Risk analysis of mudflows in the Central Caucasus

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Abstract. Hazardous natural processes, including mudflows, are changing natural geomorphological processes, mountain landscapes, threatening the safety of the population. Due to climate changes in recent decades in the Caucasus there has been reduction in the area of glaciations, increased mudflow hazard. In the work, the possibility of mudflows in the Central Caucasus based on the interpretation of time-varying satellite images is analyzed. A forecast is given for the development of mudflow processes in connection with the degradation of glaciation.

1. Introduction

Mudflows that characterize many mountain systems, including the Greater Caucasus, is an important factor in both relief and landscape formations. Catastrophic mudflows change the direction and intensity of exogenous processes, including slope, river-bed [4], transform mountain landscapes.

Hazardous natural processes, among them mudflows, cause significant damage to various sectors of the economy, threaten the safety of the population. To assess the danger of natural processes, indicators can be used that reflect the number of casualties, victims (social risk), damage (economic risk), which also account the number of destroyed, damaged buildings, structures (physical risk) [2, 3]. To assess the risk of mudflows from the point of view of economic indicators, data are needed on the natural causes and characteristics of mudflows.

In recent years, mudflow flows have become more frequent in the mountains of the Central Caucasus, and the areas of mudflow basins have changed [7]. This is largely due to the degradation of mountain glaciation following the climate change. In this case, glacial lakes which are the source of the formation of many mudflows are formed and increase in size. Breakthroughs of glacial lakes is one of the most destructive natural phenomena in the highlands. Their consequence are mudflows and floods, spreading tens of kilometers down the valleys, leading to disastrous natural and socio-economic consequences. Insufficient knowledge of the evolution of glacial lakes becomes the main reason for mudflow hazard studies. [6, 9].

Another cause of mudflows is the gradual melting of the icy core of moraine deposits, which is also observed in the study area.

There are numerous examples of the catastrophic consequences of mudflows in the Caucasus, including in the city of Tynnyauz, and villages near Bashkara Lake in 2018. Destructive mudflows that had fallen on Tynnyauz occurred in 1937, 1960, 1961, 1962, 1977, 1999 and 2000. The mudflows of July 18–25, 2000 had caused the most catastrophic socio-economic consequences in the entire history of Tynnyauz.

Geoecological monitoring of the areas with the potential risk of mudflows, including the interpretation of satellite images, is the most important way to predict and prevent mudflows and other catastrophic events.
2. **Purpose**

Risk analysis of mudflows in the Central Caucasus by means of decoding satellite images.

3. **Research objectives**

- to analyze the glaciation dynamics on the example of the Central Caucasus for 1985–2015 based on the interpretation of different images;
- to identify the most mudflow hazardous areas;
- to give a preliminary forecast for the development of mudflow processes.

4. **Research methods**

To create maps of the glaciers dynamics and identify mudflow hazardous areas, there had been performed decoding of Sentinel satellite images with a spatial resolution of 10 m.

These satellite images are in the public domain. To identify the long-term dynamics of glaciation, the relief, which was analyzed on a digital terrain model, was considered.

To determine the steepness of the slopes, work was carried out using a slope map constructed based on the digital terrain model SRTM (Fig. 1).

![Map of slope angles](image1.png)

**Figure 1.** Map of slope angles

Also, in the course of work, 3-D imaging of satellite images based on a digital terrain model was used (Fig. 2).

A study of the glaciers dynamics, beginning in 1985, is considered as the satellite images of the Landsat TM satellite (Thematic Mapper, Landsat-5) appeared in 1985. In the same year, active retreat of the Caucasus glaciers was noted.

Decryption attributes such as color, image texture, rivers, and landforms were considered. We also used multizone color gamut images. To more accurately determine the boundaries of glaciation, multichannel satellite imagery from Landsat-5, Landsat-8 and SPOT-6 satellites were superimposed on the base map – a topographic base. The boundaries of the glaciation contours were determined in the mode of visual interpretation of satellite images with a measurement error of up to several hundred meters. To identify the most mudflow hazardous areas, primarily periglacial lakes and their dynamics, were deciphered, moraine deposits were analyzed if possible.
5. Results

Based on the interpretation of satellite images for 1985 and 2015, the maps of the glaciation dynamics of the Central Caucasus were performed using the ArcMap 10.3 program (Fig. 3, 4).

The length of the study area is about 200 km from the northwest to the southeast with a maximum width of 50 km and an area of 5 thousand km².

Figure 2. Visualization of a landslide near Tegenekli

Figure 3. The boundaries of glaciation in 1985

Figure 4. The boundaries of glaciation in 2015
Since 1985, the average annual temperature in Terskol (data from the Terskol weather station) has increased by an average of 0.5 °C, winter precipitation has increased by 20 %, and summer precipitation has remained at the same level [7].

The glaciers dynamics of the Central Caucasus was analyzed based on the data on glacier areas for 1970 according to the Catalog of Glaciers of the USSR [3] and since calculation of the areas in ArcMap 10.3 software using decrypted images for 1985 and 2015. 84 glaciers with their sizes ranging from 0.2 to 36.2 km² were investigated.

