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ASSESSMENT OF CHARACTERISTICS OF FLOODS FORMED BY THE OUTBURSTS OF HIGH MOUNTAIN MORAINE LAKES

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Table of contents

Introduction

The urgency of the research. In modern conditions of a non-stationary climate, the area of glaciation in mountain ranges is decreasing, which has a significant impact on the dynamics of nival-glacial landscapes. In particular, changes are occurring in limne-glacial complexes: the size of existing lakes is increasing, and new lakes are forming in areas freed from ice. Moraine-dammed lakes are unstable and short-lived on a geological time scale. A rapid increase in the water volume in a lake can lead to weakening of the dam and subsequent outburst. As a result of the outburst catastrophic outburst floods and associated mudflows of various sizes are formed: from small and imperceptible to humans to leading to glacial catastrophes that cause large-scale damage to the territories located downstream (flooding of territories, destruction of infrastructure and loss of population) (Golubev, 1976; Vinogradov, 1977; Clarke, 2003; Vinogradova et al., 2017; Chernomorets et al., 2018; Mergili et al, 2019; Zheng et al, 2021). According to existing assessments (Carrivick, Tweed, 2016; Bekkiev et al., 2023), an increase in the number of hazardous natural phenomena, including those associated with the deglaciation processes of mountain areas, should be expected in the World. Therefore, a comprehensive study of the processes of outburst floods formation is not just a scientific task, but is the basis for forecasting such phenomena in order to prevent and protect the population and territories. Due to the fact that periglacial and moraine lakes outbursts occur suddenly and quickly (the duration of these phenomena is minutes or hours), organizing observations of them is extremely difficult and unsafe.

Therefore, to study the outburst process and obtain such characteristics of a outburst flood as maximum discharge, flow velocity and duration of the outburst, it is advisable and often the only possible use of mathematical modelling methods. Currently, in our country there are no methods for calculating the outburst flood wave characteristics formed during moraine-dammed lakes outbursts, which would include several mechanisms of a lake outburst and take into account the heterogeneous composition of the moraine dam. Modelling the movement of a outburst wave along a valley and mudflows that are formed during mountain moraine-dammed lakes outbursts is carried out using hydrodynamic models in which the outburst flood hydrograph is most often specified schematically or calculated using simplified formulas that do not take into account the dam destruction process.

We also note that in the mountains, in order to monitor dangerous phenomena associated with the outburst floods formation, an important issue, in addition to calculating their characteristics, is the detection of potentially outburst hazardous lakes. The current classification of lake development stages does not include the hydrological and morphometric characteristics of lakes, which makes it difficult to identify lakes with increasing water volumes. That is why identifying the specific features of the level regime of each stage in conditions of poor hydrological knowledge of mountain areas will reduce the degree of information uncertainty.

The aim of the thesis is assessment the characteristics of outburst floods formed during of high-mountain moraine-dammed lakes outbursts, based on mathematical modelling, field investigations and Earth remote sensing data.

To achieve this aim, the following **tasks** were solved:

1. Analysis of published scientific works on the research topic.
2. Development of a methodology for calculating the outburst floods characteristics, taking into account two trigger mechanisms of outburst and the heterogeneous composition of the moraine.
3. Approbation of the calculation methodology on data obtained during physical experiments and data from real outbursts of moraine lakes.
4. Compilation of a catalog of moraine-dammed lakes in the Altai Mountains and identification of spatiotemporal variability in the distribution of reservoirs under changing climate conditions.
5. Identification of features of the level regime of moraine-dammed lakes at different stages of development.
6. Calculation of the outburst flood characteristics based on the developed methodology, which takes into account two trigger mechanisms of outburst and the heterogeneous composition of the moraine.

Approbation of the developed approaches and methods outlined in thesis was carried out for a number of objects located in the Central and South-Eastern Altai. Despite the fact that the region as a whole is not active in terms of outburst phenomena, a number of events have been recorded here: the outburst of a moraine-dammed lake located near the Left Aktru glacier in June 1969 (North-Chuya ridge, Russia) (Dushkin, 1976), outburst of the landslide Lake Maashey (North-Chuya ridge, Russia) in July 2012 (Bykov, 2013), outburst of moraine-dammed lake located in the northern part of the Kharkhiraa mountain massif (North-Western Mongolia) in July 2010 (Walther et al, 2024); outburst of moraine-dammed Lake Nurgan (Tsambagarav mountain range, North-Western Mongolia) in the middle of the 20th century (Pryakhina et al., 2021).

