GLOFCA PROJECT
«Reducing vulnerabilities of populations in the Central Asia region from glacier lake outburst floods in a changing climate»

Report on task 3 part 2:

Preliminary comprehensive analysis of GLOF formation conditions for identified critical lakes in the Ala-Archa River basin based on remote sensing data and available special published data

and

Report on task 5 part 2:

Joint lead-authorship together with UZH on the best practice guidance for mapping hazards and risks in the Ala-Archa river basin (GLOF)

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1. Factors determining the degree of lake outburst hazard in the Ala-Archa River basin

Introduction.

Extreme floods formed in the high-mountain zone are based on a complex of factors corresponding to the main elements of the natural system. Among these factors, the main ones are meteorological, glaciological, geomorphological, lithological, hydrogeological, hydrological, limnological, and exogenous processes. Outburst prone lakes in this system are considered under the limnological factor and are one of the elements of the system. In order to assess the role of each of these factors in the formation of extreme floods and associated mudflows, the peculiarities of each of them were analyzed in the Ala-Archa River basin and, in particular, in the Adygene River basin.

In the first section of the report, the main method of analysis of the above-mentioned factors, except for meteorological, which is considered in Section 2, is the analysis of multi-temporal optical satellite images with resolution from 0.5 to 10 m/pixel, with different combinations of spectral channels, as well as the analysis of digital elevation models ASTER/ASTGTM.003, NASA/METI, 2000-2013 and SRTM (2000). The results of the Sentinel 1 radar satellite data analysis were also used. The results of earlier studies of glacier change were also used in the report.

1.1 Glaciological conditions

The role of glaciers in the formation of extreme floods is, firstly, that they are a source of surface runoff, which can reach extreme values depending on the size of the glacier area, the amount of precipitation falling on the surface of its basin, and changes in air temperature affecting the intensity of snow and ice melting. Secondly, an important role is played by the probability of glacier movement or a significant collapse of the glacier terminus edge with the formation of an ice avalanche capturing lakes on the way. These phenomena, which depend on the factors of formation of water flow from the glacier, also depend on the features of the landform of the glacier and its bedrock, the magnitude of the slopes of the glacier surface and the bedrock, the presence of icefalls on sharp bends of the landform profile, the speed of ice movement. The process of glacier area reduction as a result of global warming and retreat of glacier tongues is associated with the formation of new glacial lakes and increase in the area of existing periglacial lakes.

During the period from the 70s of the 20th century to 2013-16, according to the Catalog of Glaciers of Kyrgyzstan [1], based on the analysis of Landsat 8 satellite images, there was a 28% reduction in the area of glaciers in the Ala-Archa River basin. Thus, as of 2013-16, 43 glaciers with an area of 38.7 km^2 were recorded in the Ala-Archa River basin, including 17 glaciers with sizes less than 0.1 km^2 each, with a total area of 0.9 km^2. And according to the Catalog of Glaciers of the USSR [10], there were 33 glaciers in this basin, with a total area of 53.6 km^2, including: 30 glaciers with sizes more than 0.1 km^2 each with a total area of 53.5 km^2 and 3 glaciers with sizes less than 0.1 km^2 each with a total area 0.1 km^2. According to the estimation of the area of glaciers in the Ala-Archa basin in the publication [2], the total area of glaciers in the period from 1964 to 2010 has changed from 41 km^2 to 33 km^2, i.e. decreased by 19.5%. All these results, in general, correspond to the rate of the observed long-term trend in the reduction of glaciation on the territory of Kyrgyzstan and, in particular, within the Kyrgyz ridge, described earlier in publications [3,4,5,6,7]. In this case, local variations in glacier area change depend on the accuracy of the data used for their estimation, the time period of glacier change estimation and their location within the ridge in terms of exposure, altitude.

In the Adygene River basin, which is part of the Ala-Archa River basin, according to the Catalog of glaciers of Kyrgyzstan [1], with numbering according to the scheme of this catalog, there are five glaciers № 229, 230, 232, 234, 235, and also, in this case we consider the glacier № 230-1, which is not included in this catalog, with an area of 0.01 km^2 (Fig. 1). In the Adygene River basin, as can be seen in Table 1, according to the results of detailed analysis of aerial photo from 1962 and high-resolution satellite images "Corona" from 12/09/1961, "Quick Bird" from 24/06/ 2006, "World View-2" from 13/08/2017, "Sentinel 2" from 18/08/2022, for glaciers № 234, 235, glacier area decreased from 1961 to 2022 by 8-13%, and for the period 2017- 2022, for glacier № 235 by 1.4%. During the same period, for glaciers № 229, 230-1, 232 no change in area was detected, glacier № 230 decreased insignificantly, and for glacier № 234 an insignificant increase in area was determined. In the last two cases, these area changes are close to the interpretation error, which, on the one hand, is related to the low resolution of the satellite image from 2022, with the minimum possible interpretation accuracy of ±10 m, and, on the other hand, to the small time interval between the compared glacier areas. In addition, the scale of area reduction is influenced by the altitudinal location of the glacier terminus. Thus, the termini of glaciers № 229, 230, 230-1, 232, as can be seen from Table 1, are located at a relatively higher absolute height, by a maximum of 100-200 m, relative to those of glaciers № 234, 235, which causes their lesser degradation during warming.

The area reduction for all glaciers is due to the retreat of the lower parts of glacier terminus and, to a lesser extent, due to the narrowing of tongue widths within the ablation zone. Within the ablation zone, there is also a long-term decrease in the thickness of glacier tongues. The higher located parts of glaciers, located above the zero average annual isotherm, practically do not change towards a reduction in area; this also applies to relatively high located small cirque and hanging glaciers. The retreat of glaciers contributes to the emergence of new lakes and an increase in the area of existing periglacial lakes, as can be seen in Figures 1, 28 for glacier № 235 and, thereby, increases the risk of outburst floods during extreme draining of these lakes. The extent of coverage of the ice surface of the glaciers under consideration by surface moraines is insignificant (Fig.5,8,9,10,11), they are observed mainly on glaciers № 234 and № 235, in their niche glacier parts, where they are formed due to clastic material of rocky ledges and valley slopes. Thus, the generation of the modern cover of moraine deposits of these glaciers has a small scale, with the formation of a moraine cover of small thickness with upward displacement of its upper boundary along the surface of the glacier tongue. The retreating glaciers are covered with a moraine mantle.

Table 1

Glacier number according to the Catalog	Area (km^2), in different years				Ice movement speed (m/day)	Surface slope (º/ inclination)	Area measurement values (km^2÷ %)	Altitude of the terminus (m), (DEM)
	1961, 1962	2006	2017	2022				
235	3,3	2.97	2,92	2,88	E- flow-0,029 W-flow-0,047	-	**1961-2022:** -0,42 кm^2÷ -12,7% 60 years-0,007 кm^2/year, -0,2%/year **2017-2022:** -0,04 кm^2÷-1,4% 5years -0,008 кm^2/year, -0,3%/year	3650-3675
234	0,35		0,32	0,32	0,03	16(0,29)	-0,029 км^2÷ -8,3% 0,0	3720-3740
232			0,5	0,5	0,019	18(0,32)	0,0	3810-3840
230			0,09	0,085	-	26(0,48)	-0,005 ÷ -5,6%	3780-3790
230-1			0,01	0,01	-	21(0,38)	0,0	3970-3980
229			0,21	0,21	0,023	29(0,55)	0,0	3840

Note: Parameters related to the period 1961-2022 are highlighted in black, parameters related to the period 2017-2022 are highlighted in green.

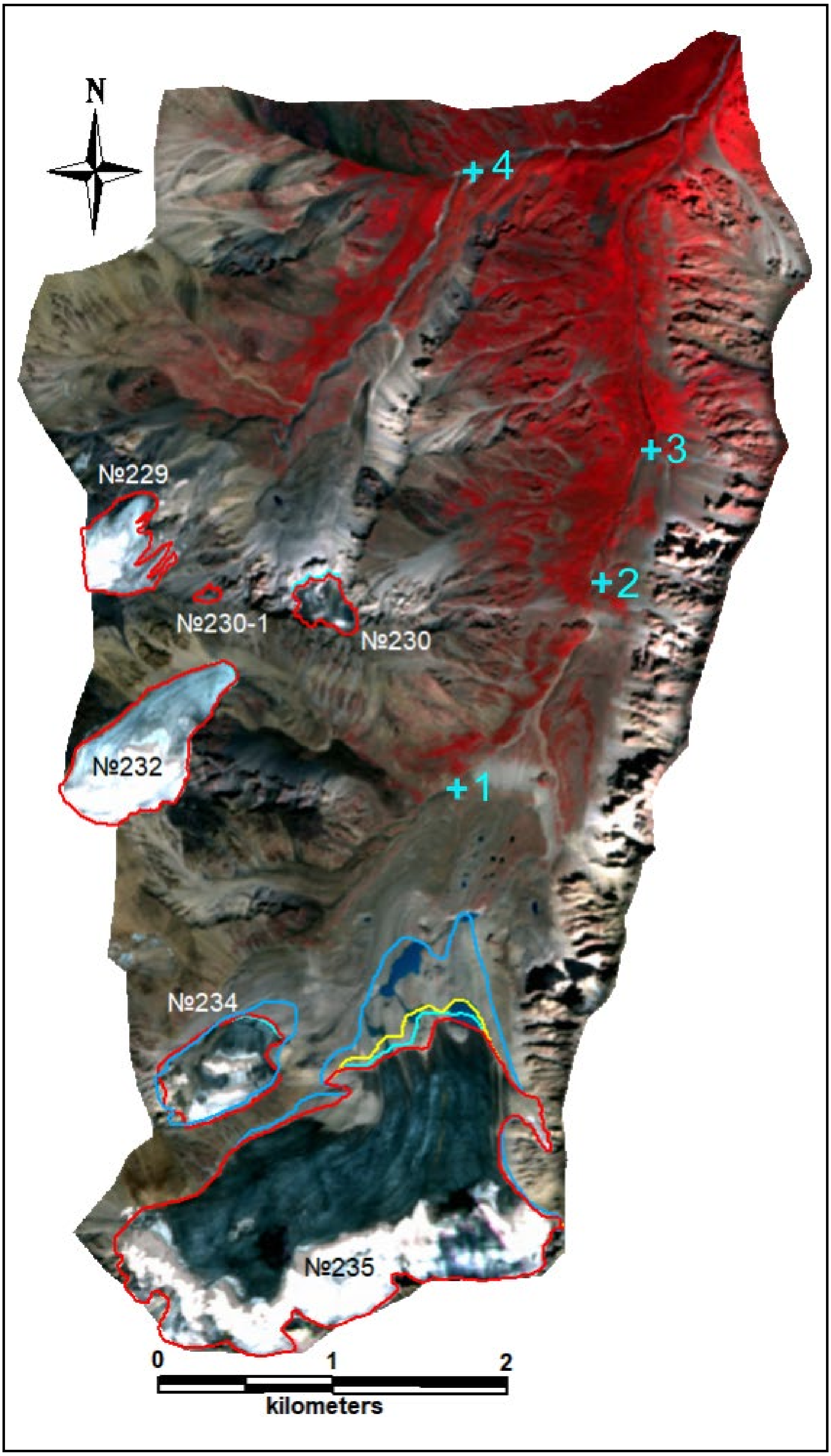

Fig.1 Location of glaciers in 2022 in the Adygene River basin and the position of their boundaries in different years. Red boundary - 2022, blue -2017, yellow - 2006, blue - 1961. Background - image of the satellite "Sentinel 2" from 18/08/2022. Blue cross is an outlet to the surface of underground water in the form of springs.

The analysis of the landform features of the surface of glaciers in the Adygene River basin was carried out using the above-mentioned satellite images and digital elevation models: (DEM) ASTER/ASTGTM.003, NASA/METI, 2000-2013 and SRTM (2000). In spite of the fact that the state of landform according to DEMs refers to the period 2000-2013, this information is mostly still valid and can be clarified during further studies.

As the analysis of satellite images and DEMs shows, the topography of the terminus of the glaciers under consideration is mainly gentle dipping under the overlying cover of moraine deposits in glaciers № 234, 235, and in glaciers № 229, 230, 230-1, 232 - evenly adjacent to the bedrock of the basin. The exception is the eastern part of the terminus of glacier № 235, in the area of the adjacent periglacial lake № 1, where the tongue edge has a precipitous character with a cliff height of up to 10 m (Fig. 2). This creates preconditions for the observed periodic collapses of ice blocks into the lake and may pose a danger in case of ice movement and collapse of large volumes of ice capable of causing a short-term release of water from the lake.

Fig.2 Lake № 1 (according to the catalog of the Ministry of Emergency Situations: Adygene periglacial (Ч-9-3), located on the northern slope of the Kyrgyz ridge is actively expanding due to degrading glacier № 235, from which ice blocks break off into the lake.
(Source: "Factors of formation of outburst hazard conditions of moraine-glacial lakes of the Tien-Shan". Erokhin S.A., Chontoev D.T., Zaginaev V.V. (Institute of Water Problems and Hydropower Engineering of the National Academy of Sciences of the Kyrgyz Republic)).

The features of the surface landforms of glaciers in the river basin Adygene was analyzed using the above-mentioned DEM, using profiles drawn along lines close to the axial lines for the main glacier ice streams. The location of these profiles for glaciers № 234, 235 is shown in Figure 12. For Glacier № 235, profiles were made for the eastern and western streams; similarly, profiles were made for Glacier № 230, which has two streams separated by rocky ledges. For the remaining glaciers with a simpler ice flow structure represented by a single stream, a single profile was carried out. The average values of surface slopes of small glaciers, which have a relatively uniform slope from the top to the bottom of the glaciers, are shown in Table 2.

Table 2

Glacier No.	229	232	234	230E	230W	230-1
Average slope: gradient/degree	0,55/29^0	0,32/18^0	0.29/16^0	0,48/26°	0,51/27°	0,38/21°

Peculiarities of the landform of the largest glacier № 235, which has a more complex topography, with the presence of a steep slope in the upper part of the ice basin and a relatively gentle lower part, consisting of two main ice flows, are shown in the flow profiles in Figures 3,4. The observed slope of the glacier's surface might suggest the absence of clear indications for ice surges or significant ice collapses at the terminus, except for the eastern flow of glacier № 235, which has a precipitous feature. However, it should be taken into account that this glacier has a relatively large slope (14°) of the surface landform in the western ice flow of section № 1 (Fig.5), where a low-amplitude icefall was formed at the bend of the landform of the bedrock of the ice basin, manifested in the form of transverse, relative to the main direction of the ice flow, increased ice fracturing (Fig.6). A similar area of increased fracturing of ice № 2 (Fig.5,7), having the same nature and feature of fracturing as in area № 1, is also observed in the eastern ice flow. The location of these areas at a considerable distance from the terminus and a small amplitude of the glacier surface height difference (30-40 m at 200-250 m) allow us to consider their possible role in the occurrence of ice movement as unlikely.

For other small glaciers in the considered part of the Ala-Archa River basin, transverse, relative to the direction of ice movement, increased fracturing occur mainly in the form of bergschrunds in the upper parts of ice basins, without signs of extreme development, as can be seen in Figures 9,10,11. An exception is glacier № 229 (Fig. 8), which has a relatively large average surface slope of about 30° and, in its upper part, in the area of accumulation, there is an intensive formation of cracks and separation of the ice massif into large blocks with signs of tendency to intensify this process in the form of expansion of cracks in the period from 2013 to 2017. These features may contribute to the formation of ice collapse and, consequently, ice avalanche with high kinetic energy in the basin of the Tez-Tor River.

Thus, for most of the considered glaciers, transverse cracks are observed on their surface, both in the upper part of the glacier accumulation zone and in its parts located hypsometrically below, in some places their density and width are increased at bends in the landform of the underlying glacier bedrock, but no icefalls with a significant slope of the glacier surface are observed. On some glaciers (№ 229) it is necessary to pay attention to the nature and degree of development of fracturing in the upper part of the glacier accumulation zone.

One of the important characteristics of a glacier that determines the dynamics of its ice mass and, consequently, the occurrences of negative phenomena in the form of ice surges is the speed of ice movement, particularly the assessable speed of glacier surface movement. This parameter for the glaciers under consideration in the Ala-Archa River basin was determined from the data of the service of the Friedrich-Alexander University in Erlangen and Nuremberg, which presents the velocities of ice movement on the glacier surface based on the results of the analysis of radar data from the Sentinel 1 satellite (RETREAT, 2021). Ice surface velocities derived from Sentinel-1, Version 1. http://retreat.geographie.uni-erlangen.de). In this case, ice movement velocities on the glacier surfaces within the Adygene River basin were considered for the period from 2015 to 2021, mainly in August and occasionally in the following months. The values of ice velocities on the surface of glaciers (Table 3), are determined along the axial lines of the main ice streams, as can be seen in Figure 12 for glaciers № 234, 235, and for the latter along its two main streams - east and west.

