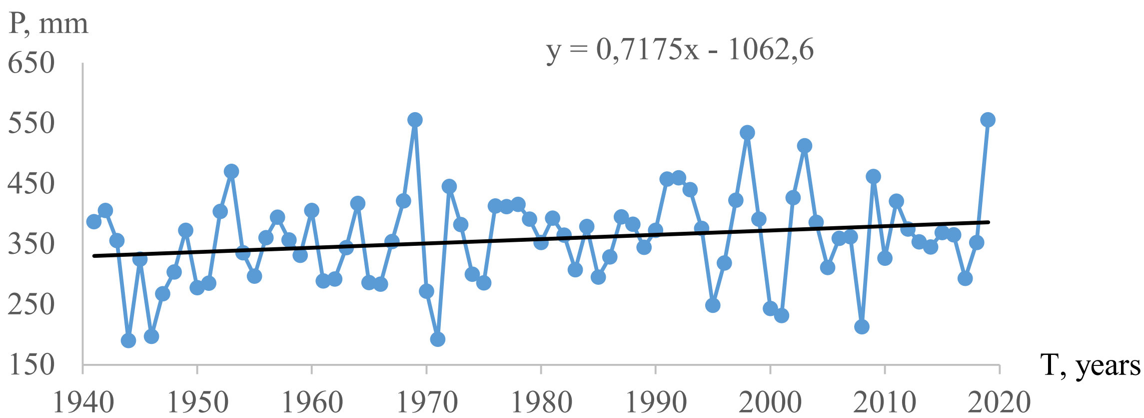


Fig.9. Graph of variations of the average yearly precipitation totals recorded at observation stations of the Surkhandarya River basin

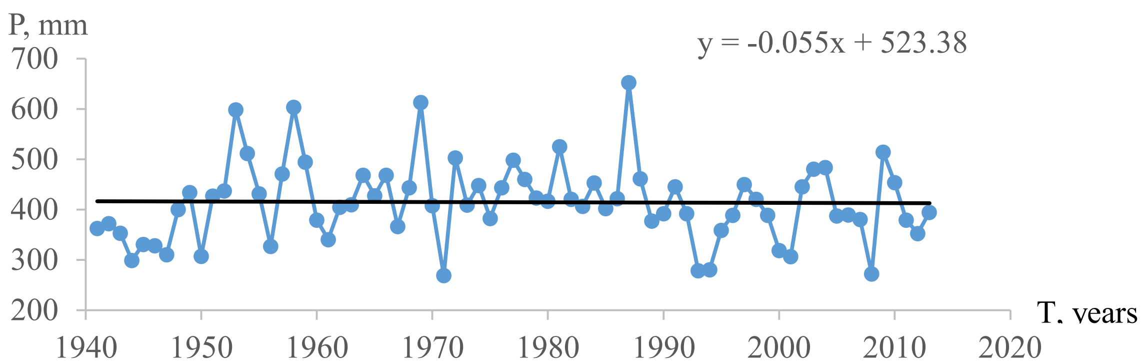


Fig.10. Graph of variations of the average yearly precipitation totals recorded at observation stations in Tajikistan

Calculations for the northern part of Afghanistan were not performed as information was not available.

Method of isohyets. With the traditional calculation of the average precipitation amount falling in the basin the isohyets are constructed manually by the data recorded at the station. With the development of IT technologies and application of GIS technologies in different types of mapping, we used new directions in the solution of our problem.

For the basins of the Tajikistan rivers and the Surkhandarya River the maps of isohyets were constructed, and the average long-term yearly precipitation totals in the studied regions were calculated. The commonly used formula was used for calculations:

$$X_0 = X_1*f_1 + X_2*f_2 + \ldots + X_n*f_n/ F,$$

where X_1, X_2, X_n are the average precipitation values between neighbor isohyets; f_1, f_2, f_n – partial areas between neighbor isohyets; F – total basin area. Based on the logic of the studies, we constructed maps for the conditionally-natural period, i.e., for the period before the construction of the Karakum canal – from 1941 till 1955; we comparatively assessed the flow at the Kerki hydrological station in conditionally-natural state and the subsequent stages of anthropogenic load on the Amudarya River flow. The results of isohyets' construction are presented on figures 11 and 12 (as an example).

In the result of our work we calculated the average yearly precipitation totals recorded on the investigated basins. It is necessary to note that the values of the yearly precipitation totals calculated with two methods for Surkhandarya river basin were almost similar. For the basins of the Tajikistan rivers the results differ considerably. This is due to insufficient observation data for the left-side basins of Tajikistan rivers. Because of the complex orography with significantly crossed relief of the territory we managed to use only three stations. It was also impossible to use data of the low-mountainous stations on the whole territory of the Tajikistan river basins.