We also note that the territory of Altai is characterized by:

• little (compared to other mountains, such as the Caucasus, the Tien Shan, the Pamir, the Himalayas) knowledge in terms of the formation and potential for the breakthrough of dammed moraine reservoirs that are part of lake-glacier complexes;

• an increase in the number of periglacial and moraine lakes and an increase in the size of existing lakes revealed in recent decades (Rasputina et al., 2022);

• the insufficiently studied hydrological regime of water bodies in the high mountain areas of Altai in comparison with similar objects in other mountainous countries;

• a sharp increase in tourist activity and the intensity of development of the economy and logistics routes, which significantly increases the risks and potential damage from hazardous hydrological phenomena.

Also, the choice of the Altai Mountains as a study area was determined by perennial complex expeditions of the Institute of Earth Sciences of St. Petersburg State University in the Russian and Mongolian parts of the Altai Mountains territory (the Mongun-Taiga and the Tavan-Bogdo-Ola mountain massifs, the Tsambagarav, the Katunsky, the North-Chuya and the South-Chuya mountain ridges), during which hydrological and morphometric characteristics of moraine and periglacial lakes in areas of glaciation degradation were obtained.

The objects of the research are moraine and periglacial lakes in the Altai highlands, located on modern moraines and the Little Ice Age moraines.

The subject of the research is the characteristics of outburst floods formed during outbursts of moraine-dammed lakes.

Research methods. During performing the dissertation research, an integrated approach was used, including: interpretation of satellite images to analyze the spatial and temporal variability of periglacial and moraine lakes; field hydrological studies on moraine lakes of Central and South-Eastern Altai in 2019, 2021, 2022 and 2023 (water level observations, bathymetric surveys of lakes, tacheometric surveys of lake basins, meteorological observations), which made it possible to describe the features of the level regime of lakes located at different stages of development; mathematical modelling of the outburst floods characteristics based on the calculation methodology developed within the framework of this thesis.

The author's individual contribution lies in carrying out the bulk of the research outlined in this thesis. The author took part in all field work carried out in 2019, 2021-2023 on moraine and periglacial lakes of Altai, collected and processed the obtained materials, participated in conducting physical experiments on the destruction of soil dams and processing the results obtained, personally interpreted satellite images, analyzed the spatiotemporal variability of lakes and compiled a catalog of moraine lakes in the Altai Mountains. With the participation of the author, detailed criteria were developed for the classification of moraine lakes by stages of development, and a methodology was developed for calculating the outburst floods characteristics. The author personally wrote a computer program for calculations in the MatLab.

The scientific novelty. In work for the first time:

- a methodology have been developed for calculating the outburst flood characteristics, taking into account two outburst mechanisms and the heterogeneous composition of the moraine;

- features of the level regime for moraine lakes at different stages of development have been identified;

- various trends in changes in the spatial distribution and temporal variability of moraine and periglacial lakes in Altai have been identified; differences in trends are due to different climatic features of Central and South-Eastern Altai;

- an increase of 100-200 m in the altitudinal interval of the largest distribution of periglacial and moraine lakes and an increase in their total area over the past 20 years from 6 to 130% were revealed.

Theoretical and practical significance of the thesis. A description of the development stages of moraine and periglacial lakes, as well as the process of lake outburst, make a theoretical contribution to the understanding of the process of lakes evolution both in the Altai territory and other mountain systems. The compiled catalog of lakes enables the user to obtain information about the basic characteristics of moraine lakes of the Altai Mountains (area, height, lake type, type of dam, type of drain, etc.). The classification of stages of moraine lakes supplemented by hydrological and morphometric characteristics makes it possible to more reasonably identify potential outburst hazard. The results of the calculation of the outburst floods characteristics can be used to model assessments of the zones of flooding of territories and for calculations of mudflows.