Table 3

Glacier No.	229	232	234	235(W)	235(E)
Average velocity along the profile m/day	0.023	0.019	0.03	0.047	0.029

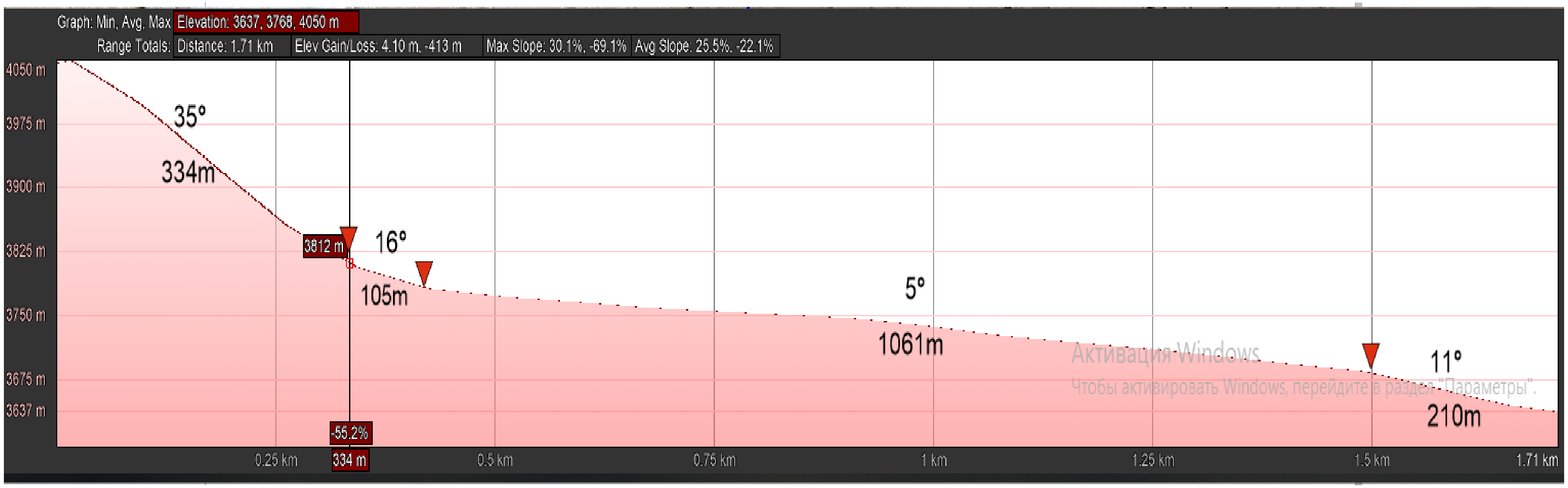

Fig. 3 Profile along the axial lines of the eastern ice flow of Glacier № 235. Figures represent- slope value in degrees and length of sections with a relatively constant slope

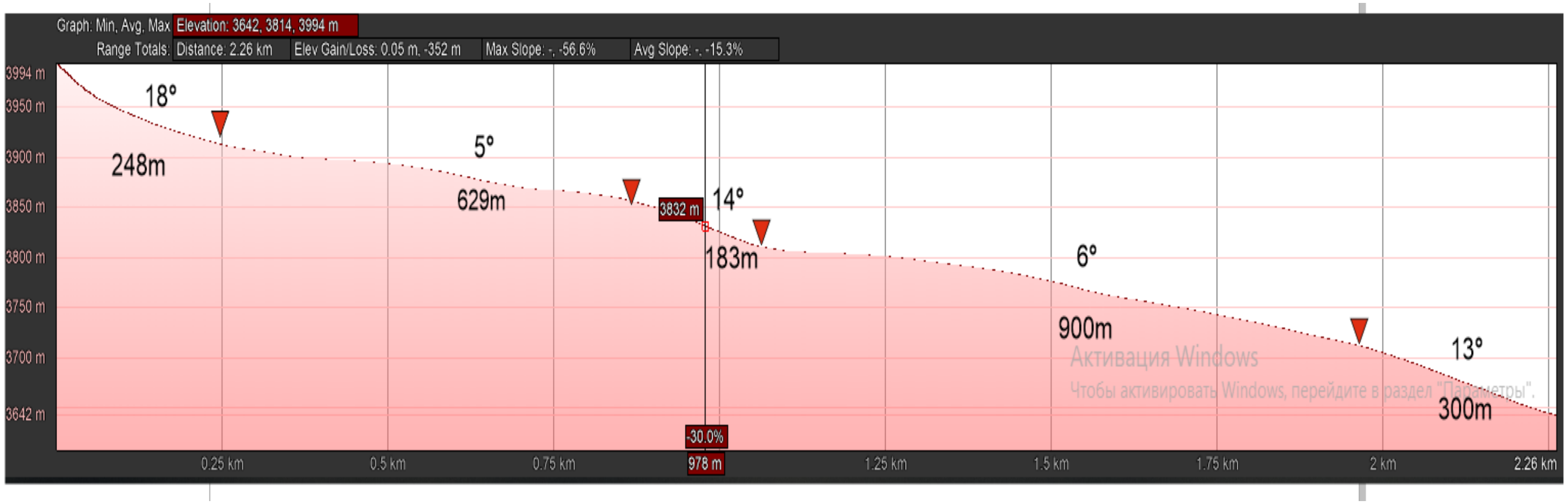

Fig. 4 Profile along axial lines of the western ice flow of Glacier № 235. Figures represent- slope value in degrees and length of sections with a relatively constant slope

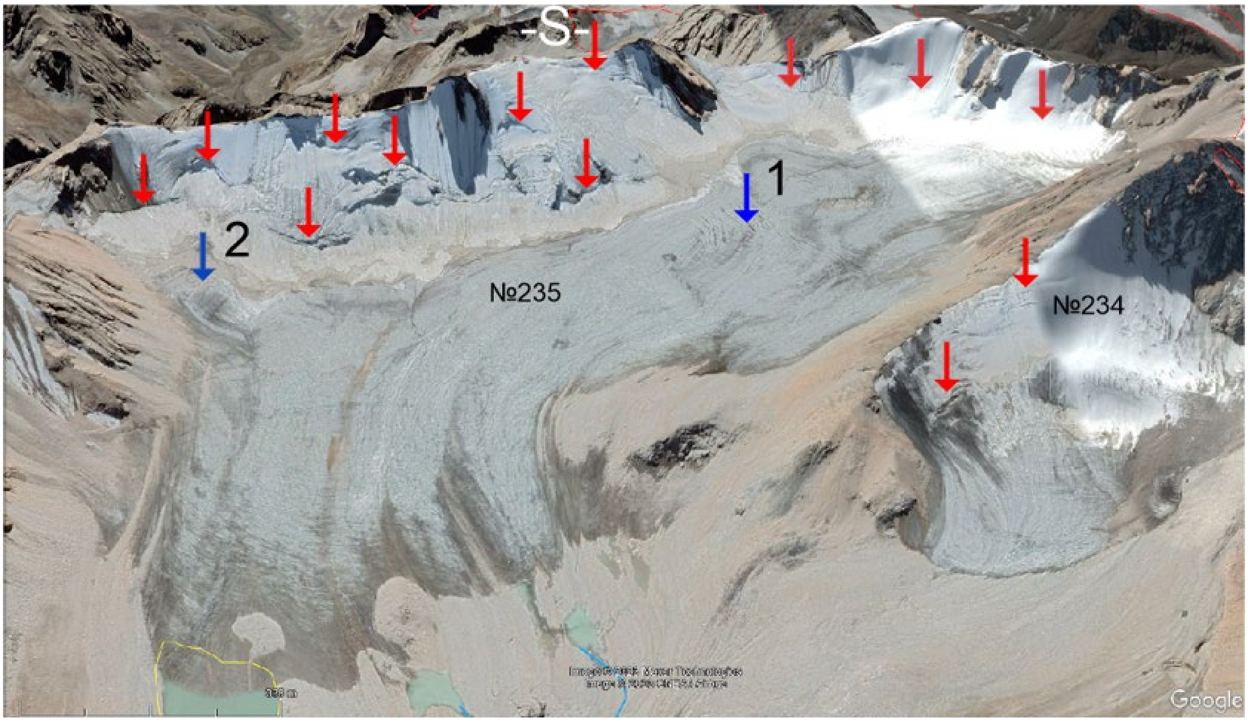

Fig. 5 View southward to the glaciers № 234, 235, transverse ice fracturing relative to the ice flow direction. Site № 1 - zone of increased cracking on the western and № 2 - on the eastern ice flows of glacier No. 235. Red arrows - bergschrund cracks on the slope of the glacier basin. Background - satellite image "World View-2" dated 30/08/2014.

Fig. 6 Site № 1 of increased ice fracturing on glacier № 235.

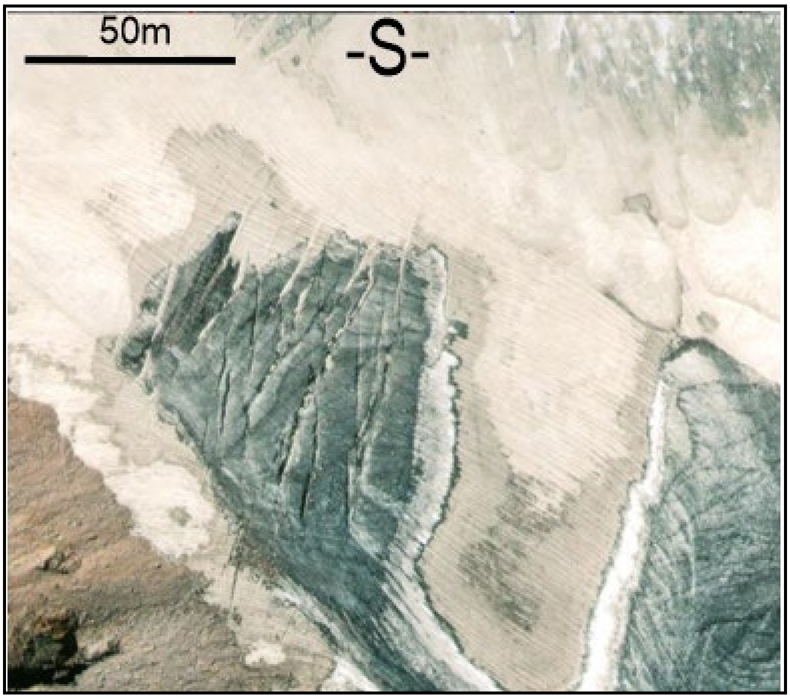

Fig.7 Site № 2 of increased ice fracturing on glacier № 235.

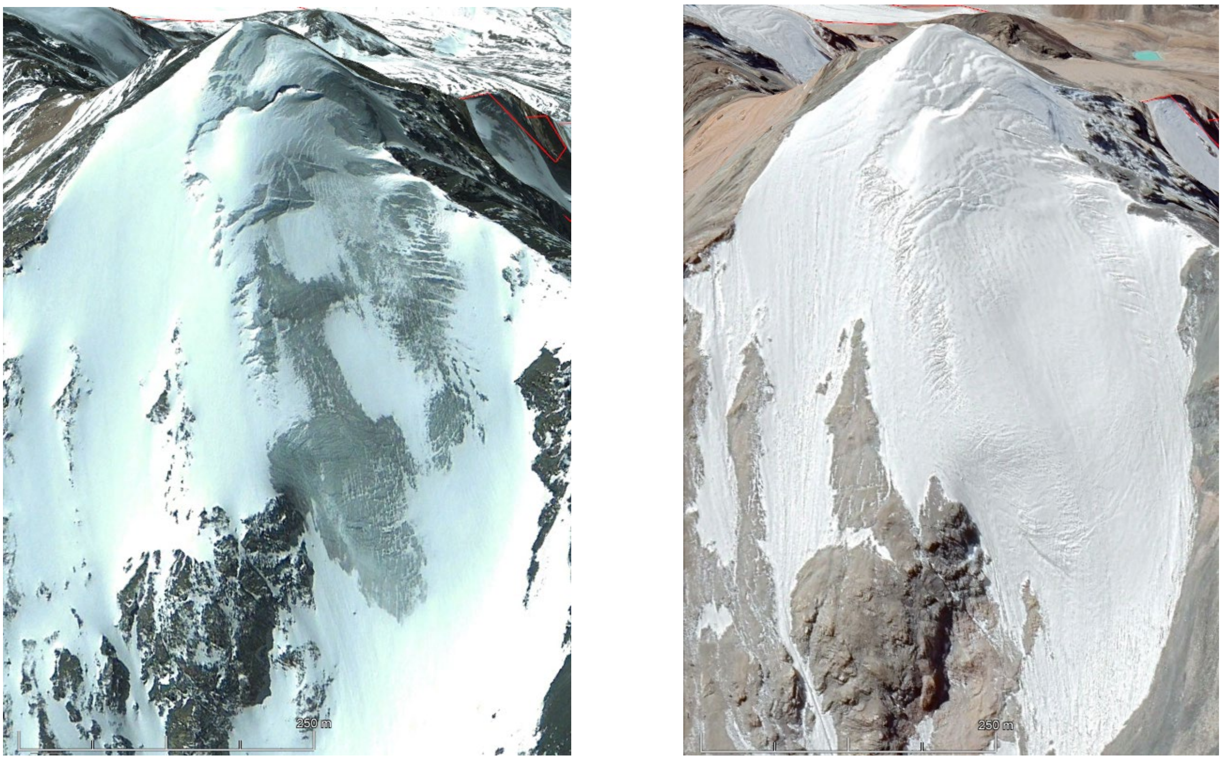

Fig. 8 Glacier № 229, as of 2013 on the left and 2017 on the right, view to the south.

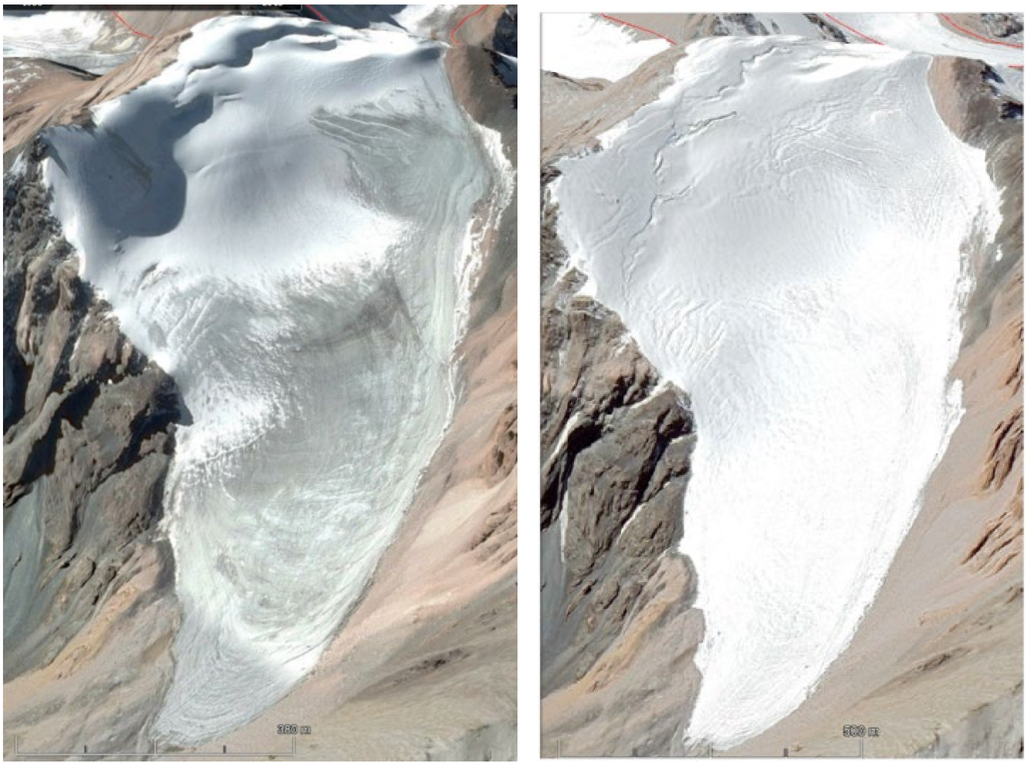

Fig. 9 Glacier № 232, as of 2013 on the left and 2017 on the right, view to the south.

Fig. 10 Glaciers № 230 and № 230-1 as of 2017, view to the south.

Fig. 11 Glacier № 234 as of 2013, view to the south.

The distribution of ice velocities on the surface of the considered glaciers along the profiles in different years is shown in Figures 13,14, 15. It follows from these figures, that in different years the velocities can vary significantly at the same points of the profile in accordance with changes in external factors and glacier condition, but in most cases, they are in a close range of values. Significant deviations from the average values can be associated both with special conditions on the glacier and with errors in velocity measurements. The variation in the velocities along the profile is due to both: the elevation difference and, accordingly, manifests itself in the form of the local fracture zones and by the general trend of velocity decrease upon approaching the terminus. In general, the velocity parameters are consistent with the slopes of the glacier relief surface determined from the DEM. No definite long-term trend was found, in the period 2015-2021, in changes of surface ice velocities of the glaciers under consideration, at a given accuracy of their determination,

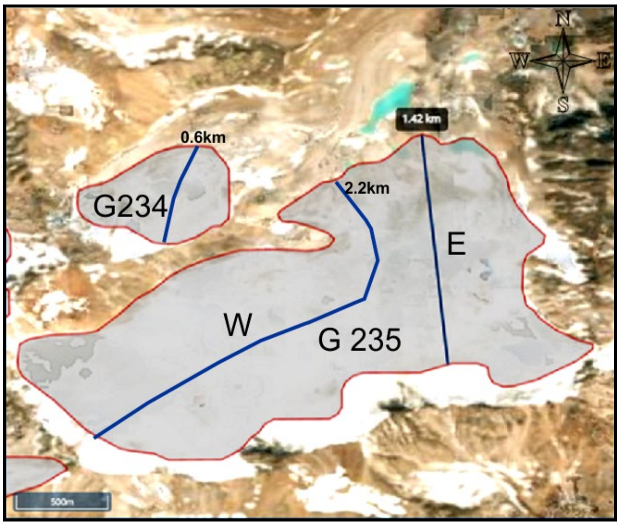

Fig. 12 Profiles of ice velocity determination on the surface of glaciers № 234, 235. Numbers show the length of the profile from the upper part to the lower part; for glacier №235 two profiles are shown, for the eastern (E) and western (W) streams.