After completion of tasks mentioned above, we reached the solution of the main problem: estimation of relationship between precipitation in the studied basins and flow of the Amudarya river in the Kerki hydrological cross-section for the conditionally-natural period.

Further it was interesting for us to determine the total losses in the result of anthropogenic activities and under the impact of the natural Kerki hydrological cross-section. The results of calculations are presented in Fig.14 and in Table.5. The difference between the discharge values is the value of losses.

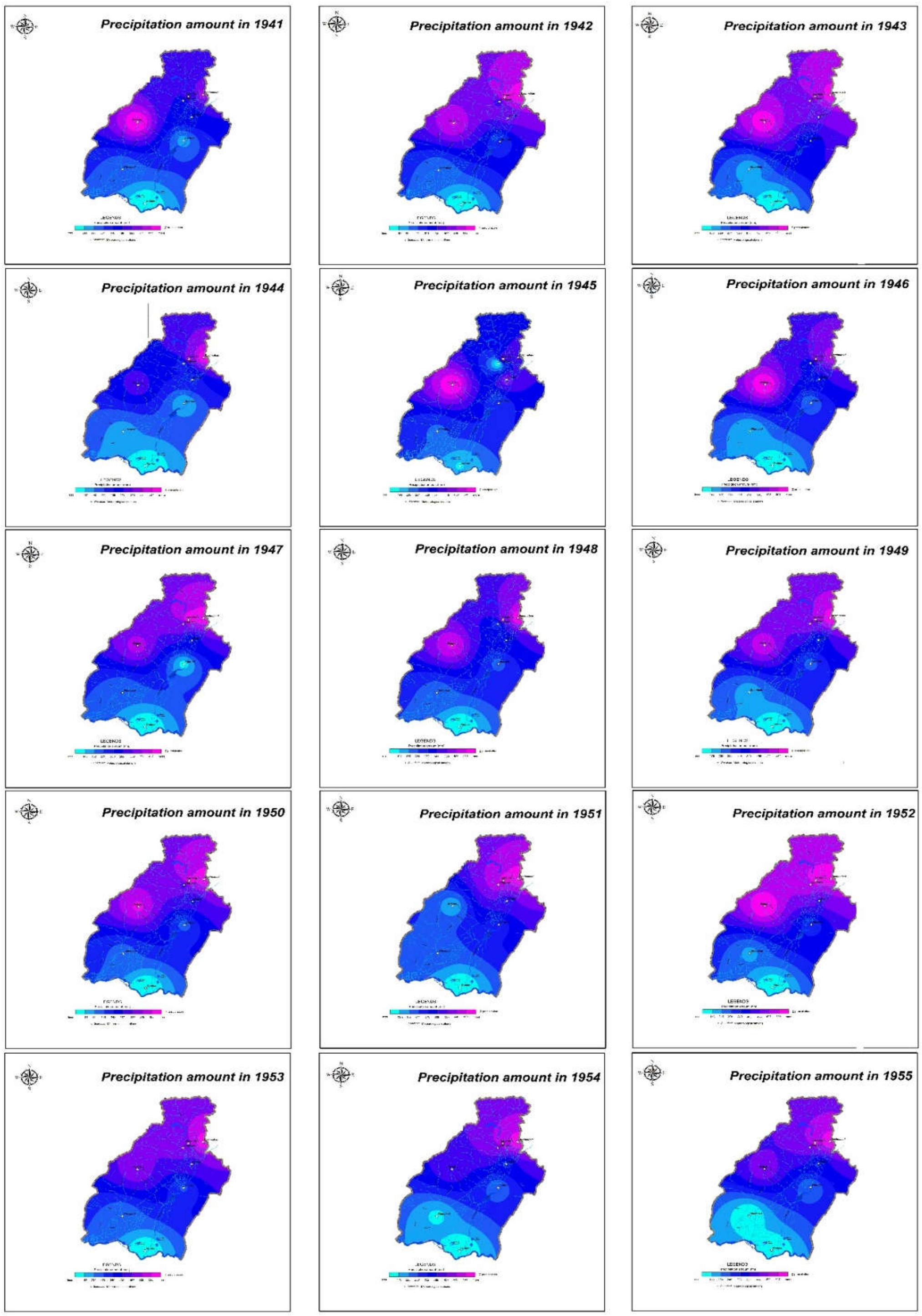


Fig.11. Maps of isohyets for the Surkhandarya River basin

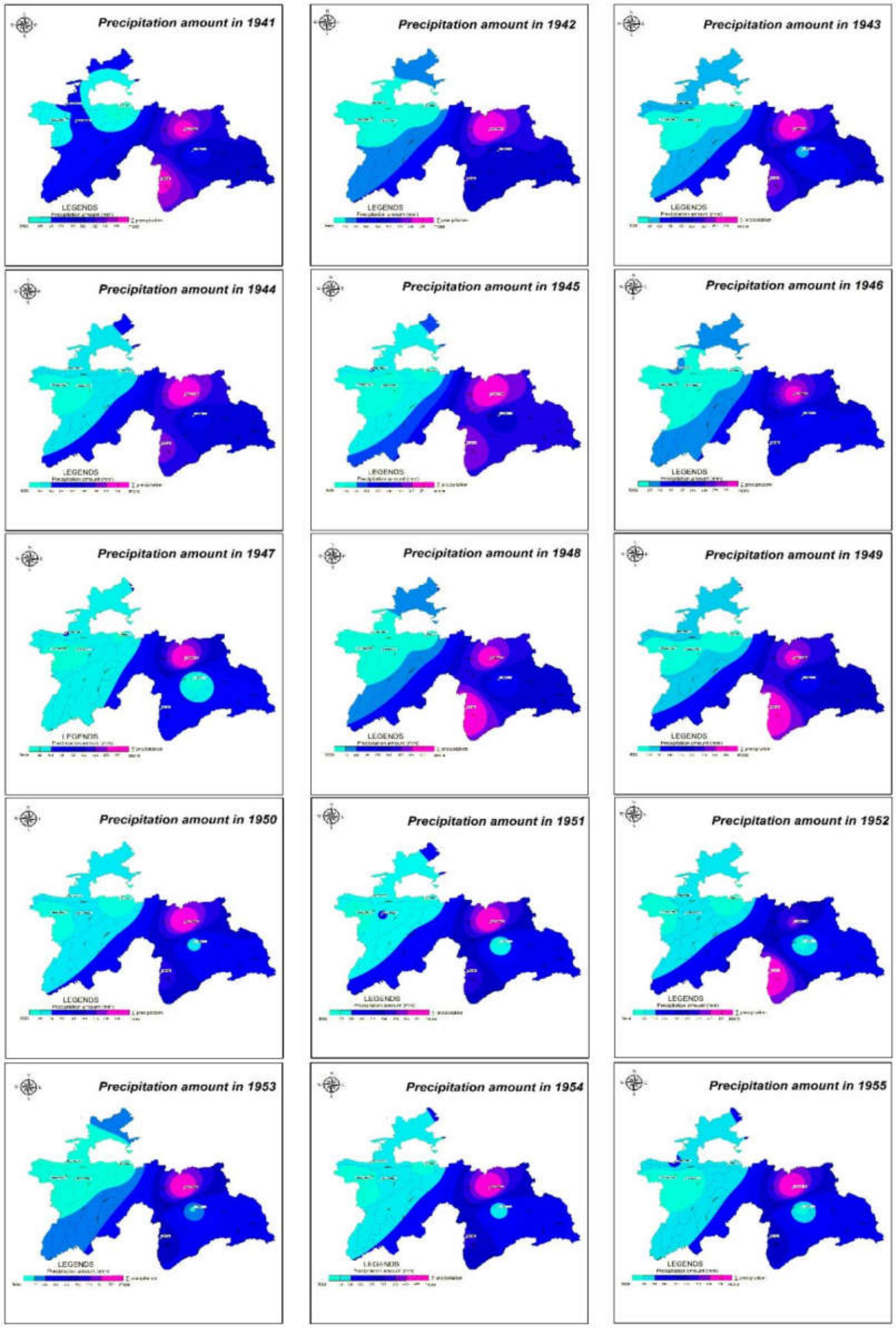