The degree of reliability and the results approbation. The results of the thesis were presented at the following conferences: All-Russian scientific-practical conference «Modern problems of hydrometeorology and sustainable development of the Russian Federation» (St. Petersburg, 2019); VII All-Russian scientific-practical conference with international participation «Modern problems of reservoirs and their catchments» (Perm, 2019); International scientific conference «The Fourth Vinogradov Readings. Hydrology: from learning to worldview» (St. Petersburg, 2020); IV All-Russian scientific conference with international participation «Water and environmental problems of Siberia and Central Asia» (Barnaul, 2022); International scientific-practical conference «Fifth Vinogradov Readings. Hydrology in an era of change» (St. Petersburg, 2023); Glaciological conference «Past, current and future changes in climate and glaciosphere» (Moscow, 2023).

The results of the thesis were reflected in the carrying-out of RFBR projects No. 19-05-00535 A « Natural catastrophes and transformation of the landscapes of the South-Eastern Altai and North-Western Mongolia in the period from the maximum of the last glaciation», RSF No. 22-67-00020 «Changes in climate, glaciers and landscapes of Altai in the past, present and future as the basis for a model of adaptation of the population of inland mountainous regions of Eurasia to climate-induced environmental changes» and RSF No. 23-27-00171 «Modelling of outbursts of reservoirs dammed by natural dams».

Publications. 6 articles have been published on the topic of the thesis. A certificate of registration of the computer program was also received.

1. **Rasputina V.A.**, Pryakhina G.V., Ganyushkin D.A., Bantcev D.V., Paniutin N.A. The water level regime of periglacial lakes during the growth stage (the lakes of the Tavan-Bogdo-Ola

mountain massif, South-Eastern Altai) // Ice and Snow. 2022. T.62. No. 3. P. 441-454. (In Russian). (RSCI, Scopus, Web of Science).

2. **Rasputina V.A.,** Pryakhina G.V. A programme for calculating the characteristics of an outburst flood formed due to a soil dam outbursts (OutburstFloodFormation). Certificate of registration of the computer program RU 2022685622, 12/26/2022. Application No. 2022685452 dated 12/19/2022/. (In Russian).
3. **Rasputina V.A**., Ganyushkin D.A., Bantcev D.V., Pryakhina G.V., Vuglinsky V.S., Svirepov S.S., Panyutin N.A., Volkova D.D., Nikolaev M.R., Syroezhko E.V. Outburst hazard of little-studied lakes assessment at the Mongun-Taiga massif // Vestnik of Saint Petersburg University. Earth Sciences. 2021. Vol. 66. Iss. 3. P. 487-509. (In Russian). (RSCI, Scopus, Web of Science).
4. Ganyushkin D., Bantcev D., Derkach E., Agatova A., Nepop R., Griga S., **Rasputina V.**, Ostanin O., Dyakova G., Pryakhina G., Chistyakov K., Kurochkin Y., Gorbunova Y. Post-little ice age glacier recession in the North-Chuya ridge and dynamics of the Bolshoi Maashei glacier, Altai // Remote Sensing. 2023. T. 15. № 8. P. 2186. (Scopus, Web of Science).
5. Ganyushkin D., Chistyakov K., Derkach E., Bantcev D., Kunaeva E., **Rasputina V.**, Terekhov A. Glacier recession in the Altai mountains after the LIA maximum // Remote Sensing. 2022. T. 14. № 6. P. 1508. (Scopus, Web of Science).
6. Pryakhina G.V., Kashkevich M.P., Popov S.V., **Rasputina V.A.**, Boronina A.S., Ganyushkin D.A., Agatova A.R., Nepop R.K. Formation and evolution of moraine-dammed (periglacial) Lake Nurgan, Northwestern Mongolia // Earth`s Cryosphere. 2021. Vol. XXV. No. 4. P. 26-35. (In Russian). (RSCI, Scopus, Web of Science).
7. Pryakhina G.V., Boronina A.S., Popov S.V., **Rasputina V.A.**, Voinarovskii A.E. Physical modelling of the destruction of reservoir ground dam in consequence of the overflow of water body // Proceedings of the Russian Geographical Society. 2019. T. 151. No. 2. P. 51-63. (In Russian). (RSCI).

Structure and size of the thesis. The thesis consists of an introduction, five chapters, a conclusion, acknowledgments, a list of references and 3 appendixes. The size of work is 111 pages. The text of the study is illustrated with 54 figures and 5 tables. The list of references used includes 137 names.

This thesis corresponds to paragraphs 10 and 12 of the passport of the scientific specialty 1.6.16 «Land hydrology, water resources, hydrochemistry».