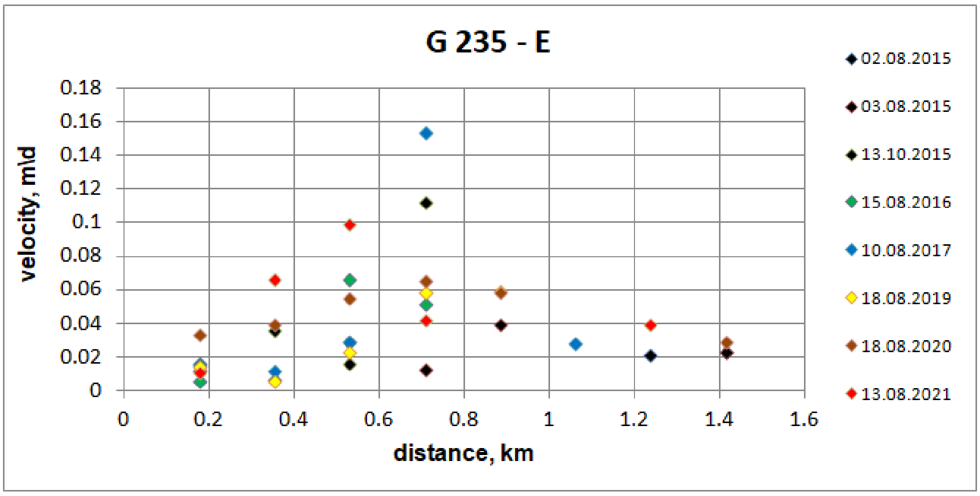

Fig. 13 Ice motion velocities on the surface of Glacier №. 235, east flow, based on the results of analysis of radar data from the Sentinel 1 satellite

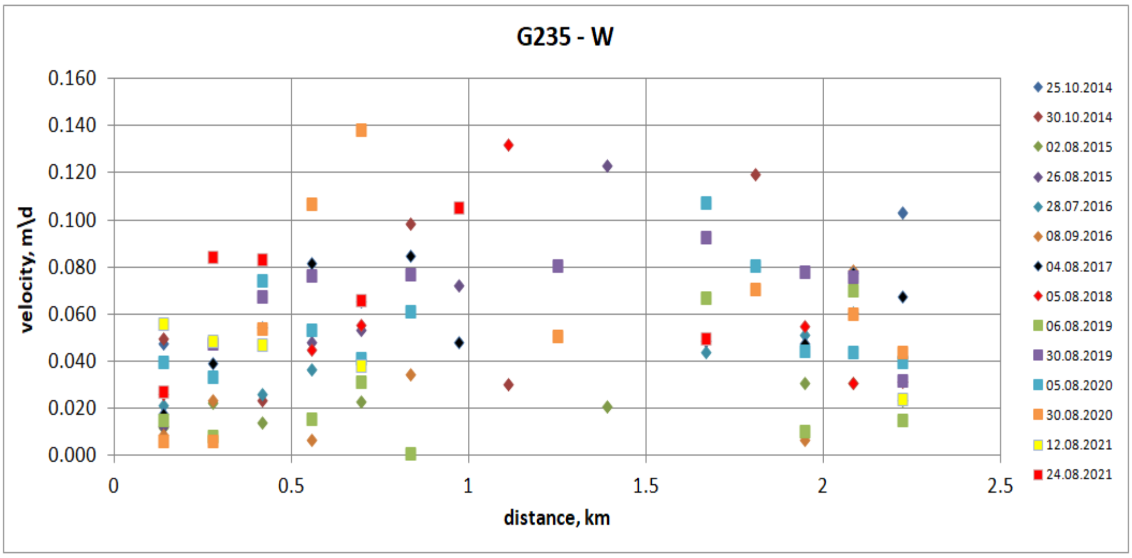

Fig.14 Ice velocities on the surface of glacier №235, western flow, based on the results of analyzing radar data from the Sentinel 1 satellite

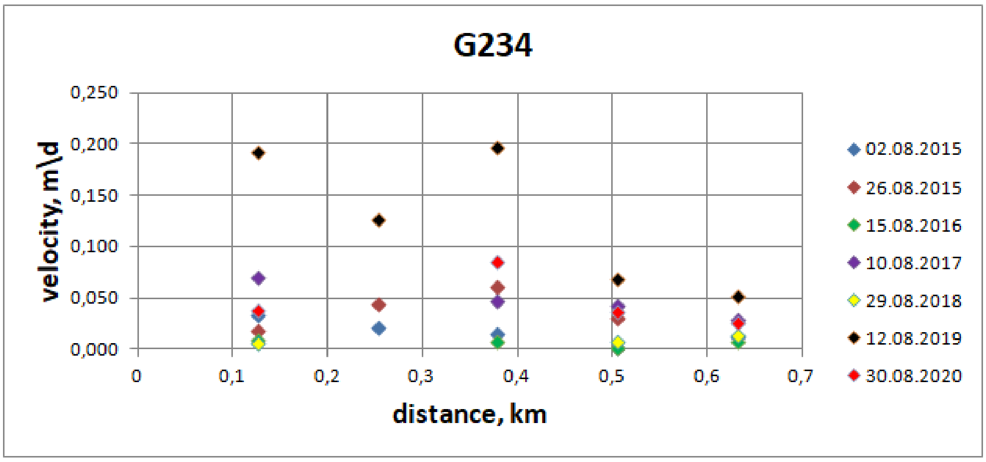

Fig. 15 Ice velocities on the surface of glacier № 234 based on the results of analysis of radar data from the Sentinel 1 satellite.

The analysis of glacial factor of extreme floods formation in the Ala-Archa river valley and, in particular, in the valleys of the Adygene and Tez-Tor rivers has shown the necessity of glacier condition monitoring in the aspect of observing the state of local ice fracturing zones, both in the area of accumulation and ablation, especially near the terminus with precipitous character, as well as the velocity of ice movement on the glacier surface. Moreover, in the warm period it is necessary to assess the rate of change of the ablation area, to record the occurrence and magnitude of extreme precipitation on the glacier surface, formation of sinkholes, funnels, surface and intraglacial runoff channels.

Of the considered glaciers, it is necessary to pay special attention to glacier № 235 due to the hazard of extreme floods initiation owing to the presence of the largest area, significant surface slopes in the accumulation zone, areas of increased ice fracturing and, accordingly, increased ice velocity, as well as ice collapses at the glacier terminus. In addition, it is necessary to monitor Glacier № 229 due to the significant average surface slope, the presence of an extensive zone of ice fracturing in the accumulation area, with a possible tendency of its further development.

1.2 Surface topography of the basin

One of the main factors in the formation of extreme floods is the nature of the landform in the high-mountain zone, characterized by high contrast and, accordingly, significant differences in absolute heights over short distances, which determines the high kinetic energy of water flows formed under these conditions. The overall basis of the landform in this zone is determined by the landform of the bedrock of the basin, which controls both the landform of glaciers and the landform of the moraine complex, dealluvial, proluvial deposits composed of loose coarse clastic rocks.

The role of the relief, mainly determined by the tectonic structure of the rocky basin foundation and accumulative moraine formations, is evident in controlling the locations of lakes. These lakes form notably in places with rocky ledges within the basin foundation, promoting the creation of local depressions with rocky barriers that serve as damming barriers for lakes. These barriers can be covered by layers of debris rocks of varying thickness. On the accumulative landforms shaped by moraine deposits, characterized by alternating moraine ridges, mounds, local depressions, and basins, lakes may form due to reduced water permeability of the ground in the lake bed and along its edges. This happens because of increased fine-grained filler content within coarse moraine deposits or the presence of buried ice from ancient glacier tongues or the buried terminus of present-day glacier, as well as newly formed cemented ice.

A significant part of the highest relief of the river basin Adygene is represented by the relief of glaciers. In this case, its nature is considered in Figures 3, 4, 17, 20 based on relief profiles built using the DEM mentioned above. Profiles for the glacier basin № 234, 235, including the ground surface, are shown in Figures 16, 17, 18, 19, 20. Along the profile A-A (Fig. 16, 17), the surface of glacier № 235 with a slope of the main gentle surface of about several degrees and in places up to 11-14° (Fig. 3, 4), is replaced in the northern direction by a ground surface with a slope of about 15°, represented by the slope of the bedrock of the basin, overlain by the youngest coarse deposits of the moraine complex, of relatively small thickness, about 10-20 m. Along the profile A-A (Fig.16, 17) the surface of glacier № 235 with the slope of the main gentle surface of about several degrees and in some places up to 11-14º (Fig.3,4), is replaced in the northern direction by a ground surface with a slope of about 15º, represented by the slope of the bedrock of the basin, overlain by the youngest coarse-clastic deposits of the moraine complex, of relatively low thickness, of about 10-20 m. This relief section is distributed in the range of absolute altitudes of about 36,000-3,500m. Then the surface flattens to subhorizontal on the massif of moraine deposits formed in the past by glaciers № 234, 235, in the form of an area about 800 m long in the northern direction and about 700 m wide in the direction from west to east, with a surface slope of 3-5.5° along the C-C profile (Fig. 19), abrupted in the northern direction by a frontal ledge of the moraine complex up to 100 m high. A more detailed view of this area is shown in Figure 18, along the B-B profile. Further, in the northern direction, for 2 km, with a width of 500 to 200 m, ancient moraine deposits with a thickness of up to 30-40 m are observed, the lower hypsometric boundary of which, expressed in the relief by a frontal ledge, is located at an absolute elevation of 2970 m. The surface topography of Glacier № 234 and the moraine complex formed by it in the past is shown in Figure 20 along the K-K profile (Fig. 16). In general, the nature of the topography of this glacier and its moraine complex is similar to that observed for glacier № 235, but on a smaller scale, the slope of the relief of the moraine complex starting from terminus of glacier № 234 to the intersection with profile A-A is of about several degrees. A relief ledge with a slope of 20°, in the altitude range of 3665-3715 m, is probably associated with a ledge in the bedrock of the basin, the outcrops of which are shown in Figure 16. Further in the northern direction the K-K profile comes out on the gentle surface of the already mentioned massif of moraine deposits, located at absolute elevations of 3550-3500 m, with relief surface inclination angles of 3-7° (Fig.19, 20). The maximum thickness of moraine deposits lying here on the bedrock is approximately 80-100 m.

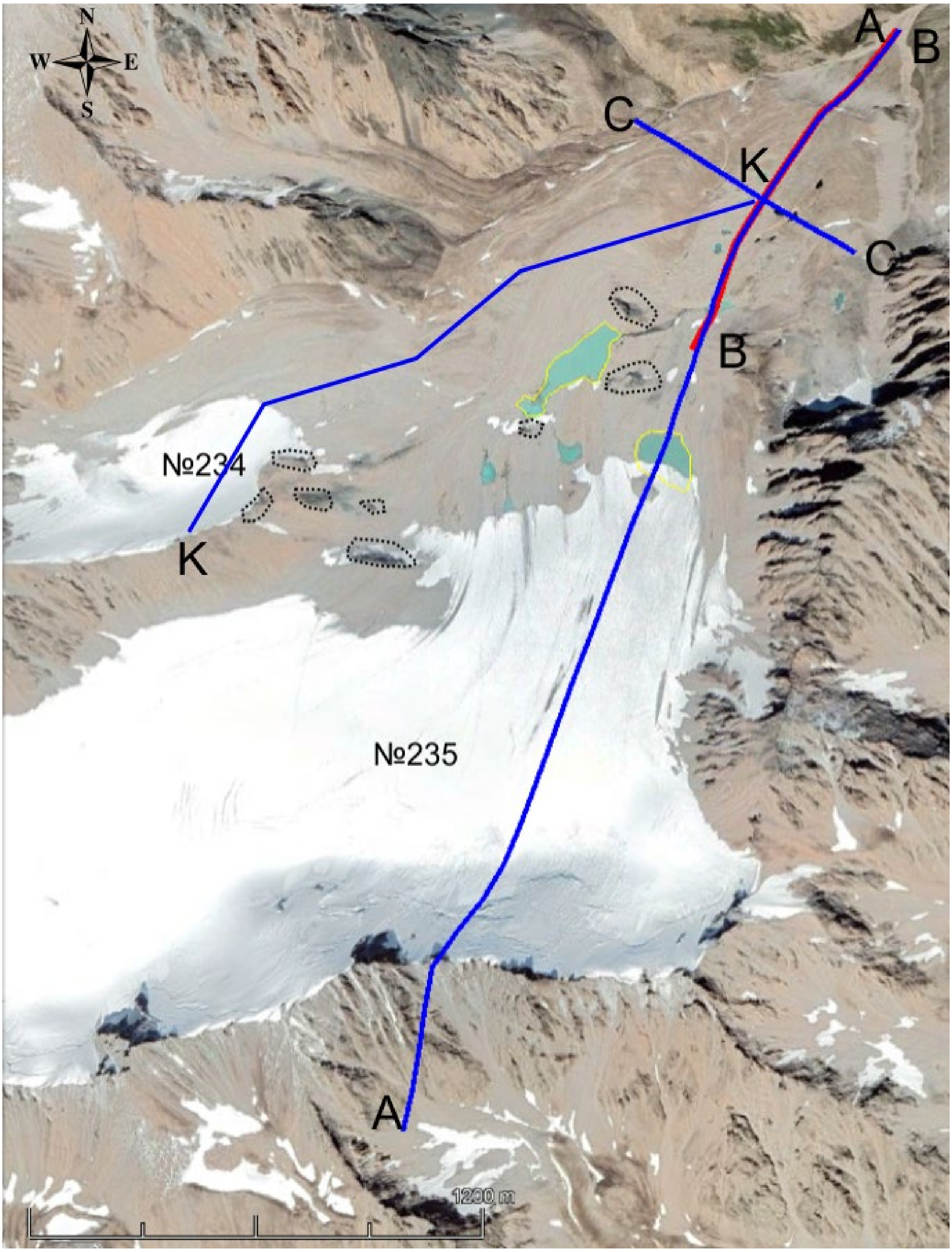

Fig. 16 Relief profiles A-A, B-B, C-C, K-K in the basin of the Adygene River water flow and glaciers № 234 and № 235. Black dashed contours show the outcrops of the basin bedrock through the moraine cover.

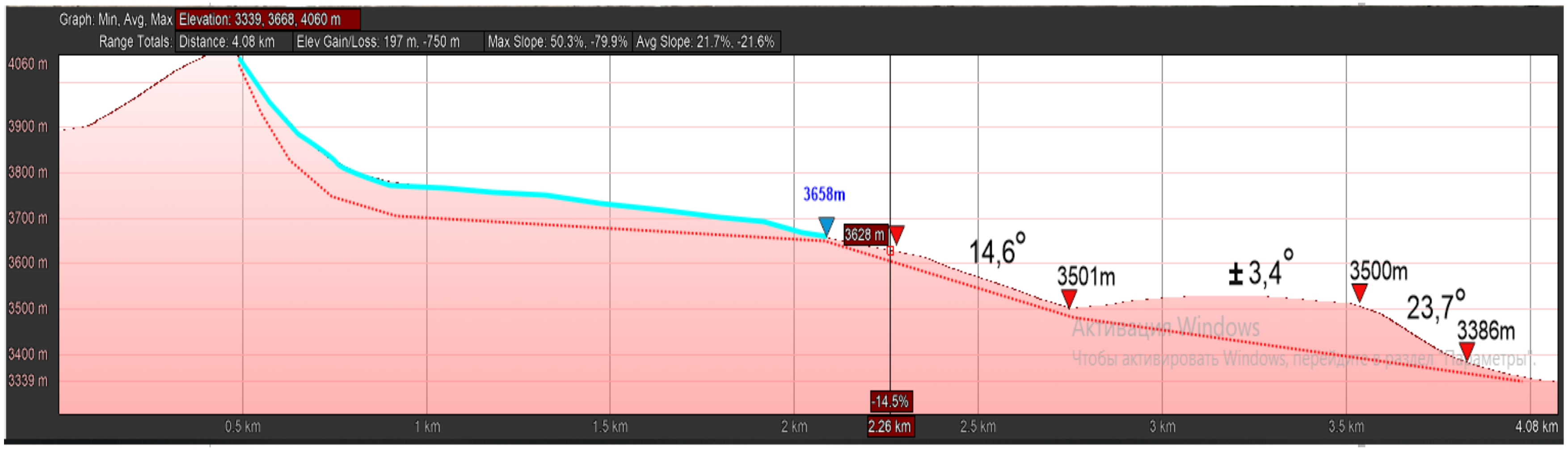

Fig.17 Relief profile A-A (see Fig.16). The absolute elevation of 3628 m corresponds to the position of the water edge at the northern shore of periglacial lake № 1, 160 m north of the terminus of glacier № 235, located at the absolute elevation of 3648 m in 2022. Blue line - surface of glacier № 235, blue triangle - absolute elevation of the terminus of the glacier. The dotted red line is the approximate position of the bedrock.

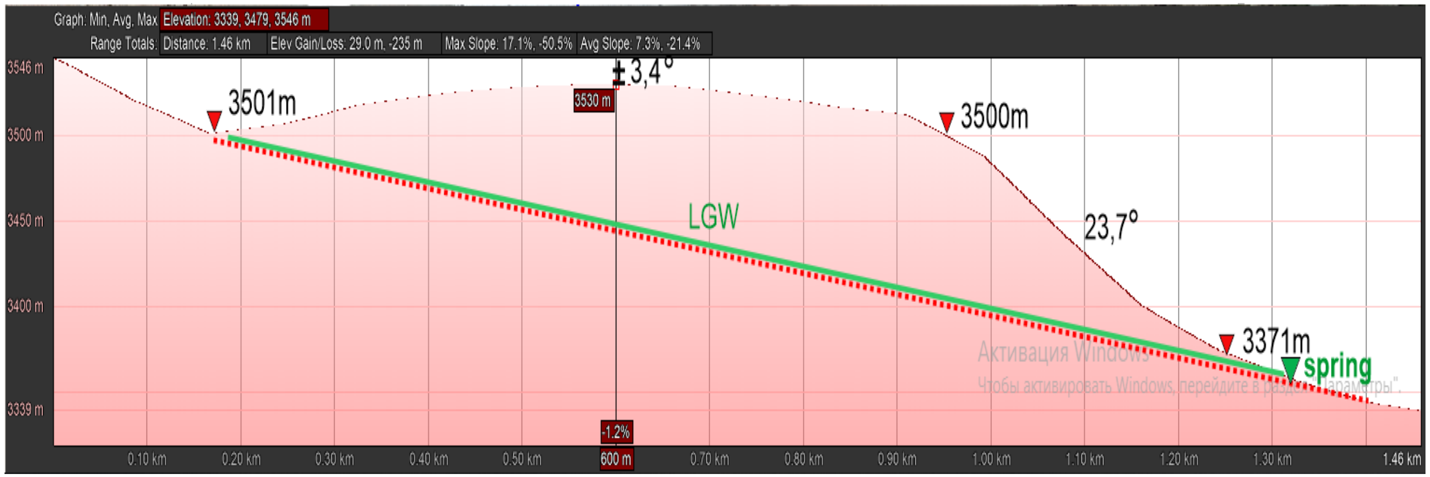

Fig.18 Relief profile B-B (see Fig.16). Absolute elevation 3530m corresponds to the highest absolute height of the moraine complex surface on this profile and is the point of intersection with profile C-C. The dotted red line is the approximate position of the bedrock. Green line - probable position of groundwater level (LGW) and the place of its discharge in the form of springs.