Fig.12. Maps of isohyets for the Tajikistan river basins

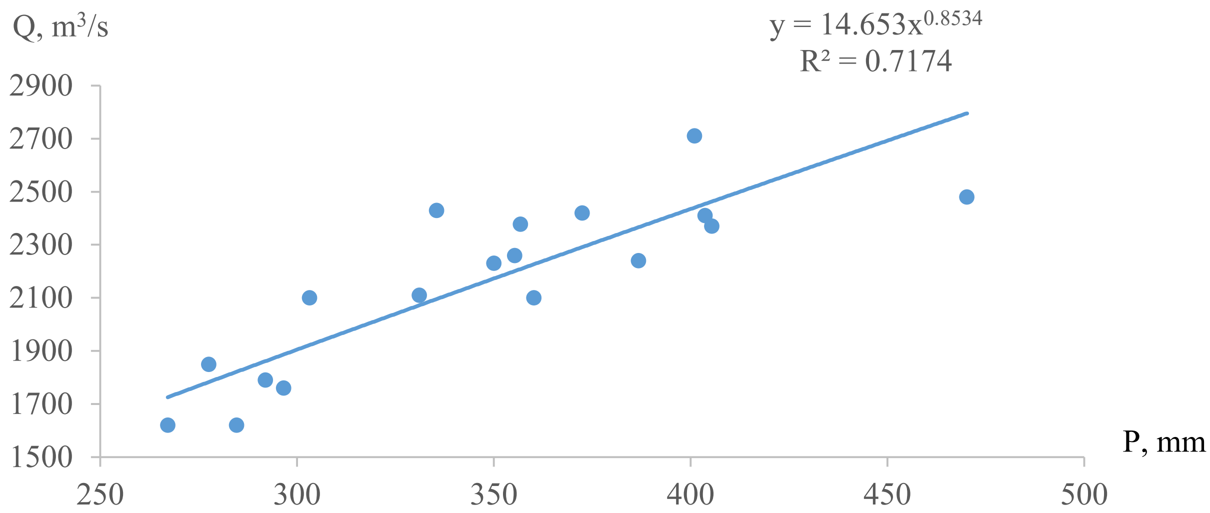


Fig.13. Graph of correlation between flow recorded at the Kerki hydrological station and average yearly precipitation totals on the Surkhandarya River basin

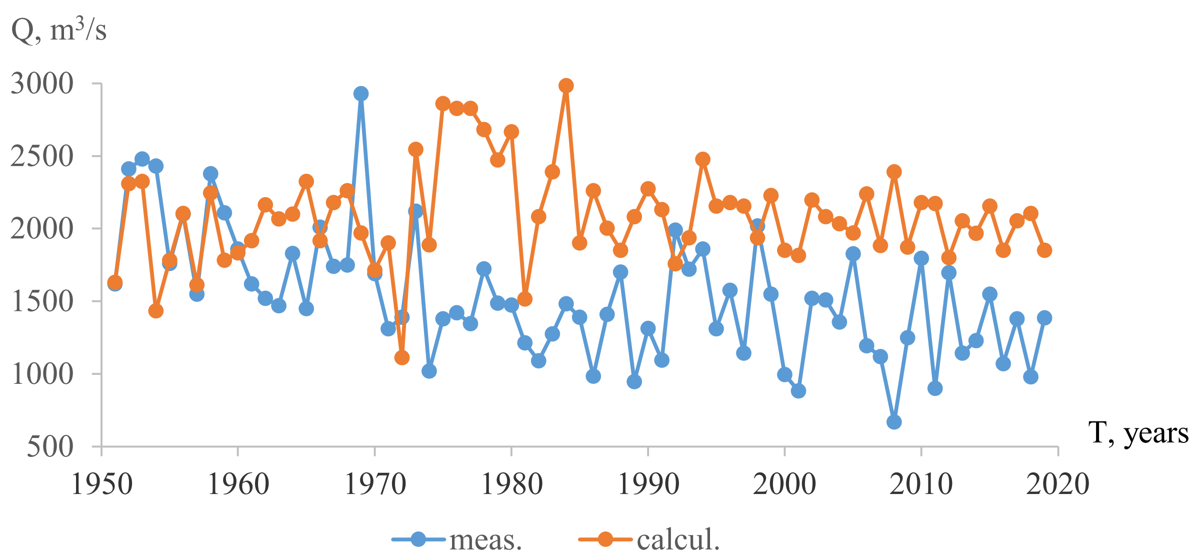


Fig. 14. Graph of variations between the measured and calculated discharge values at the Kerki hydrological station

Table 5

Mean flow characteristics in the Kerki hydrological cross-section and losses in the result of anthropogenic activities and impact of the natural factors by periods

№	Period	Discharge (Q m³/s) measured at Kerki		Losses in %	Average losses in %
		$Q_{measur.}$	$Q_{calcul.}$		
1	1941 - 1960	2114	2183	+ 14 - -55	- 4,64
2	1961 - 2019	1444	2058	+ 33 - -258	- 55,0
3	1941 - 2019	1619	2232	+ 14 - -182	-47,8

Main conclusions. After analyzing the obtained results the following conclusions can be made:

- Losses for the conditionally-natural period of 1941 – 1960 were 4,64 %, which is within the admissible error for discharge measurements;
- Losses for the period of the Karakum canal operation from 1961 up to 2019 are in the range of + 33 to -258 %, and are 55,0 % in average;
- Losses for the whole studied period from 1941 to 2019 were 47,8% in average.

It is supposed to use the results obtained in this work in the studying of flow dynamics and losses downstream of the Amudarya River. These issues will be considered in further studies.

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