Main scientific results.

1. A methodology has been proposed for calculating the characteristics of outburst floods formed during outbursts of moraine and periglacial lakes, taking into account the two main trigger mechanisms of outburst (erosion of the filtration channel in the moraine dam body and the water overflow through the dam crest) and the heterogeneous composition of the moraine, which is the main advantage of the proposed calculation methodology unlike similar existing models. The proposed approximation of the cross-sectional shape of the breach, according to the author, more accurately reflects the process of its formation than traditionally used (triangular and trapezoidal) (Rasputina and Pryakhina, 2022).
2. It was established that the reduction in the glaciation area in the Altai mountainous territories led to an altitudinal shift in the area of maximum distribution of moraine and periglacial lakes and an increase in their number and total area from 2000 to 2022 (Rasputina et al., 2022, p. 445-446).
3. The existing classification of stages of development of lakes (Zimnitsky, 2005) was supplemented based on field studies and Earth remote sensing data: the concept of a quasi-stable stage of development was introduced; morphological and hydrological-morphometric characteristics of each stage are proposed, mainly the features of the level regime of lakes at different stages of development are described (Pryakhina et al., 2021, p. 29-31; Rasputina et al., 2022, p. 451-452; Pryakhina et al., 2023, p. 170-173).
4. It was established that in the period preceding the outburst, the lakes that actually outburst were in a transgressive stage of development: they actively increased in size and had an unstable level regime (Pryakhina et al., 2021, p. 29-30).

Thesis statements to be defended.

1. The developed methodology for calculating (including the computer programme) of the outburst floods characteristics formed during outbursts of moraine-dammed lakes takes into account two trigger outburst mechanisms and the heterogeneous composition of the moraine.
2. A significant increase in the number of moraine and periglacial lakes in the territory of Altai with an altitudinal displacing of the area of their maximum distribution and an increase in the total area of the lakes from 2000 to 2022 is a reliable indicator of the process of mountainous territories deglaciation.
3. Each stage of lake development (transgressive, regressive, quasi-stable) is characterized by a special level regime. In conditions of insufficient hydrological knowledge, the

determination of the lake development stage is the only source of information about the level of the water regime.

Chapter 1. Analytical review of researches of moraine-dammed lake outbursts: main directions, methods and approaches

Reservoirs dammed by natural dams are widespread in areas of modern glaciation on the Earth: from mountainous areas to Antarctic oases. Depending on the location and type of lake basin, supraglacial, intraglacial, subglacial, periglacial, moraine and landslide lakes are distinguished. A feature of the hydrological regime of such lakes is the formation of outburst floods as a result of the dam destruction, which can lead to catastrophic consequences: flooding of territories, destruction of infrastructure and loss of the population. The most destructive are floods associated with mudflows, formed during outbursts of periglacial and moraine lakes located in mountainous areas. Historically, mountain lakes outbursts caused serious damage to the population. In the world, the most destructive glacial disasters include the outburst of a lake in the Cordillera Blanca Mountains near the city of Huaraz (Peru) in December 1941. As a result of the passage of the mudflow, more than 6000 people died (Carey, 2005). On the territory of the USSR and Russia, similar catastrophic events were: the Issyk mudflow (July 7, 1963), which led to a lake outburst, which, according to various estimates, killed from 52 to 100 people (Dokukin, 2014), and the Lake Bashkara outburst, which occurred September 1, 2017 (Chernomorets et al., 2018; Kidyaeva et al., 2018).

Assessment of the outburst floods characteristics is impossible without a comprehensive study of the lakes dynamics, a description of the process of outburst floods formation and identification of outburst mechanisms, therefore the review of published scientific works covered several areas of research related to the study of moraine lakes outbursts.

In general, the issue of studying the process of outburst floods formation, as well as identifying trigger mechanisms and factors influencing lakes outbursts, has received a lot of attention in both national and foreign studies (Costa, Schuster, 1988; Awal et al, 2011; Emmer, Cochachin, 2013; Liu et al, 2013; Westoby et al, 2014; Kidyaeva et al., 2018; Neupane et al, 2019). There are several directions in which lake outburst research is being conducted:

1. Analysis of the distribution and dynamics of moraine lakes, their stages of development.
2. Assessment of lake outburst hazard.
3. Identification and study of trigger mechanisms influencing outburst.
4. Mathematical modelling of outburst floods formed during mountain lakes outbursts.