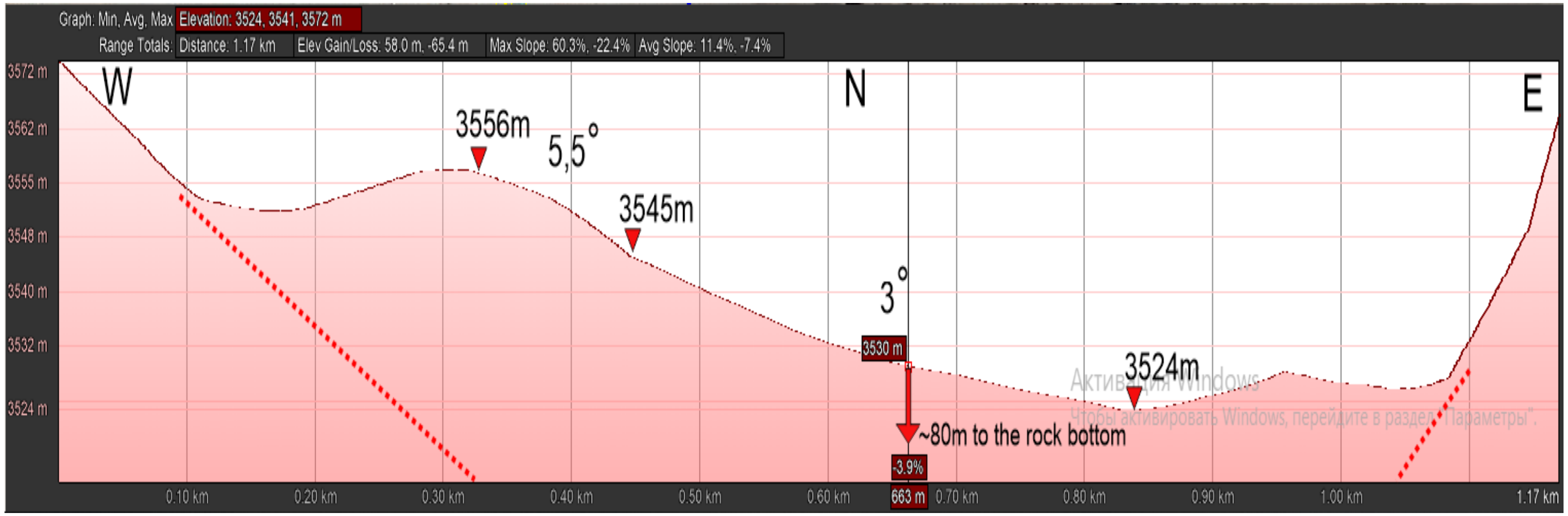

Fig.19 Relief profile C - C (see Fig.16). Transverse profile through the moraine complex, absolute elevation 3530m corresponds to the point of intersection with profiles A-A, B-B. Absolute elevation 3524m corresponds to the thalweg of the Adygene river valley.

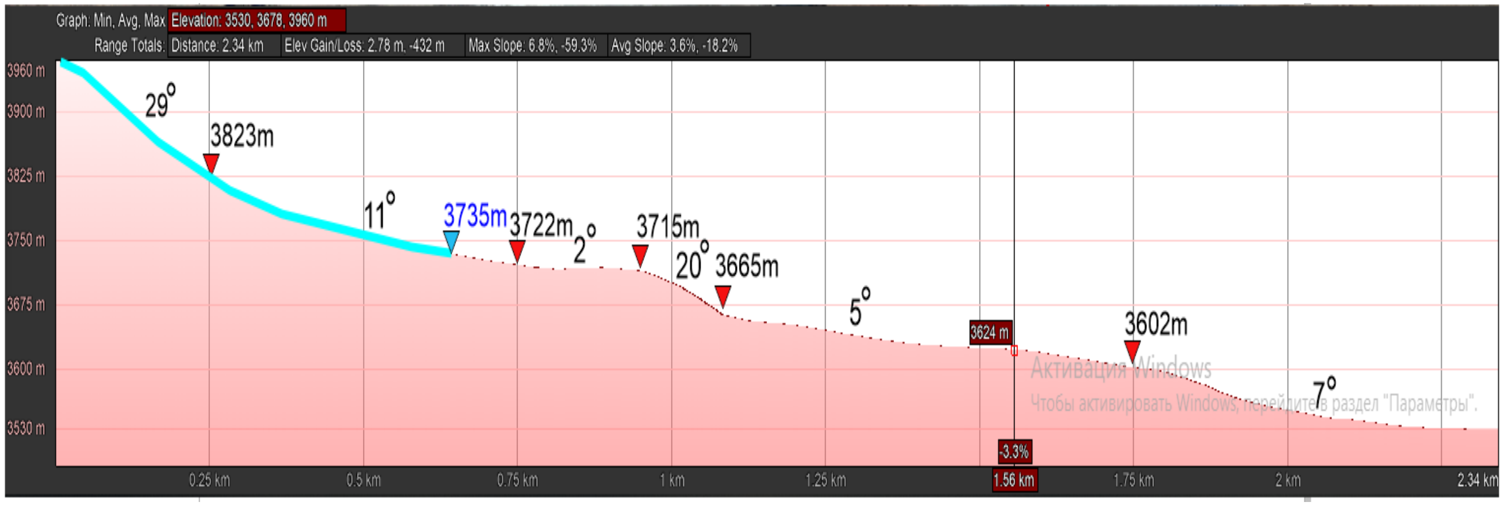

Fig.20 Relief profile K - K (see Fig.16). The profile through glacier № 234 and the moraine complex formed by it, absolute elevation 3624m corresponds to the central part of the lake cavity of Lake № 6. The northern end of the profile corresponds to the point of intersection with profiles A-A, B-B.

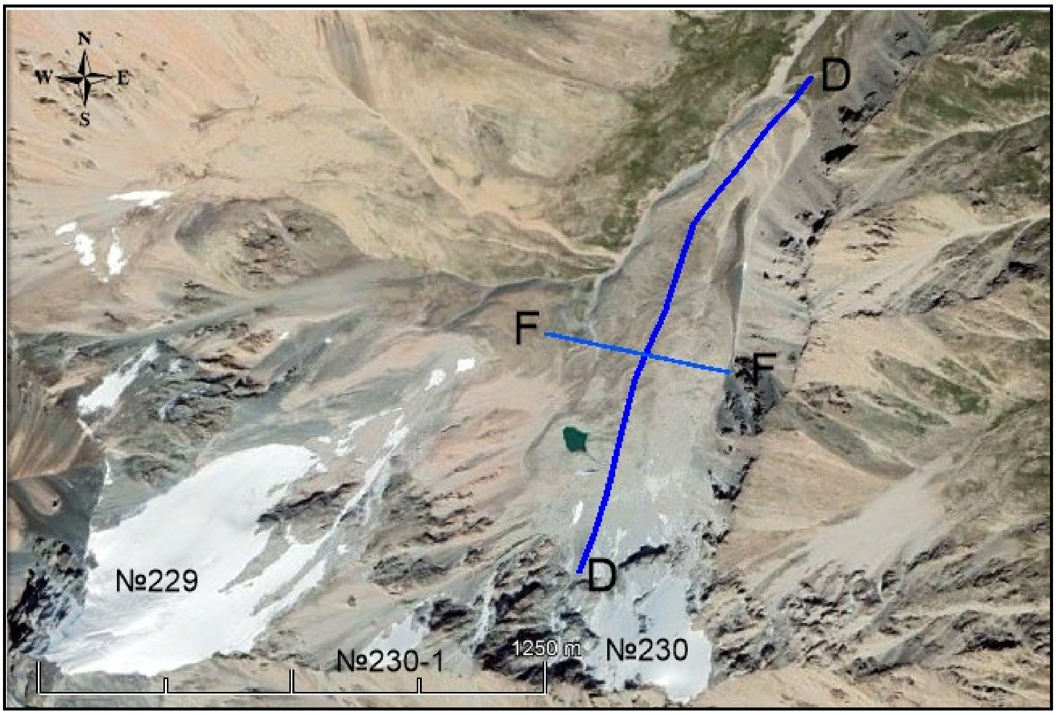

Fig. 21 D-D, F-F relief profiles in the basin of glaciers № 229, 230, 230-1 and the Tez-Tor River.

In the Tez-Tor river basin, the moraine complex is formed by glaciers № 229, 230, 230-1, and the largest in area, its eastern part, is formed by glaciers № 230 and № 230-1. At present, the moraine cover of these glaciers is separated from the glacier tongues by an outcrop on the surface of the bedrock of the basin. At glacier № 229, the moraine cover is continuous, starting from the glacier tongue to more ancient moraine deposits. The relief features of the moraine complex of these three glaciers are shown in Figures 21, 22. As can be seen on the D-D profile, the maximum steepness of the moraine ground relief, about 25°, is observed near the terminus of Glacier № 230, then for 500 m there is a subhorizontal surface with a relief slope of about 2°, which is replaced in the northern direction by a relief surface, about 1300 m long, with a slope of about 11°, which ends with a frontal scarp, about 25 m high, of ancient moraine deposits with a surface slope of about 17°. The maximum approximate thickness of moraine deposits here can reach 80-90m (Fig. 21). In cross-section, the eastern part of the moraine complex under consideration, as can be seen in Figure 22, along profile F-F, has a symmetrical structure, with a maximum height of about 30 m in the central part, relative to the eastern and western thalwegs of the valley.

In the Tez-Tor River basin, no rock outcrops of the basin bedrock on the surface of the moraine complex were found, but there may be tectonic structures of the bedrock hidden beneath loose clastic moraine deposits, causing changes in the slopes of the relief, in the formation of ledges and other forms of relief. In particular, the subhorizontal section of moraine deposits mentioned above may be due to this factor.

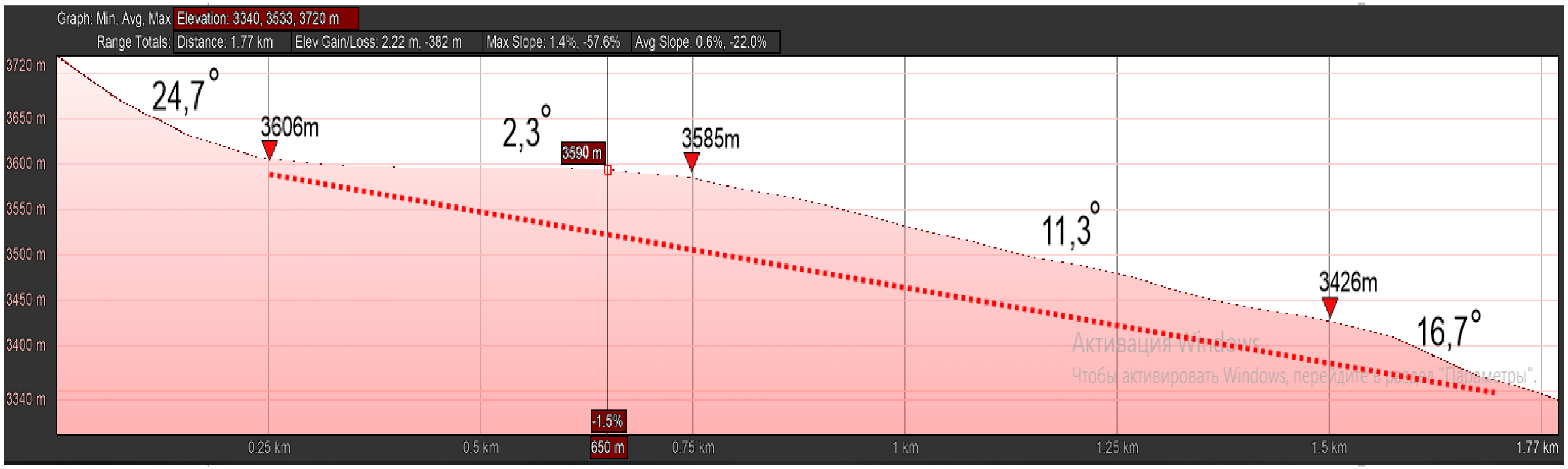

Fig. 22 Relief profile D-D (see Fig. 20). The absolute elevation of 3590 m corresponds to the point of intersection with the F-F profile. The dotted line is the approximate position of the bedrock.

Fig. 23 Relief profile F-F (see Fig. 20). Absolute elevation of 3590m corresponds to the point of intersection with profile D-D. The dotted line is the approximate position of the bedrock.

1.3 Peculiarities of composition and structure of the moraine complex deposits.

Deposits of the moraine complex of the Adygene River basin are represented by typical coarse clastic non-rounded material in a wide range of sizes, with fine-grained sandy and dusty (fraction commensurate with clay) aggregate in the space between larger clasts (Fig. 24).

Fig. 24 Characteristic view of coarse clastic moraine deposits, including rock fragments of a size about 1 m or more, up to sandy-dust fine-grained deposits.

The moraine complex in the Adygene River basin is represented by debris of mainly igneous rocks with fine-grained aggregate formed from the same rocks. Depending on the amount of the latter, the water permeability of moraine deposits and the possibility of water accumulation in surface depressions of the relief or water filtration underground varies.

The distribution of fine-grained clastic material in the section and over the area of the moraine complex can be uneven, with the formation of irregular layers of varying thickness along the strike, enriched with fine-grained coarse clastic material. In plan, such interbeds may have small areas with predominantly transverse strike relative to the general slope of the relief complex, in accordance with the process of successive formation of moraines of different ages forming the complex as the glacier retreats. These layers can play the role of sporadically distributed local impermeability layers, causing both the formation of lakes and sporadically distributed, small-area underground aquifers located at different depths in the thickness of moraine deposits. In addition, the moraine complex typically contains buried monolithic ice of the glacier tongue, which, as it moves away from the modern terminus of the glacier, with a high probability may not be directly connected with it, and as it moves away from the modern end of the glacier tongue, the probability of finding buried ice in the thickness of moraine deposits decreases. The location of the moraine complex in the permafrost zone also determines the possibility of the formation of cementation ice in the interclastic space of moraine deposits and its subsequent transformation into secondary interbeds of monolithic ice. The presence of buried ice under the cover of moraine deposits is diagnosed by thermokarst depressions and lakes with characteristic funnel-shaped depressions, and by series of cracks or forms of ground flow on the moraine surface. In the case of the Adygene River basin, buried ice may be present in the areas of lakes № 6,8,18 (Fig. 28).

At the base of the moraine complex in the Adygene River basin, there is the rocky basement of the basin, composed mainly of igneous rocks, which as a result of tectonic movements can form various forms of relief in the form of ledges, dams, both hidden under the cover of the moraine material and coming to the surface with the discontinuity of the moraine cover.

In the Adygene River basin, the largest and relatively young by time of formation massif of the moraine complex is the massif formed by the moraines of glaciers № 234 and № 235. It is about 1.5 km long from south to north and about 0.5 km wide. The relative height of this massif of moraine deposits, compared to the nearest lowest erosional incisions, is maximum, about 100 m along the northern frontal ledge, and at the eastern boundary-ledge is about 50 m. The northern border - the ledge probably has a rocky dam at its base, as a continuation of the spur of the western slope of the valley in the eastern direction, similarly with a spur 0.95 km down the valley. Further to the north, along the Adygene River valley, there are at least two more ancient generations of moraine complexes with ending frontal ledges at absolute elevations of the valley bottom of 2960 m and 2630m, having a relative height from the valley thalweg of about 50 m.

The second largest in the Adygene River basin is the massif of the moraine complex in the Tez-Tor River basin. It is formed by glaciers № 229, 230, 230-1. Its length is 0.5 km from south to north and about 0.7 km from east to west, the height of moraine deposits, relative to the valley thalweg, is about 50m. Down the Tez-Tor River valley there are at least two more ancient generations of moraine complexes with ending frontal ledges at absolute elevations of the valley bottom of 3360 m and 2830 m with relative surface height from the valley thalweg of about 50m.

The considered moraine complexes can have a maximum thickness of coarse clastic deposits up to 100m according to a rough estimate based on the relief profiles presented earlier. Thus, the considered moraine complexes are an unlimited potential source of mudflow material and the basis for the formation of outburst lakes.

1.4 Hydrogeological conditions

In terms of filtration properties, moraine deposits are analogous to boulder-pebble deposits with sandy-argillaceous aggregate. The main difference is the predominance of non-rounded clastic material, which determines a less dense texture and, accordingly, the presence of a larger volume of interclastic space. Besides, the fine fraction of the aggregate does not contain clay minerals, but rather dusty particles (similar in size to clay particles), which are more prone to leaching out of the porous space. Thus, moraine deposits have high filtration properties, especially in the case of a low content of silty aggregate. However, their location in the permafrost zone determines the specificity of water permeability due to the presence in their thickness of both buried glacier ice and interclastic ice, both in the aeration zone and in groundwater horizons. These ice inclusions in moraine clastic rocks are associated with thermokarst phenomena, periodicity of appearance and disappearance of lakes, as well as their outbursts through both underground and surface runoff channels. In the cold period of the year, groundwater completely freezes to the entire depth of the moraine complex with the formation of ice in the interclastic and pore space, which contributes to an increase in the volume of rocks and their concomitant loosening during the period of subsequent thawing, which contributes to an increase in their water permeability in the warm period of the year and the possibility of increasing runoff from surface water bodies and groundwater horizons.