The glaciers included in the sample have clearly distinguishable boundaries in the image and differ in the noticeable dynamics of their boundaries. 84 glaciers were explored.

According to the results of studies, it was found that in 2015 the area of glaciers decreased significantly compared to 1985. The retreat of the ice sheet is observed, and in some places its complete disappearance [1]. The area of glaciation had decreased by 260 km², which is 22 % of the original area of ice cover. The most unfavorable period for the glaciers of the Northern Hemisphere was the decade from 1990 to 2000, and intensive degradation of glaciation was also noted in the Caucasus.

The results of the study of some Central Caucasus glaciers for 1970 according to the Catalog of Glaciers of the USSR [5], 1985, 2015 (based on the calculation of the areas in the ArcMap 10.3 program using decrypted images) are presented in the table (Table 1).

| №   | Title                        | The name of the river flowing from the glacier | Morphological type | Total exposure | Area, km² | 1970 | 1985 | 2015 |
|-----|------------------------------|----------------------------------------------|-------------------|---------------|-----------|------|------|------|
| 1   | Ulluchiran                   | Malka (Kizilkol)                            | conical.          | N             | 12.4      | 8.6  | 8.4  |
| 2   | Karachaul trib.              | Malki River (Kyzylkol)                       | conical.          | N             | 5.7       | 5.5  | 4.8  |
| 3   | Ullucol trib.                | Malki River (Kyzylkol)                       | conical.          | N             | 5.3       | 4.7  | 4.1  |
| 4   | Mikelchiran trib.            | Birjalisu                                    | conical.          | NE            | 4.5       | 4.5  | 3.9  |
| 5   | Jikaugenkez                  | Birjalisu                                    | conical.          | NE            | 27.8      | 25.3 | 19.8 |
| 6   | Irikchat                     | Irikchat                                     | val.              | SE            | 1.8       | 1.8  | 1.3  |
| 7   | Irik                         | Irik                                         | val.              | SE            | 10.5      | 8.7  | 8.4  |
| 8   | Terskol                      | Terskol                                      | conical.          | SE            | 7.7       | 7.6  | 7.3  |
| 9   | Garabashi                    | Garabashi                                    | conical.          | SE            | 2.8       | 2.6  | 2.4  |
| 10  | Small Azau trib.             | Azau river                                   | conical.          | S             | 9.7       | 7.4  | 7.0  |
| 11  | Big Azau                     | Azau                                         | val.              | SE            | 19.6      | 18.7 | 14.9 |
| 12  | Shekhelds                    | Shekhelds                                    | val.              | N             | 5.6       | 5.3  | 4.7  |
| 13  | Kashkhatu trib.              | riv. Adylsu                                  | cor.-val.         | N             | 2.5       | 2.9  | 2.4  |
| 14  | Bashkara                     | Adylsu                                       | val.              | N             | 3.4       | 3.0  | 2.6  |
| 15  | Janquat                      | trib. riv. Adylsu                            | val.              | NW            | 1.9       | 1.8  | 1.3  |

Most of the glaciers of the Central Caucasus have decreased over the study period, however, some glaciers, such as Mikelchiran, Irikchat and Sughan are in a sustainable condition, the Dykh-su, Kashkhatu, Adyrsu glaciers have increased in size by an average of 0.1–0.5 km².

The most dramatic changes saw the glaciers of the southern slope of the Main Caucasus Range. Less intense melting of the northern slope glaciers was noted. Unlike the glaciers of the Main Caucasian Range, the glacier areas of Elbrus have changed slightly. We can observe the most significant changes in the complex valley and large valley glaciers, whose tongues descend far down into the valleys. For example, the Garabashi glacier, which in recent decades has been actively retreating and currently ends at an altitude of 3250 m.

The least changed are the corrie and hanging glaciers. They are relatively sustainable, the first is due to the constancy of snowstorm and avalanche food, and the second is due to their location at significant altitudes.

Due to the decrease in the area of glaciers, an increase in the area of glacial lakes is observed, which leads to increased mudflow hazard. Lakes can also contribute to faster ice melting, as ice melts
more quickly when it meets warm lake waters. The most mudflow-hazardous areas in the Central Caucasus in the periglacial zone of glaciers were revealed: Bashkara, Syltran, Birjaly.

6. Conclusions
- From 1985 to 2015 there was an increase in average summer temperature by 0.5 °C and winter precipitation by 20%.
- The area of mountain glaciation of the Central Caucasus for the period of 1985–2015 had reduced by 260 km$^2$. The most noticeable dynamics of glaciation can be seen on the southern slopes of the Main Caucasian Range.
- The most significant changes saw complex valley and large valley glaciers of the southern slope of the Caucasus.
- Degradation of glaciation leads to an increase in the area of glacial lakes in the mountains, which in turn leads to an increase in mudflow risk. The most mudflow hazardous areas are noted in the Central Caucasus in the periglacial zone of the Bashkara, Syltran, Birjaly glaciers.

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