1.1. Analysis of the distribution and dynamics of moraine-dammed lakes, stages of lakes development

To identify ongoing spatiotemporal changes in glacial, periglacial and moraine lakes, Earth remote sensing data (satellite imageries, aerial imageries, orthophotoplans) are widely used. The use of satellite images when studying the development of lakes helps to assess their condition, as well as identify the development stage and establish a possible trigger mechanism for the outburst.

Thus, the article (Shugar et al, 2020) examines the dynamics of periglacial lakes and their distribution around the world based on satellite images from 1990 to 2018. It is shown that during the study period the number of lakes and their total area increased by 53% and 51%, respectively. The authors also found that the fastest growing lakes (by area) are located in the Scandinavian countries, Iceland and Russia. A scientific study by scientists from Germany (Veh et al, 2019) is devoted to identifying outbursts of moraine lakes in the Himalayas based on an analysis of Landsat satellite images from 1980 to 2017 and controlled classification of satellite images (assigning each pixel to a certain class of objects on the ground). The use of the Random Forest classifier (Veh et al, 2018) made it possible to detect lake outbursts that had occurred. The work (Harrison et al, 2018) presents the first global spatiotemporal assessment of outburst floods resulting from moraine and periglacial lakes outbursts, based on regional inventories and surveys (165 moraine dams located in the Alps, the Pamirs, the Tien Shan, the Himalayas were selected, USA and South America), which provides historical insight into outburst floods and their distribution under current and future global climate change. An increase in the frequency and regularity of outburst floods was found around 1930, which likely represents a delayed response to warming after the Little Ice Age.

Currently, there are databases and catalogs of lakes of glacial origin and their outbursts, created on the basis of interpretation of satellite images. An online database (URL: http://glofs-database.org) of periglacial lakes outbursts, includes information on the lakes location, their type, the lakes dam, the outburst genesis and its trigger, the outburst flood volume and the magnitude of damage in the Peruvian Andes, Patagonian Andes and Cordillera (Emmer et al, 2016). Researchers from China and the USA based on an analysis of Landsat TM/ETM+ satellite images for 1990, 2000 and 2010 created a database of glacial lakes and found that there are about 5700 glacial lakes in the Tibetan mountains, more than 1000 of which are connected to glaciers (Zhang et al, 2015). For the territory of the Zebak and Wakhan regions (Badakhshan province, mountains of northern Afghanistan), based on the interpretation of Landsat-8 OLI satellite images, a catalog of lakes was created, which includes 347 objects (Chernomorets et al., 2015), where the following characteristics are given for each lake: location, area, height of the water edge, position relative to the glacier, type of flow from the lake, type of dam, cascading, etc. According to the study, most of the lakes (60%) are dammed by a moraine dam.

Analysis of the temporal variability of the morphometric characteristics of periglacial and moraine lakes helps to determine whether a lake has potential outburst hazard and to identify the mechanisms of its outburst. The work (Dokukin and Shagin, 2014) provides data on the dynamics of glacial lakes with underground drainage channels on the territory of the Kabardino-Balkarian Republic (the Central Caucasus) and other mountainous regions. A similar study of the lakes dynamics of the Bolshoi Azau glacier based on multi-temporal aerospace information is presented in (Adzhiev et al., 2023). According to the study, it was established that the disappearance of lakes occurs as a result of the melting of snow dams, as well as through subglacial and underground drainage channels. In the work (Dokukin, 2014), based on materials from Earth remote sensing, the conditions for the formation and consequences of outburst floods in the Himalayas, the Andes and the Altai are considered, and in (Dokukin et al., 2022), using multi-temporal aerospace and cartographic information and field observations, an analysis of the lakes dynamics located near the Dzhikiugankez glacier (the Caucasus) was carried out, and their outburst mechanisms (surface overflow and water outflow through filtration channels) were established. Identification of potentially outburst hazardous lakes, and timely organization of observations of these objects, as well as the implementation of preventive measures for the controlled drainage of lakes and the implementation of safe drainage, allows us to avoid tragic consequences.