The underground seasonal flow in the Adygene River basin is controlled, first of all, by the relief of the bedrock of the basin due to its tectonic structure. Groundwater is formed mainly by filtration of surface runoff into the clastic rocks of the moraine complex overlying the bedrock. An insignificant part of groundwater is formed in the zone of open fracturing and tectonic faults of the bedrock of the basin. Moraine deposits with a low content of fine-grained soil have high water permeability and are well drained due to their high location relative to local runoff bases. The main aquifer in them is confined to the bedrock of the basin as a regional aquifer and has an insignificant thickness of up to 1m of groundwater layer. This aquifer may be thicker in local depressions of the basement topography or in the presence of backwater by weakly permeable rocks of the moraine complex, downstream of groundwater in the Adygene groundwater flow basin, mainly in a northerly direction.

Rocks, as well as clastic rocks with a high content of fine grained-soil and all types of ice, are aquitards that prevent the movement of groundwater. The peculiarities of the distribution of these water-retaining formations within specific areas of the moraine complex determine the hydrogeological conditions within its boundaries. Thus, in areas with a relatively high content of fine-grained soil in the moraine deposits, groundwater of limited distribution in terms of plan and thickness of the water layer, like perched water, which is not directly connected with the main groundwater horizon on the bedrock may be formed. In contrast to the fine-grained aggregate forming stable aquitards, ice aquitards both from buried monolithic ancient ice localized in lake dams and in the area of moraine complex and cementation ice formed at different depths in the thickness of moraine deposits are unstable, temporary, capable of both easy destruction and restoration under appropriate changes in temperature and hydrological conditions.

In the conditions of the Adygene River basin in the moraine complex of glaciers № 234, 235, the main discharge of groundwater occurs in the form of springs, mainly in the area of frontal ledges of moraine complexes, as it can be seen in Figure 1. Intermediate discharge was recorded at the moraine complex at point No. 1, probably from the perched aquifer. At these identified locations, it is possible to measure the discharge rate of draining groundwater passing to surface runoff. In the Tez-Tor River basin, groundwater is discharged at a considerable distance from the accumulation area at the extreme northern boundary of ancient moraine deposits.

Thus, in the moraine complex, groundwater is distributed mainly at its base at the boundary with the bedrock of the basin, forming an unconfined aquifer with a free surface. Their flow is directed to the north in accordance with the general slope of the basin relief. They emerge to the ground surface mainly at the boundaries of frontal ledges of moraine complexes and in places of backwater from rocks of the base of the basin in the form of springs (Fig. 18). The position of the groundwater level relative to the bedrock shown in profile BB in Figure 18 is similar to all other profiles shown above. In the upper part of the moraine complex there is no continuous groundwater horizon, only sporadic presence of perched water-table is possible in limited areas, which exists due to water-bearing layers of moraine enriched with fine-grained material or water-bearing layers represented by ice interlayers or ice cementation and massifs of buried ice.

1.5 Hydrological conditions

Surface runoff in the river basin Adygene is controlled by the topography of its surface, which in turn is determined by the tectonic structure of the basin, erosional and accumulative processes within its boundaries. An important role in the formation of both surface and underground runoff is played by parts of the bedrock of the basin in the form of rocky ledges, which come to the surface or lie shallowly under the cover of clastic rocks. These relief forms cause the formation of local depressions with rocky runoff thresholds, which play the role of lake dams, which can be covered by a cover of clastic rocks of varying thickness and contribute to the formation of lakes.

The early spring surface runoff in the Adygene River basin is formed by atmospheric precipitation, both solid and liquid, and in the later spring mainly due to glacier melting. Surface runoff is observed directly on the surface of glaciers in the form of small streams, in particular on the largest glacier № 235. No large glacial and intraglacial channels and glacial lakes are observed on this glacier and other glaciers of the Adygene River basin. Surface runoff from glacier № 235 enters lakes № 1, 2, 3, 4 (Fig. 28), located in the uppermost part of the moraine complex and, through permanent surface watercourses, feeds lakes № 5, 7 located below on the moraine complex (Fig. 28). In other cases, surface runoff passes into underground runoff and manifests itself again in the downstream part of the basin in the form of springs (Fig. 1), forming the Adygene River.

In the river basin Tez-Tor, surface runoff in the summer-autumn period is not observed in the moraine complex throughout the entire valley, that is, mainly underground runoff occurs here, which only in the most northern part of the valley turns into surface runoff in the form of springs (Fig. 1). It should be noted that this description of the pattern and distribution of surface runoff refers mainly to the summer period of the year, while in the spring period there is probably a more diverse temporary surface runoff along the low relief areas due to snow melting and rainfall in the basin area, which feeds the lakes located on the surface of the moraine complex at a considerable distance from the glaciers, in particular lakes № 9-17 (Fig. 28).

Possible options for surface runoff in accordance with the type of the surface topography of the moraine complex are shown in Figures 25, 26. Here are depicted both the current surface water flows in the area of glacier № 235 (Fig. 25) and temporary flows, including those that could potentially occur in the event of lakes overflowing and filling currently dry depressions within the moraine complex.

It should be noted that in the cases considered above, there is a high probability that along the main trajectories of surface runoff movement there is also movement of the main groundwater flows in the clastic rocks of the moraine complex. However, considering the high filtration properties of the clastic rocks of the moraine complex, such correspondence may not be observed, and over a significant area of the moraine complex there will be water filtration up to the level of the bedrock of the basin, with subsequent flow in the direction of the general depression of the basin relief, regardless of the type of the relief on the surface of the sedimentary clastic rock strata.

Fig.25 Blue lines represent current and potential surface runoff paths in case of lake overflow. Dotted line indicates outcrops of bedrock of the basin.

Fig. 26 Blue lines represent potential surface runoff paths in case of lake overflow and waterless basins.

1.6 Limnological conditions

High-mountain lakes in the Adygene River basin are one of the main factors contributing to the potential occurrence of extreme flooding in the event of a rapid release of the water volume stored in these lakes. Extreme discharge of the lakes is possible due to the erosion of the dam of the lake when the lake basin is filled with water, due to an increase in the hydrostatic pressure of the water and the presence of conditions for the washout of clastic rocks forming the dam, due to the presence of loosened areas or easily erodible and washable parts in the dam, as well as the presence of easily fusible ice inclusions. Dams formed by rocky formations are not susceptible to such processes. In addition, lake drainage can occur due to the rapid influx of a large volume of rocks or ice into them during rockfalls from mountain slopes or avalanches and movements of ice masses of the glacier.

In the process of deciphering multi-temporal satellite images in the territory of the Adygene River basin, a group of lakes was discovered, as shown in Figure 28. The boundaries of these lakes correspond to the state as of 2022 and were obtained from a satellite image of "Sentinel 2" with a resolution of 10 m/pixel. The main parameters of these lakes as of 2022 are shown in Table 4. The table does not include values of the depths and water volumes of most lakes, which can be obtained further during field research.

Among the lakes recorded in 2022, a group of lakes numbered 1, 2, 3, 4, and 5 stands out. They are the most highly hypsometrically located and in close proximity to the terminus of glacier № 235, and the largest by area. The formation of these lakes is highly likely to be associated with the shallow bedding of the bedrock of the basin, overlain by a moraine cover with a thickness of about 10-30 meters, which in some places reaches the ground surface (Fig. 16, 25), forming rocky dam barriers. This peculiarity is most clearly reflected in Lake № 5. For lakes № 1,2,3,4 the presence of a rocky lake dam under the low thickness of moraine cover requires geophysical confirmation. Lakes № 1,3, having direct contact with terminus of glacier № 235, can be referred to the type of glacial lakes. All recorded lakes are located on coarse clastic moraine deposits. The formation of lakes № 6, 8, 18 is likely to be of thermokarst nature, as there are currently manifestations of monolithic ice in the margins of their lake basins and they exhibit a characteristic funnel-shaped form. Lakes № 9 and 10 probably have a similar nature, in terms of the shape of the basins, but their thermokarst development has probably ended and at present they are not associated with buried ice. From the analysis of multi-temporal satellite images, it is evident that lakes № 6, 9,10 existed in 1961 and are observed at present in approximately the same position and with the same surface area. In 1961, Lakes № 1, 2, 3, 4, 5, and 7 were absent as they were covered by glacier № 235 (Fig. 1). Lakes № 1,4,5,6,7,8,9,10, 11,12, 13, 14, 15,16, 17, 18 were observed on satellite images in 2006. This year the initial stage of development of lake № 1 was observed. In 2017, all lakes recorded in 2022 were observed, but lake № 6 was small and had a size of 42 x 68 m in June, and 8 x 11 m in August. Unlike all the other lakes, lake № 1 is expanding its area due to the retreat of the edge of glacier tongue № 235 in the southern direction. Meanwhile, the northern boundary of this lake remains constant. Most of the lakes mapped in 2022 have a constant location during the multi-year period and relatively constant water surface area, i.e., they are permanent by the regime of functioning, except for lakes 6,8,18 of probable thermokarst nature, which with a constant location, periodically change the area up to complete disappearance and are non-permanent by the regime of functioning. An exceptional functioning regime is observed in lake №

1, where despite its constant location, the water surface area increases due to the retreat of the edge of glacier tongue № 235.

The lakes under consideration are fed by atmospheric precipitation and glacial waters through surface and underground runoff, and the occurrence of surface runoff in the area of lakes № 1,2,3,4,7 is likely due to the shallow depth of the basin's bedrock (Fig. 17) and possibly buried beneath a layer of glacial moraine. The fact that lakes are fed directly by glacial melt water is diagnosed by the light green color of their water surface on satellite images, due to the presence of suspended dusty particles (glacial flour) in the water, and in lakes with no obvious signs of glacial feeding in the summer-autumn period of the year, the color of the water surface is dark blue. In this case, the feeding might occur through underground water sources from the upper aquifers, formed due to the presence of local aquifers from moraine sediments enriched with fine-grained clastic material, or in the presence of buried or cementation ice, playing the role of a water table. The latter case is most probable for lakes of thermokarst nature. In this aspect, attention is drawn to lakes № 9,10,11,12,13,14,15,16,17, which have obviously close absolute elevation values of lake levels (Table 4, Fig. 27), similar surface areas, and are concentrated in a limited area within the moraine complex, which may indicate the presence of a local aquitard on which a limited-area underground aquifer of the perched water type is formed. This aquifer is not hydraulically connected laterally with other similar possible sites within the moraine complex and with the main aquifer that forms on the surface of the basin's bedrock, underlying the deposits of the moraine complex. The connection of these aquifers occurs through a discrete top-to-bottom water flow process.

Regarding the other lakes located in the basin of glaciers № 234, 235, the absolute elevation levels of these lakes differ significantly (Table 4) and the question of groundwater feeding remains open, as these lakes are located on the surface of a moraine complex with substantial thickness of coarse debris deposits, which have good water permeability, consequently, shallow groundwater may be sporadically distributed in these areas. The same applies to the lakes within the Tez-Tor river basin.

In any case, for all considered lakes and groundwater of the upper aquifers of the moraine complex, their water supply is primarily sustained by seasonal atmospheric precipitation and temporary local surface runoff. In the discharge part of the water balance of lakes, there is, of course, insignificant evaporation.

The runoff from a part of the considered lakes, № 2,3,4,5, occurs by surface way as it can be seen on Fig.1,25, at the same time, for a large part of lakes surface runoff is not observed, that is, it occurs either by underground way, or the lake has close to zero balance with minimum inflow, runoff and evaporation, (lakes № 9,10,11,12,13,14,15,16,17).

For the formation of high-mountain lakes, it is necessary to have a sufficiently high water impermeability of the rocks that make up the lake basin. These conditions may be due to the presence of bedrock beneath the lake depression, buried monolithic ice, or by the presence of increased content of fine-grained aggregate represented by sandy and dusty fractions in the clastic moraine material; this clastic material may also form secondary aquifers due to colmatization of the interclastic space of clastic moraine sediments, in case it is brought by water flows into the moraine basins. Furthermore, the presence of moraine deposits in the permafrost zone can lead to the formation of cementation ice in the moraine coarse clastic sediments both in the interclastic space and in the form of interlayers of newly formed ice at different depths and with different thickness and extent, creating an ice-cemented zone that acts as an aquiclude. All scenarios are applicable to the lakes discussed above, but for specifying particular conditions, field research involving geophysical methods is necessary.

Among the listed formation scenarios, lakes with fine-grained and rocky aquicludes in dam-like barriers are the most stable in terms of runoff regime and are less prone to breaches. Ice-covered aquifers are the most unstable and outburst prone. Ice-covered aquifers are the most unstable and outburst prone. The lakes developed on buried ice include thermokarst lakes, the development of which occurs due to local melting of buried ice in the process of surface water filtration into the cracks of the buried ice massif. As the thermokarst lake basin develops, two processes take place: either the colmatization of clastic rocks at its bottom, reducing water filtration into the ice cracks, or the sealing of these cracks, ceasing the filtration through them. As a result, the lake adopts a stable regime with a balanced intake of temporary surface and underground runoff, atmospheric precipitation, and outflow through evaporation and underground drainage via the lake basin's edges and bottom. In principle, such lakes can exist for a long time even if there is complete degradation of the buried ice beneath them. In our case, they may have a hanging nature, meaning they are not hydraulically connected to the underlying aquifer due to the significant thickness of the moraine deposits in their distribution area.

Since the high-mountain lakes in the Adygene River basin are located in the permafrost zone, the processes related to ice formation and degradation in moraine deposits are relevant for them, and the issue of the role of cementation ice in the occurrence and outbursts of lakes requires specific research.

Therefore, from the analysis of the formation and functioning conditions of lakes in the Adygene River basin, it follows that the main risk regarding extreme outbursts is posed by lakes diagnosed with thermokarstic origins.

In our case, these are lakes № 6, 8, 18, further, with more detailed study, the number of such lakes may increase. These are lakes with a non-permanent regime of functioning (disappearing and reappearing) fed by groundwater from moraine deposits, temporary surface runoff and atmospheric precipitation. There is basically no surface drainage from them; water discharge occurs underground and through evaporation.

Lake № 6 (Fig.28) is located in the western part of the moraine complex of glaciers № 234, 235, its formation is most likely associated with the buried ice of the tongue of glacier № 234. When analyzing satellite images, monolithic ice was observed in the sides of its basin. In some years, the basin is almost completely empty. The accumulation and discharging of the lake is primarily subsurface. The probability of an extreme outburst is low as the lake is located 630m away from the nearest local base of the runoff in the area of lake № 7. The outburst potential as a ratio of absolute height difference - 130m, to the length of the water flow path is equal to 0.2.

Lake № 8 is located in the basin of an unmapped glacier located to the south of this lake, which has a visible area of pure ice along the bergschrund line, in the accumulation zone, of about 0.01 km^2, but perhaps a significant part of its tongue is covered by a cover of moraine deposits and has been preserved currently due to its location in the shade, in a deep gorge with a northern exposure. This could be indicated by an (icy?) ledge, approximately 2-3 meters high within the moraine deposits at the terminus of the glacier, located in close proximity to the lake under consideration. The functioning regime of the lake is variable. Accumulation is mainly due to the inflow of underground melted glacial waters; the runoff is underground. The probability of an extreme outburst is low as the lake is located 200m away from the nearest local base of the runoff, in a northward direction, in the gorge thalweg. The outburst potential as a ratio of absolute height difference - 35m, to the length of the water flow path is 0.18.

Lake № 18 (according to the catalog of outburst prone lakes of the Ministry of Emergency Situations, IWP, this is Lake Tez-Tor 1). In the basin of the Tez-Tor River, the lake is located at the contact point with the buried terminus of Glacier № 230, identified by a steep ledge approximately several meters high. The dam-like barrier is a distinct moraine ridge that frames the lake basin from the north. The lake is fed directly by glacier meltwater, surface and underground runoff, and drainage from the lake occurs underground. Within the damming barrier, the presence of buried ice is not excluded, and the processes of forming cemented ice water barriers are also possible. The functioning regime of the lake is variable. To the east of this lake, in the depression, on the moraine deposits, there is consistently a small water body, varying in size from 10x7 meters to 20x10 meters at different times. According to the coordinates of the catalog of outburst prone lakes of the Ministry of Emergency Situations, IWP, it is Lake Tez-Tor 2. In some years, it remains, even when Lake № 18 is drained. In 2022, this lake is not observed in the Sentinel 2 satellite images. The water impermiability of the lake bed is probably of colmatational nature, but the possibility of a cemented ice barrier is not excluded. According to the coordinates of the catalog of outburst prone lakes of the Ministry of Emergency Situations, IWP, Lake Tez-Tor 3 was previously located near and to north of these lakes, but it was not found on satellite images of 2013, 2014, 2017,2022.

The likelihood of an extreme breach of Lake No. 18 is low because the lake is situated 270 meters away from the nearest local drainage base in the northern direction within the valley's main stream. The outburst potential as the ratio of absolute height difference - 20 m, to the length of the water flow path is 0.07. A peculiarity of the site of this lake is the presence of an erosional depression well expressed in the relief, stretching in a northerly direction with the beginning of the erosional incision 270 m from the lake's water line, that is, there are no signs of surface flow of water from the lake over this distance, as well as traces of water streams from the surrounding slopes of the valley.

For Lake Tez-Tor 2, mentioned above, which did not exist in 2022, outbursts with the formation of floods were recorded in 2004, 2012, 2018 [8,9]. The basin of this lake is situated 430 meters away from the nearest local drainage base in the northern direction within the valley's main stream. The potential for breach, calculated as the ratio of the difference in absolute heights (-42 meters) to the distance of water flow, is 0.1. An important feature of this lake's area is the presence of an erosive depression in the relief, extending northward from the lake depression, showing signs of active surface drainage.

In addition to the possibility of extreme flooding due to the breach of dam-like barriers at the lakes, in the Adygene River basin, there is a possibility for significant water discharge from the lake basins in the event of ice movement caused by glacier shifts or collapses at their tongues. This could result in the thawing of ice aquicludes and subsequent erosion of moraine dam deposits. Particularly, during strong earthquakes historically observed in the region (Belovodskoe earthquake of 1855), large volumes of water could be released from the lake basins.

In this aspect, lakes № 1, 2, 3, 4, 5 pose the highest potential risk due to possible movements of glacier № 235 and collapses at the edge of its tongue. The likelihood of these dam-like barriers breaking is low since they have a rocky foundation at their base within the basin.

Table 4

Lake number name	Area км^2, (m^2)	Absolute water level (m)	Average lake depth (m)	Water volume (thousand m^3)	Time of area measurement, day/month/year
1	0,025 (25000) 0,016 (16000)	3628			18/08/2022 13/08/2017
2	0,0055 (5500)	3616			18/08/2022
3	0,0046 (4600)	3636			-..-
4	0,003 (3000)	3620			-..-
5 Adygene	0,036 (36000)	3585	1,9?	70?	-..-
6	0,0008 (800)	3630			-..-
7	0,004 (4000)	3499			-..-
8	0,002 (2000)	3534			-..-
9	0,001 (1000)	3531			-..-
10	0,001 (1000)	3530			-..-
11	0,0005 (500)	3532			-..-
12	0,0005 (500)	3531			-..-
13	0,0007 (700)	3528			-..-
14	0,0004 (400)	3530			-..-
15	0,0004 (400)	3535			-..-
16	0,0009 (900)	3535			-..-
17	0.001 (1000)	3531			-..-
18 Tez-Tor 1	0.003 (3000)	3600			-..-

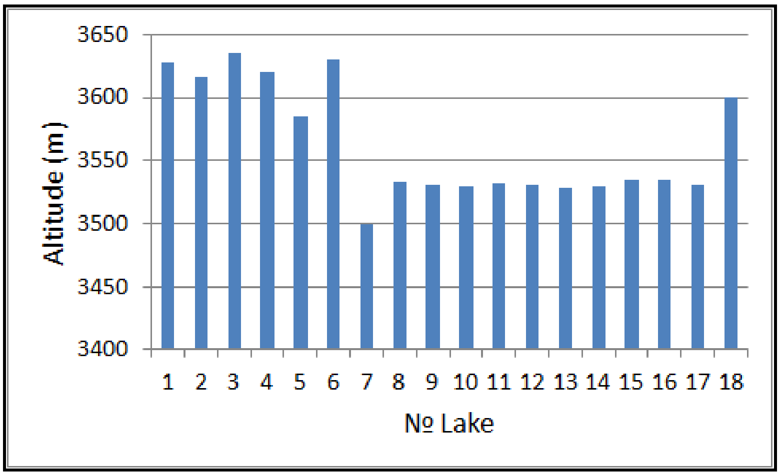

Fig. 27 Absolute heights of lake levels

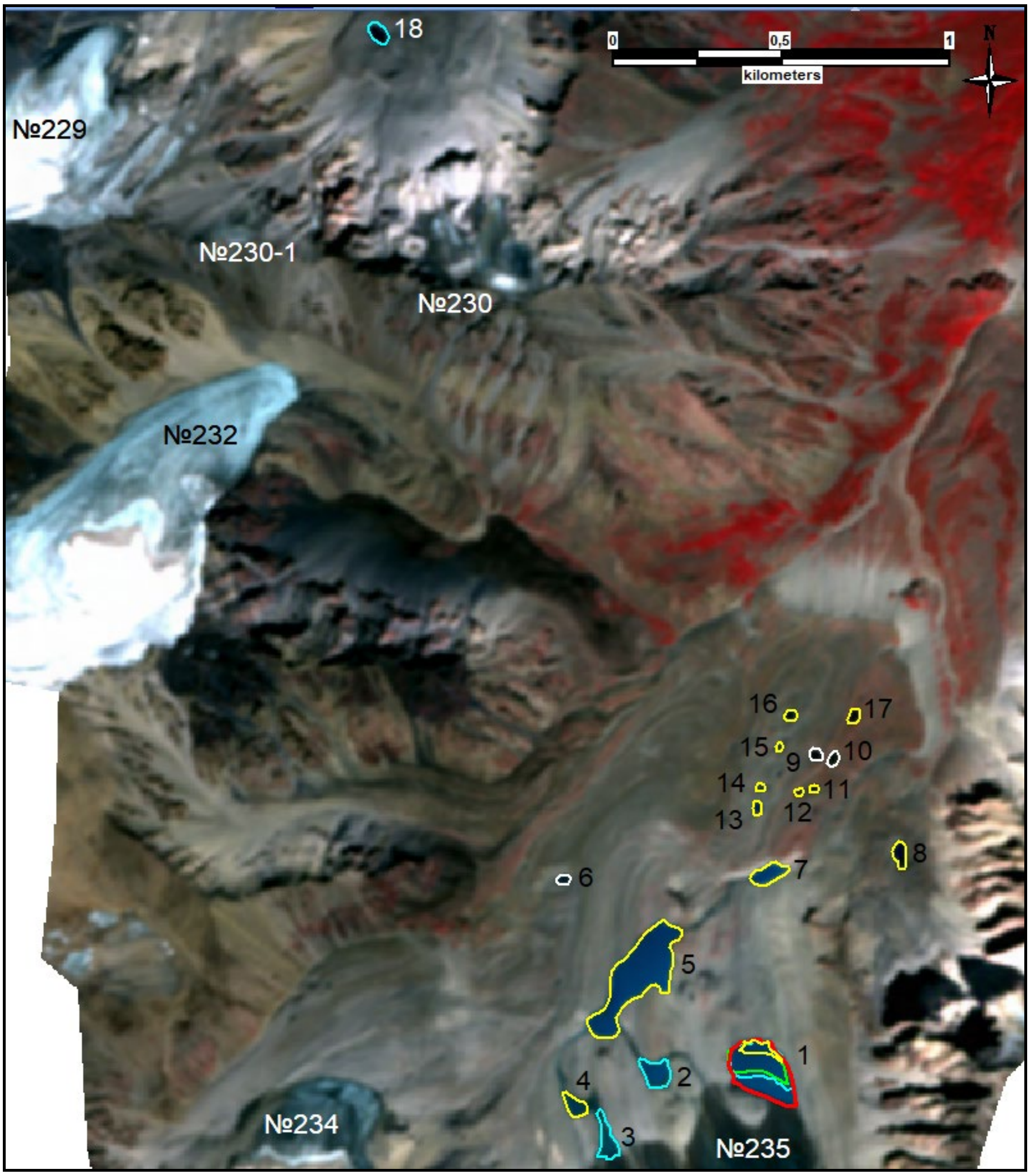

Fig. 28 The location of lakes in the Adygene River basin. The color of the lake boundaries indicates the time of their observation upon satellite image interpretation. Boundaries: red - 2022, blue - 2017, yellow - 2006, white - 1961. All marked lakes exist in 2022 within the shown boundaries, regardless of their color.

1.7 Erosional and accumulative processes

The formation of the present-day appearance of the Adygene River basin, the general view of which is shown in Figure 29, occurred in the process of both tectonic uplift of the region and continuous erosive and accumulative water activity, including in the ice phase. The result of erosional activity is observed in the form of the valleys of the Adygene and Tez-Tor rivers, and accumulative activity in the form of deposits of loose clastic rocks - deluvial on valley slopes, moraine, proluvial and alluvial deposits in the lower parts of valleys.

At present, the generation and accumulation of clastic material by glaciers continues in the Adygene River basin, with an increase in the volume of rocks of moraine complexes in both valleys and at the same time there is an erosion of both the moraine complexes and the bedrock of the basins. Figure 29 shows that the volume of potentially hazardous moraine deposits is greatest in the Adygene River valley, but it is also significant in the Tez-Tor valley. Thus, in the case of high water flow discharge, large-scale mudflows may occur in both basins. Water evacuation potential of the basins depends on their area. The area of the Adygene River basin up to the confluence with the Tez-Tor River is about 18 km^2, and the area of the Tez-Tor River basin is about 7 km^2. The energy potential of a stream depends on the slope of the stream channel in addition to its volume. The average slope of the Adygene river basin thalweg from lake № 1 to the confluence with the Tez-Tor river is 0.18, with a difference in absolute heights from 3628m to 2600m, and the average slope of the Tez-Tor river basin thalweg from lake № 18 to the confluence with the Adygene river is 0.28, with a difference in absolute heights from 3600m to 2600m while the section of the valley of the Tez-Tor River from the site of groundwater outlets at an absolute elevation of 3105 m to the confluence with the Adygene River has a slope of 0.36. In general, the difference in absolute heights of the bottoms of the two valleys along latitudinal profiles in their northern parts reaches 500m. Large gradients of the Tez-Tor river valley bottom caused increased intensity of erosive channel activity in it, which according to the results of satellite images analysis is manifested in eroded channel banks, especially in the lower reaches with the width of eroded areas up to 30-50 m, covered with debris deposits of flood flows. This means that floods with discharges higher than normal have passed through the channel. At the same time, in the valley of the Adygene River, there is a slightly eroded narrow channel about 2-3 m wide, with banks undisturbed by erosion and with a continuous vegetation cover in the area located below the most ancient moraine complex, up to the confluence with the Tez-Tor River. This may indicate that floods with extreme water discharges have not passed through this channel in recent decades. This situation with insignificant erosion development of the riverbed in the upper reaches of the Adygyne River valley is shown in more detail in Fig. 30, where narrow channel sections located in close proximity to the northern frontal ledge of the moraine complex are marked.

Thus, throughout the Adygene River valley, starting from the young massif of the moraine complex and up to the confluence with the Tez-Tor River, there are no signs of extreme water flows.

Accumulative activity of channel streams in both basins under consideration is weakly expressed and mainly localized near relatively young generations of moraine complexes, where it is manifested as proluvial channel deposits with a small area and thickness.

The most significant manifestation of clastic material accumulation is observed in the place where the Adygene River enters the valley of the Ala-Archa River (Fig. 31) with the formation of an outflow cone with an area of about 0.24km^2. A significant part of its surface is covered with vegetation, indicating insignificant flood activity in the last decade. Here channel erosion occurs mainly within the main active channel of the Adygene River.

Besides moraine accumulative landforms, accumulative landforms in the valleys of the Adygene and Tez-Tor rivers also include diluvial deposits in the form of alluvial plumes and cones of scree, as well as proluvial deposits along the valley sides. However, they are located mainly on valley slopes, not reaching the active channel zone and not affecting the main river flow. Their role as a source of clastic material for debris flows is possible in the case of floods with extremely high water flow rates. The only case of a scree cone deflecting the Adygene River channel to the west is observed in the eastern side of the Adygene River valley, in close proximity to its confluence with the Tez-Tor River (Fig. 29). At present, this cone is inactive, as evidenced by the vegetation cover at its lower part.

In general, according to the data of remote observations in recent years, erosional activity is more pronounced in the Tez-Tor River valley, which is associated with both greater compared to the valley of the Adygene River talweg gradients, and the presence of a periodically active source of floods in the form of Lake № 18, which having a thermokarst nature and, accordingly, the ice ponds in the dam periodically releases the accumulated volume of water.

Fig. 29 View to the south, on the valleys of the Adygyne and Tez-Tor rivers. Triangular marks are frontal ledges of moraine complexes, red - young, blue - ancient. Blue lines are probable trajectories of water flows in accordance with the surface topografy. Blue arrows - direction of river flow. Red arrow is a scree cone, which diverts the river channel. Asterisks - blue - place of groundwater discharge, red - confluence of Adygene and Tez-Tor rivers. Background - satellite image of 2017.

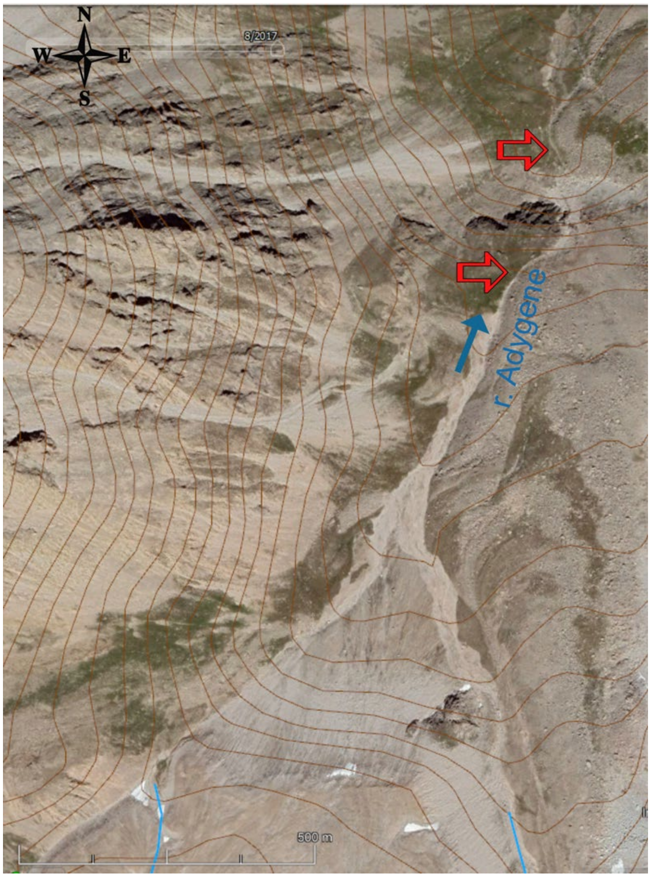

Fig. 30 Adygene River valley. Red arrows indicate areas of narrowed channel, with no signs of large flood water passing through. Background - satellite image of 2017.

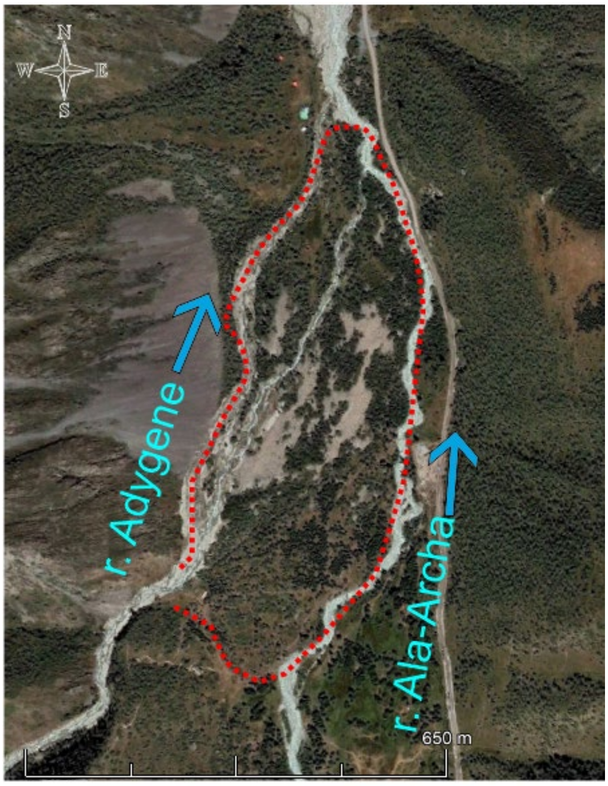

Fig. 31 Alluvial-proluvial clastic material outflow cone of the Adygene River (red dashed line), upstream of the confluence with the Ala-Archa River

Conclusion

In terms of creating an early warning system against catastrophic floods in the Adygen River basin, the main approach to effectively solve the problem is an integrated approach that takes into account all the main elements of the natural system of flood formation. In this system, high mountain lakes are an important, but not the only element to be monitored and analyzed. For a successful forecast and subsequent warning, it is necessary to carry out observation starting with the weather factor, with monitoring of air temperature and the amount of precipitation in the territory of the observed basins. The next element of the observation system should be observations of changes in surface and groundwater flow regime, lake level regime and water temperature.

An important element of the observation system is monitoring the state of glaciers in terms of changes in fracturing on their surface, the velocity of ice movement to detect signs of possible movements and collapses of the ends of the tongues.

Monitoring of this information will allow us to give an operational assessment of the degree of danger in specific conditions and be ready to respond to the signals of the early warning system.

From the above-mentioned main factors of extreme floods formation, it follows that in the Adygene river basin the greatest potential danger is posed by lakes № 1,2,3,4, 5 due to possible movements of glacier № 235 and collapses of its tongue edge. The probability of the outburst through their dense dams is low, since they have a bedrock foundation of the basin at their base. The remaining identified lakes have a lower hazard potential due to insignificant water volumes and significant width of potential dams. In the basin of the Tez-Tor River, glacier № 229 poses a hazard due to significant ice fracturing in the accumulation area, which may result in the collapse of significant ice volumes. In addition, it is necessary to monitor Lake № 18, which due to its thermokarst origin has a tendency for periodic outbursts, which is confirmed by the facts of outbursts in 2004, 2012, 2018. For the other lakes in the Adygene River basin, no outbursts have been observed in recent decades, these lakes have a minimal probability of outbursts and, given their small size, may be of secondary interest in the monitoring process. However, they should not be completely excluded from monitoring.

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2. River flow regime and climate in the Ala-Archa River basin according to the data of the "Kyrgyzhydromet" network

Executor: Kalashnikova O.Yu.

Introduction.

The basin of the Ala-Archa River is located on the northern slope of the Kyrgyz Ala-Too Range in its central, highest part. The length of the Ala-Archa River is 78 km and the basin area is 270 km^2 [1]. The area up to the Ala-Archa river hydropost - the mouth of the Kashka-Suu river is 233 km^2, glaciation of the basin occupies about 17% of the total area. The basin extends in the range of altitudes from 1570 to 4750 m above sea level (Fig.1).

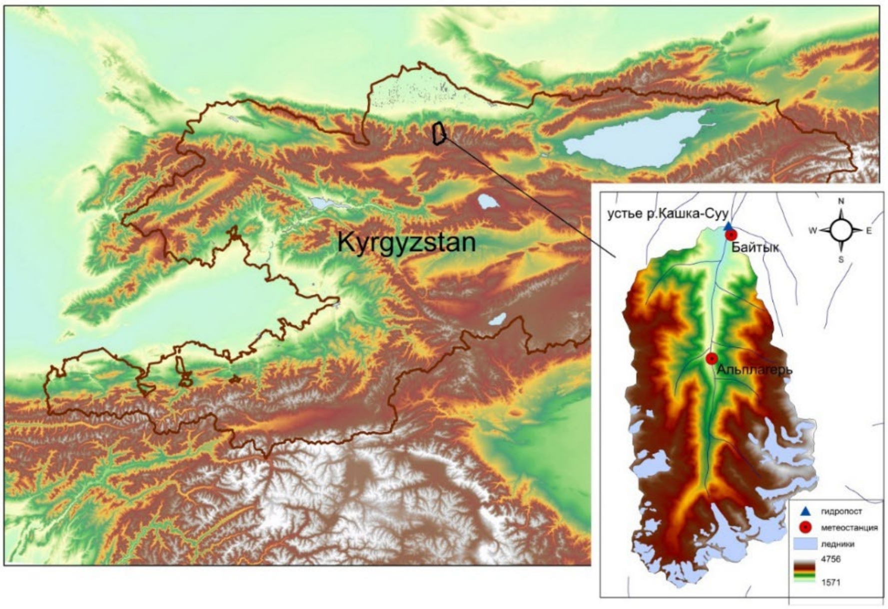


Fig.1. Location of the Ala-Archa River basin in Kyrgyzstan.

The Ala-Archa River flows through the Bishkek city, which has a population of 1,027,200 or 17% of the total population of Kyrgyzstan (as of 2019) and is extremely important for the Chui region. The waters of the Ala-Archa River are used for irrigated agriculture in the Alamedin and Sokuluk districts of the Chui region. In the lower reaches of the river there is the Ala-Archa reservoir (designed volume 39 million m^3), which is used as a source of irrigation water for irrigation in the dry summer period. In the upper reaches of the river there is the largest Orto-Alyshsky groundwater intake, which provides the capital of Kyrgyzstan, Bishkek, with 43% of drinking water.

According to the data of the hydropost of the river Ala-Archa - mouth of the river Kashka-Suu (1560 m.a.s.l.) observation network of Kyrgyzhydromet for the period of observation from 1929 to 2017, the average annual river runoff was 4.69 m^3 / s, the maximum observed water discharge was observed on June 22, 1953 and was 50.0 m^3 / s, the minimum on January 16, 1934. - 0.81 m^3/s. The average annual precipitation at an altitude of 1500-2000 m is 550 mm, the average annual air temperature is 6.5 °C (at an altitude of 1560 m according to the meteorological station Baityk) and 2.9 C (at an altitude of 2100 m according to the meteorological station Alplager). At an altitude of 2100 meters above sea level, precipitation falls mainly in the form of snow in winter and has maximum values in the spring and summer months [2,3,4].

To analyze changes in water discharge on the Ala-Archa River, stock data of Kyrgyzhydromet on the hydropost of the Ala-Archa River - mouth of the Kashka-Suu River for the period from 1929 to 2017 were used [5]. Differential-integral curve analysis and statistical analysis were used to assess runoff change in the Ala-Archa River. The hydrograph separation method was used to assess changes in the main sources of feeding (groundwater runoff, snowmelt and glacial runoff). An analysis of changes in average air temperature was carried out using stock data from Kyrgyzhydromet at the Baityk weather station for the period from 1915 to 2017. Analysis of changes in the amount of precipitation according to the same station for a shorter period - from 1926 to 1917, since there are no observations of precipitation in individual months during the period of observation from 1915 to 1925 [5].

The Baityk weather station is located at the location of the hydropost at the mouth of the river Kashka-Suu on the right bank of the Ala-Archa River, located at an altitude of 1579 m above sea level and it was opened in 1913. In the first years of observations, in some months, there were data omissions in the Kyrgyzhydromet archives, so we used a continuous series of meteorological parameter observations from 1915 to 2017 for air temperature and from 1926 to 2017 for precipitation. In the present work, the statistical method [6] was used to analyze changes in meteorological and hydrological parameters. Based on air temperature and precipitation data, estimates of linear trends were obtained corresponding to the periods: 1915 (1926)–1975 and 1976–2017.

2.1 Changes in the flow of the Ala-Archa River.

The Ala-Archa River belongs to the glacial-snow type of feeding and has an average catchment height of 3290 m above sea level. [7]. The ratio of runoff components of the Ala-Archa River is as follows: the share of groundwater runoff is 44%, snowmelt - 22%, glacial runoff - 30% and rainfall - 4% of the annual river runoff [1]. Floods on the Ala-Archa River, caused by the melting of seasonal snow and glaciers, occur between April and September. Glacial melting is observed from July to September, while the river runoff during this period is 2.5 times higher than in the period from April to June, the peak of floods is observed in July.

The graph of average annual water discharge for the period from 1926 to 2017 shows that there is a steady trend of increasing water availability in the Ala-Archa River (Fig.2). The analysis of the difference-integral curve shows that an increase in average annual values has been observed from 1976 to the present (Fig. 3). Three periods of change in average annual water discharge can be distinguished: 1929-1975 - period of decrease, 1976-1993 - period of small gradual increase, 1994-2017 - period of significant increase in runoff. The average annual water discharge from

1976 to 2017 was 5.26 m^3/s or 125% of the values for the period 1929-1975 (4.21 m^3/s), i.e., runoff increased by 25%.

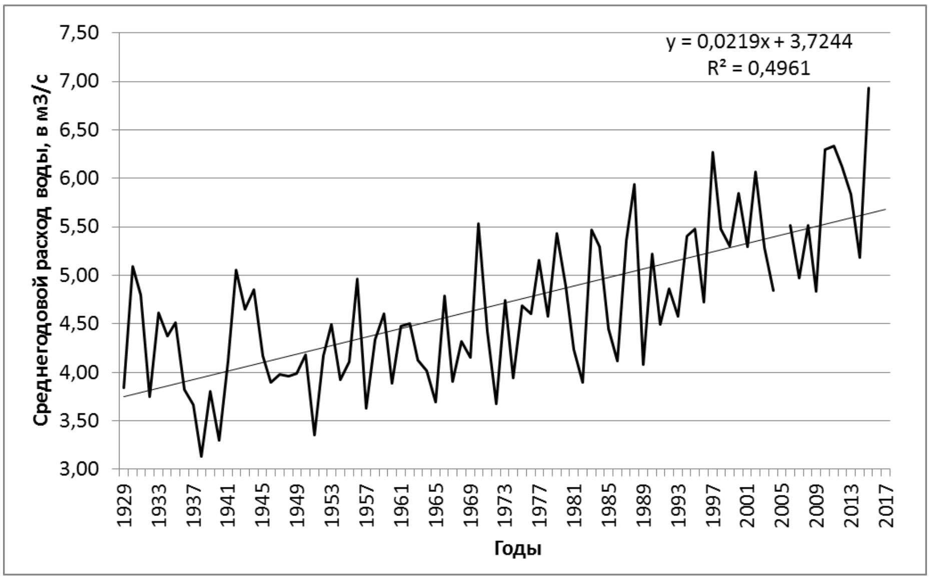


Fig.2. Change of average annual water discharge of the Ala-Archa River - mouth of the Kashka-Suu River.

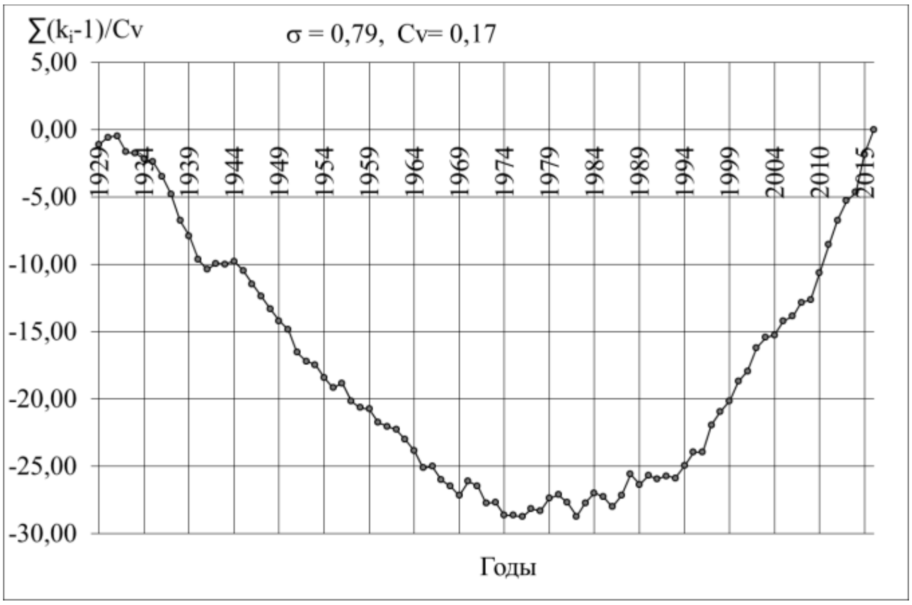


Рис.3. Fig.3. Difference-integral curve of average annual water discharge of the Ala-Archa River - mouth of the Kashka-Suu River.

The intra-annual distribution of discharge demonstrates an increase from 1974-2017 compared to the values observed from 1929-1975. There has been an increase in discharge across all months of the year, with the most significant rise occurring in July-August (Figure 4).

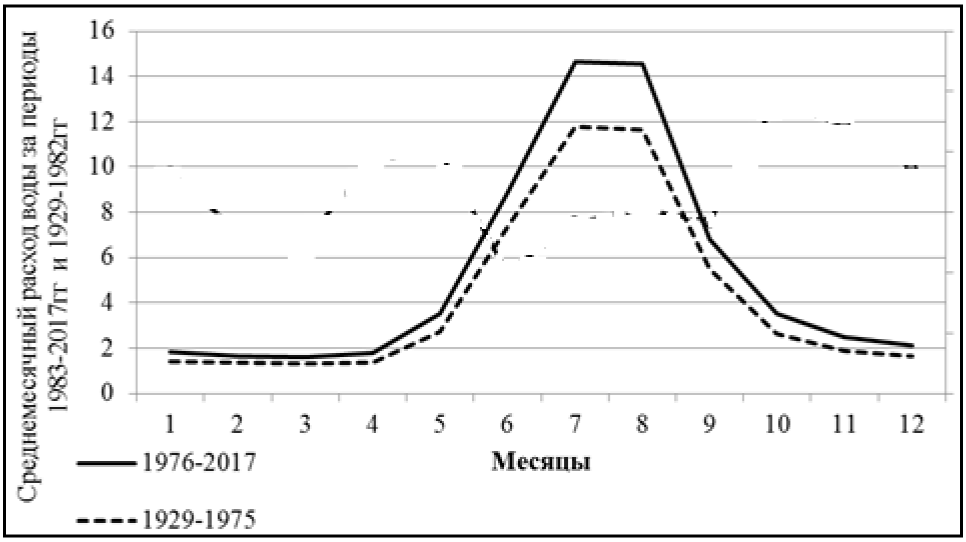


Fig. 4. Intra-annual variation of runoff (m^3/s) of the Ala-Archa River for the periods 1976-2017 and 1929-1975.

The method of the hydrograph separation to estimate changes in the main sources of feeding (groundwater runoff, snowmelt, and glacial runoff) was applied to the two main periods 1929-1975 and 1976-2017. It was determined that the average annual water discharge values in 1950 were close to the average water discharge for the period 1929-1975, and in 2008 - to water discharges for the period 1976-2017, then hydrographs were built (Figures 5 and 6).

In Table 1, calculations of the runoff share by feeding types (in million m^3) and as a percentage of the total runoff, along with the start and end dates of the seasonal snow and glacier melt periods in 1950 and 2008, are provided.

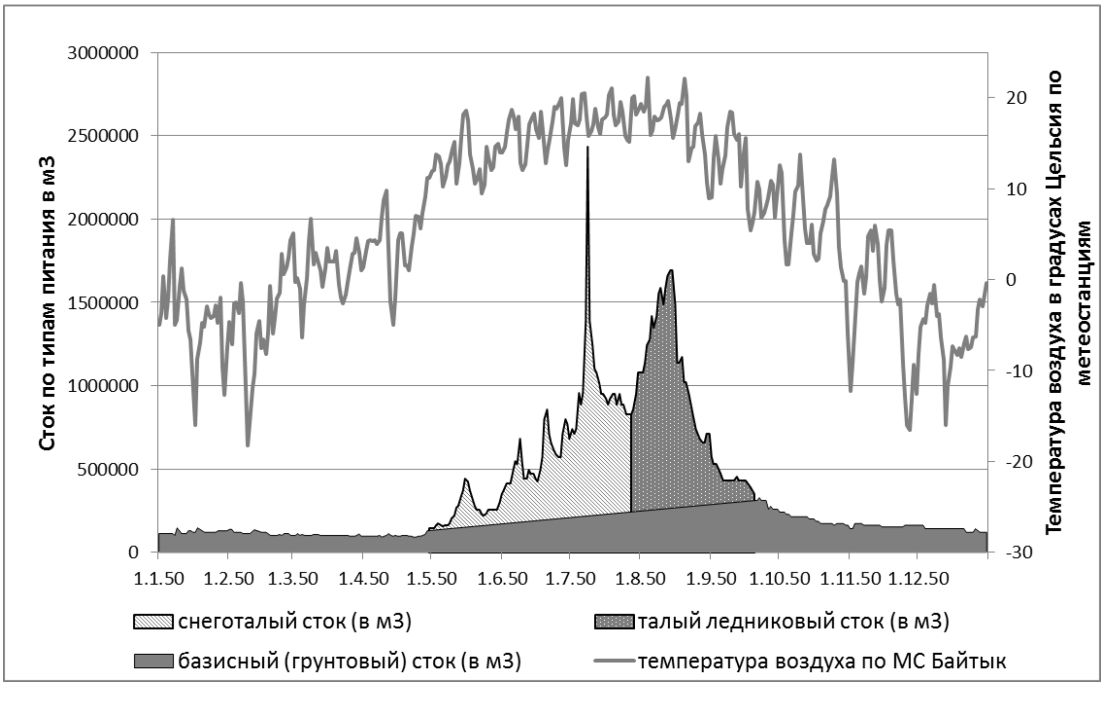


Fig.5 Graph of hydrograph separation by feeding types for 1950.

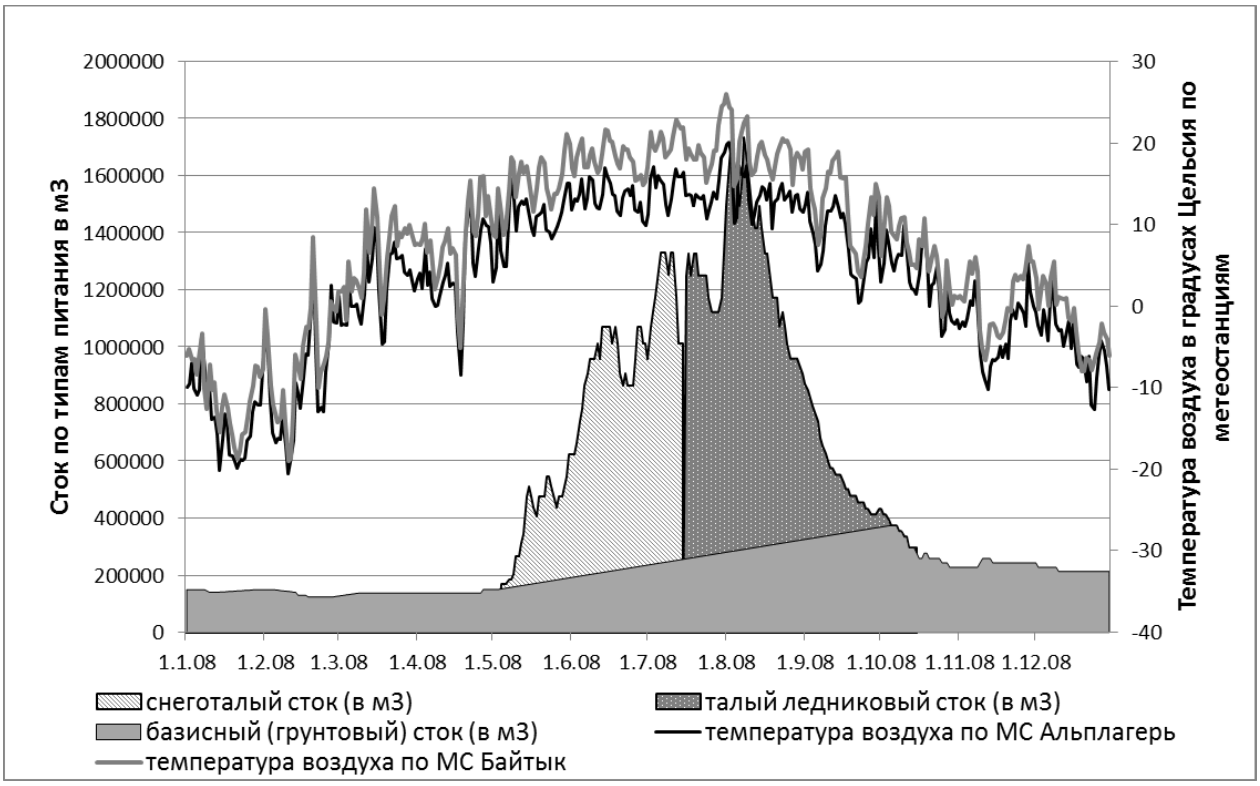


Fig.6 Graph of hydrograph separation by feeding types in 2008.

Table 1.

Share of runoff by feeding type (in million m^3) and as a percentage of total runoff, start and end dates of seasonal snow and glacier melt in 1950 and 2008.

Years	Share by feeding type in million m^3 and as a percentage of total runoff and date of beginning and end of snow and glacier melt period					
	Baseflow runoff (groundwater feeding)		Snowmelt-runoff		Glacial melt runoff	
	in mln m^3	in %	in mln m^3	in %	in mln m^3	in %
1950	63,0	48	35,8 30.04-28.07	27	32,6 29.07-20.09	25
2008	79,1	45	41,8 4.05-15.07	24	53,6 16.07-4.10	31

The analysis of changes in the runoff components by feeding types revealed that the spring flood on the Ala-Archa River in 1950 and 2008 began approximately on the same dates (late April to early May) but ended 14 days later in 2008 due to an extended warm period. The seasonal snowmelt in 2008 ended 13 days earlier (July 15) compared to 1950 (July 28), and the duration of the melting period amounted to 72 days, which is 20 days shorter than in 1950 (91 days). Accordingly, glacier melt in 2008 was observed 13 days earlier than in 1950, but the duration of glacier melt was 80 days, 27 days longer than in 1950 (53 days). According to the feeding sources, there is also an increase in the total runoff volume in 2008 compared to 1950. Thus, the volume of melted glacier water in 2008 is higher by 20 million m^3, melted snow water is higher by 6 million m^3, and groundwater feeding is higher by 16 million m^3 compared to 1950 (see Fig. 7).

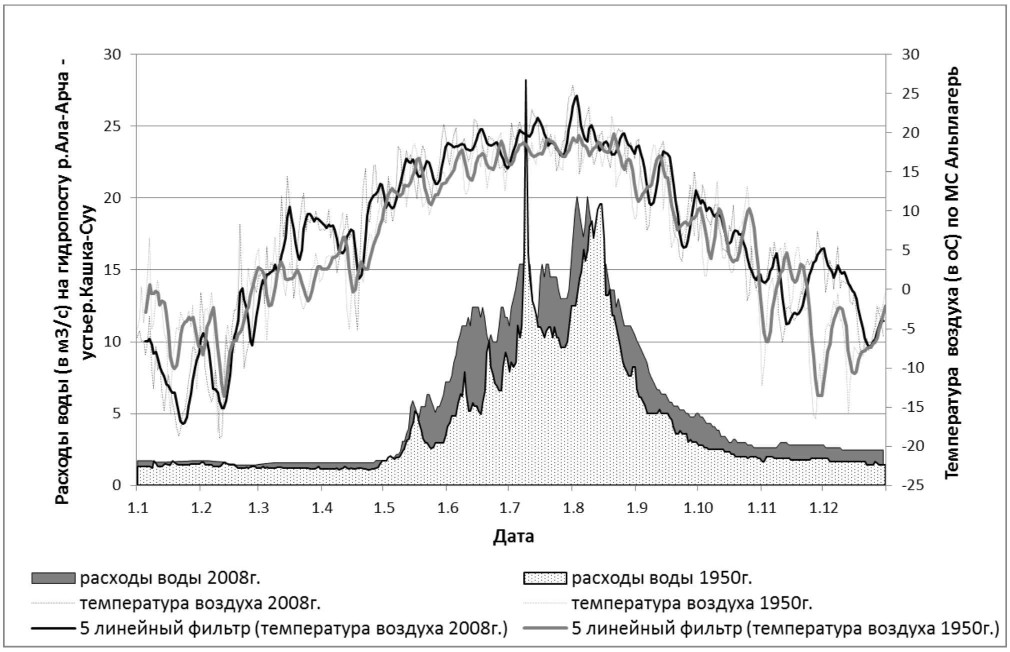
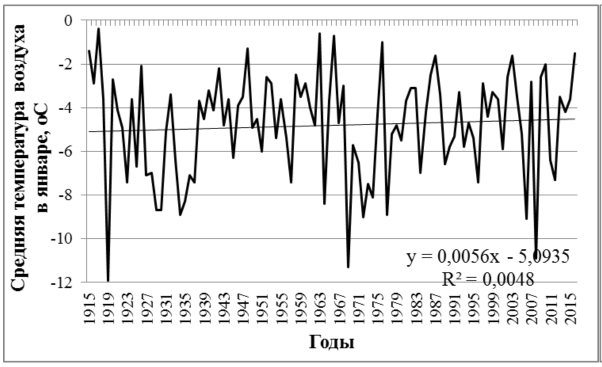


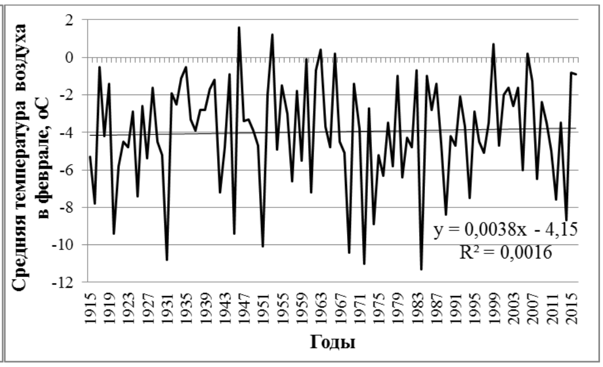
Fig.7. Combined runoff hydrograph and air temperature graph for 1950 and 2008.

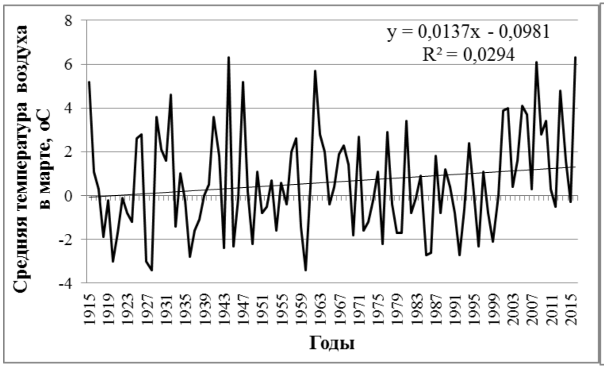
2.2 Changes in air temperature in the Ala-Archa river basin.

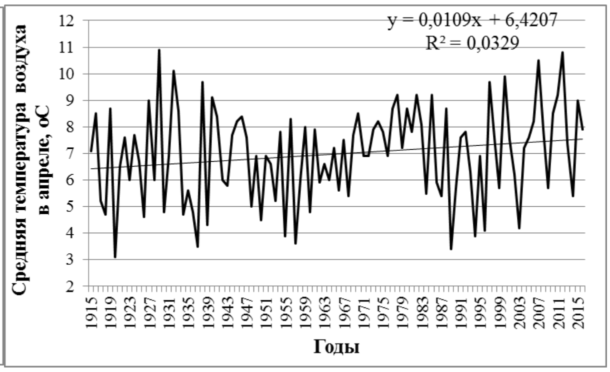
Figures 8.1 - 8.12 present graphs and trends of change in average monthly surface air temperature in degrees Celsius based on data from the Baytyk weather station. For the period of observation from 1915 to 2017, the graphs show a positive trend in air temperature change, except for October, when a negative trend is observed, i.e. the air temperature in October decreases slightly. The greatest increase in trend is observed in March, April and June, i.e. in the months of melting of the seasonal snow cover. From 2000 to 2017, the air temperature in March has positive average monthly values (with the exception of 2012 and 2015 -0.5 and -0.3°C), which indicates an increase in the warm period in the Ala-Archa River basin. There are also upward trends in September, November and December, of which November should be highlighted. In November, the air temperature from 1986 to 2016 has positive values; only in some years the air temperature is observed in the range from -1 to -0.3 ° C (1993, 1996, 1997, 2000, 2011 and 2014).

This fact also indicates an increase in the duration of the warm period of the year. The air temperature gradient for average annual temperatures at the Baytyk weather station is about 0.05°C/100 years. Table 2 shows the change in monthly average air temperature for the periods 1915-1975 and 1976-2017.


Средняя температура воздуха в январе, оС
y = 0,0056x - 5,0935
R² = 0,0048
Годы


Средняя температура воздуха в феврале, оС
y = 0,0038x - 4,15
R² = 0,0016
Годы


Средняя температура воздуха в марте, оС
y = 0,0137x - 0,0981
R² = 0,0294
Годы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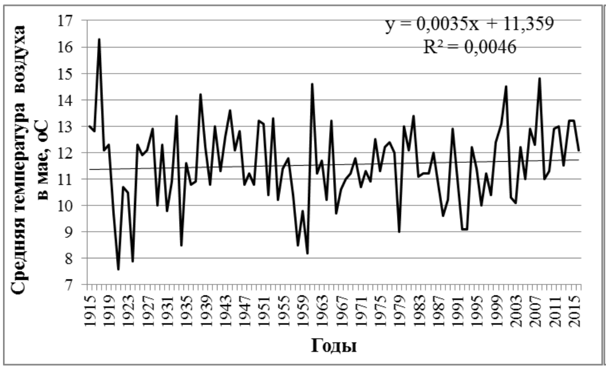
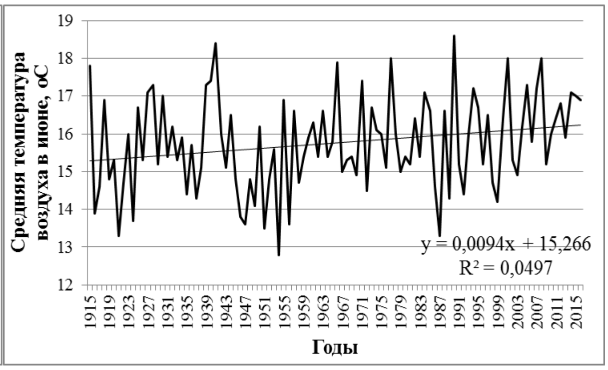
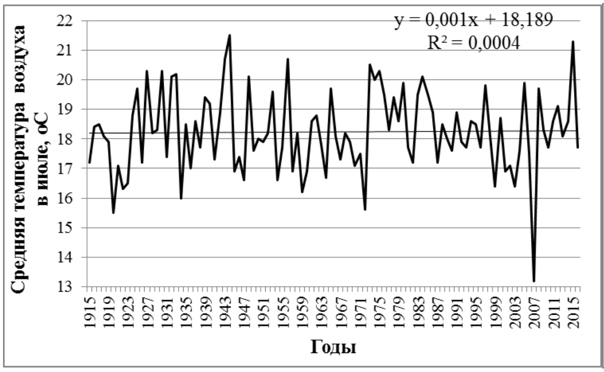
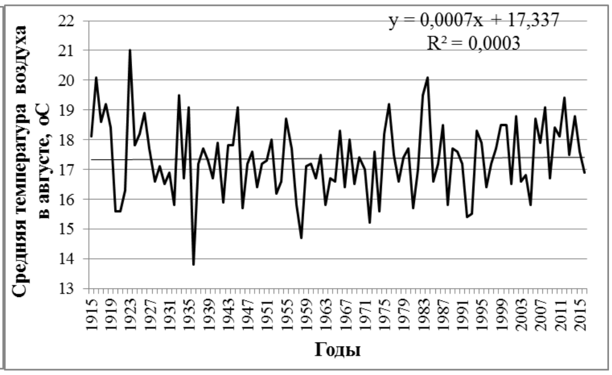
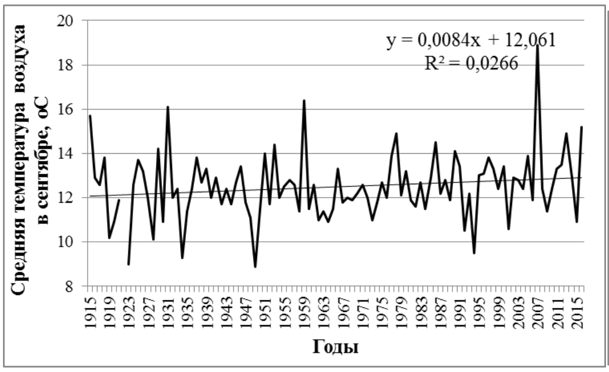
y = 0,0109x + 6,4207
R² = 0,0329
Годы


Средняя температура воздуха в мае, оС
y = 0,0035x + 11,359
R² = 0,0046
Годы


Средняя температура воздуха в июне, оС
y = 0,0094x + 15,266
R² = 0,0497
Годы


Средняя температура воздуха в июле, оС
y = 0,001x + 18,189
R² = 0,0004
Годы


Средняя температура воздуха в августе, оС
y = 0,0007x + 17,337
R² = 0,0003
Годы


Средняя температура воздуха в сентябре, оС
y = 0,0084x + 12,061
R² = 0,0266
Годы

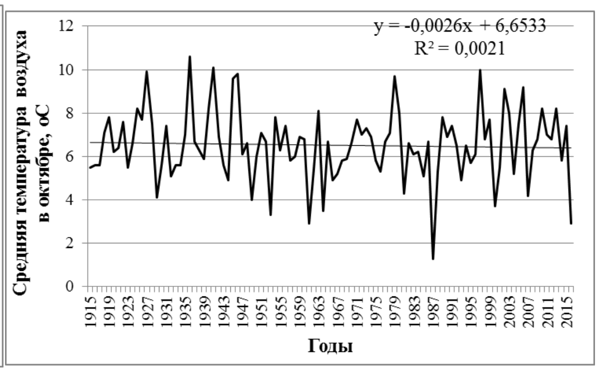

Средняя температура воздуха в октябре, оС
y = -0,0026x + 6,6533
R² = 0,0021
Годы

Fig.8.1-8.10. Change in average monthly air temperature from January to October for the period 1915-2017.

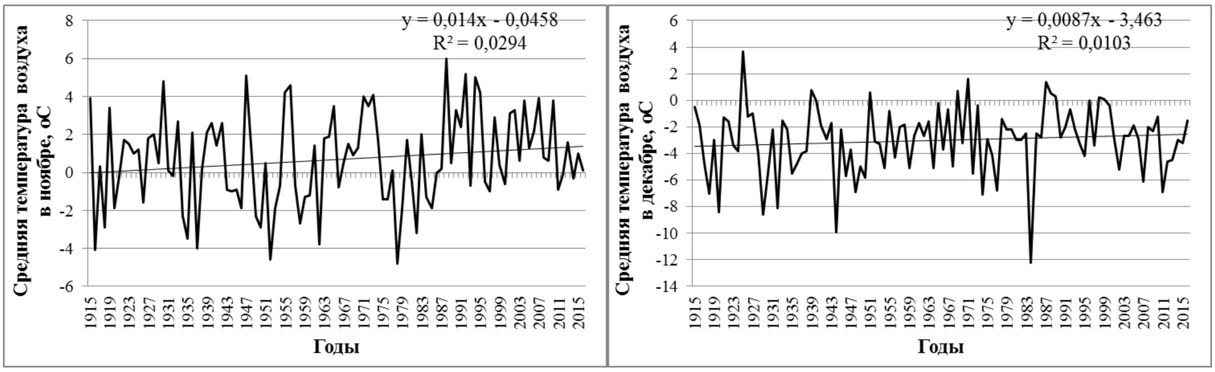


Fig.8.11-8.12. Change in average monthly air temperature in November, December for the period 1915-2017.

Table 2.

Change in average monthly air temperature (in degrees Celsius) for the periods 1915-1975 and 1976-2017.

Periods	Average monthly air temperature in degrees Celsius											
	1	2	3	4	5	6	7	8	9	10	11	12
1915-1975	-5,0	-4,0	0,5	6,7	11,4	15,5	18,2	17,2	12,3	6,5	0,5	-3,2
1976-2017	-4,5	-3,9	0,8	7,4	11,7	16,1	18,3	17,6	12,9	6,5	1,0	-2,8
Temperature difference: 1976-2017 ÷1915-1975	-0,5	-0,1	+0,3	+0,7	+0,3	+0,6	+0,1	+0,4	+0,6	0,0	+0,5	-0,4

***2** Note: In the temperature difference row, the sign indicates an increase or decrease in the absolute value of the temperature.*

2.3 Changes in precipitation in the Ala-Archa river basin.

The graphs in Figures 9.1 and 9.2 show an increase in the amount of precipitation, both in the warm period (April-September) and in the cold period (October-March) in the river basin Ala-Archa. The magnitude of the trend gradient of increasing precipitation for the cold period (0.79) is higher than the warm period (0.35) of time. Thus, for the cold period (low water period), the average precipitation in 1976-2017 was 212mm or 20% more than the average precipitation for the period 1926-1975 (176mm). During the warm period (flood season), the average precipitation during 1976-2017 was 356 mm or 4% more than the average precipitation during 1926-1975 (344 mm). During the cold season, precipitation falls predominantly as snow, forming a stock of seasonal snow cover. Thus, it should be noted that the seasonal snow reserves have increased over the past decades in the river basin Ala-Archa.

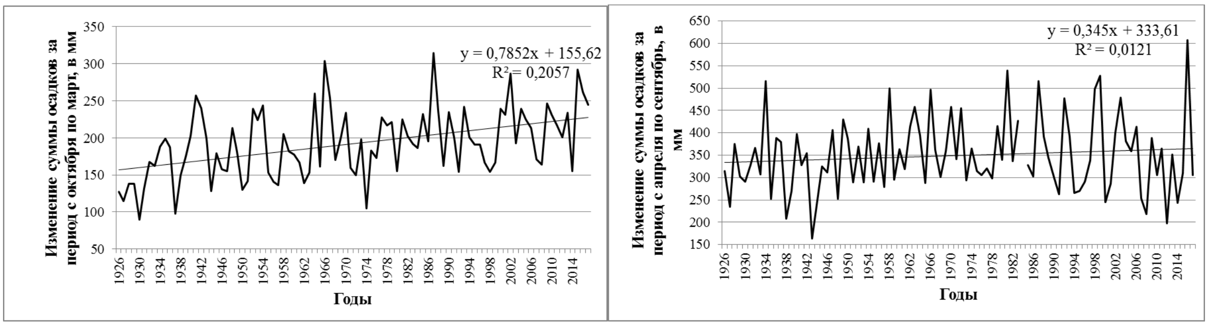


Fig. 9.1 - 9.2. Changes in precipitation for the period October-March (left) and April-September (right).

Conclusion

The increase in runoff in the Ala-Archa River in recent decades (from 1976 to the present) is associated with an increase in precipitation during both warm and, to a greater extent, cold periods of the year, as well as with an increase in glacial runoff due to climate warming (Table 1).

The tendency of increasing duration of the warm period contributes to shifting the beginning of the flood to earlier dates and, also, its end at later dates.

The greatest increase in river runoff observed from 1994 to the present is associated with an increase in snowmelt runoff due to the increase in seasonal snow cover during the cold season.

There is an increase in the volume of glacial melt water in the Ala-Archa River basin, affecting the increase in the flow of the Ala-Archa River during July-September.

The increase in the low-water flow of the Ala-Archa River is associated with an increase in the volume of groundwater runoff due to both rainfall and melt water from seasonal snow and glaciers [8].

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