In addition to Earth remote sensing data, field observation materials are used to analyze the dynamics of lakes and glaciers, such as depth surveys, which can be used to obtain information about the lake volume; data on the level regime, allowing you to establish the magnitude of fluctuations in water level both within a day and over a longer period of time; surveying the coastal areas relief of lakes to determine the lake basin configuration and the level of high waters; field meteorological observations of temperature and humidity of air and precipitation; glacier ablation value to assess the inflow of glacial meltwater into the lake; inspection of the dam. Field materials make it possible to study in more detail the hydrological regime of periglacial lakes, to identify the main trigger mechanisms of a possible outburst (Kasatkin, 2014; Aleynikova, Anatskaya, 2019; Pryakhina et al., 2021; Rasputina et al., 2022; Medeu et al., 2022), and also obtain the necessary information for further mathematical modelling of lake outbursts (Wang, 2008; Kidyaeva et al., 2017; Rasputina et al., 2021b; Yudina (Kurovskaya) et al., 2022).

An important issue related to the study of outburst hazardous lakes is the study of the process of lakes formation, their evolution and description of the development stages of lakes. At the present time, little attention is paid to this topic, and scientific works devoted to the development of moraine and periglacial lakes are few (Zimnitsky, 2005; Chernomorets et al., 2007; Torgoev et al., 2013; Dokukin and Khatkutov, 2016; Aleynikova, Anatskaya, 2019; Pryakhina et al., 2021; Rasputina et al., 2022). It is worth noting the work (Zimnitsky, 2005), in which the author describes the development stages of periglacial lakes: transgressive and regressive. The article (Pryakhina et al., 2021) examines the formation and development stages of the periglacial Lake Nurgan (Northwestern Mongolia): transgressive (growth of the lake, increase in its area and volume), regressive (the lake outburst) and post-regressive (existence of the lake after the outburst) stages.

Quite a lot of scientific works related to the study area considered in this thesis (the Altai mountainous country) are devoted to the analysis of the paleolakes dynamics and the formation of superfloods (Rudoj, 1981; Butvilovsky, 1985; Rudoj, Korolev, 1984; Rudoj, Kiryanova, 1994;

Borodavko, Akhmatov, 2006; Zolnikov et al., 2023). However, there is practically no work related to the development of modern periglacial and moraine lakes.

1.2. Assessment of the outburst hazard of moraine-dammed lakes

When studying moraine-dammed lakes, an important issue is the classification of lakes according to the outburst hazard degree, which is confirmed by the wide distribution of studies devoted to assessment of the lakes outburst hazard (Huggel et al., 2004; Richardson, Reynolds, 2000; Wang et al, 2008; Kidyaeva, 2014; Viskhadzhieva , Chernomorets, 2015; Erokhin and Zaginaev, 2020). Ranking of lakes according to the outburst hazard degree is usually carried out according to the criteria for outburst hazard (Rounce et al, 2016; Agarrwal, 2016; Erokhin, Zaginaev, 2020) and using the scoring method. In these cases, the probability of an each specific moraine-dammed lake outburst is a function of a set of dam stability parameters and the result of the influence of an external trigger (Petrakov, 2008; Torgoev et al., 2013; Rasputina et al., 2021a).

Petrakov D.A. in (Petrakov, 2008) proposed a scheme for assessment of the lake outburst probability based on multifactor analysis and the use of an interval scale in accordance with the methodology of Yu.G. Simonov (Simonov, 1997). Each factor influencing an outburst has a weight from 0 to 100 points. The probability of lake outburst (low, medium or high) is a function of the stability of the dam and the impact of the external trigger (Richardson and Reynolds, 2000). According to Petrakov D.A., the dam stability depends on the dam type, the height of the dam lowest point above the water edge, the ratio of the dam width to the dam height, the type of flow from the lake through the dam and the lake volume.

External triggers affecting the dam stability may be different depending on the regional features of the territories for which the outburst hazard is assessed. External triggers often include waves formed during avalanches, landslides, and the breaking off of a glacier parts; extreme heat and rainfall.

Ranking of lakes according to the degree of an outburst probability can be carried out according to outburst hazard criteria, such as type flow through the dam, rise in water level, condition of the moraine dam, cascading, etc. The study (Erokhin, Zaginaev, 2020) provides criteria in accordance with the lake type (glacial, moraine-glacial, moraine-rigel, landslide): the existence of an intraglacial flow channel in the dam body, icefalls, underground flow through the dam, lake filling, large amplitude fluctuations in water level in a lake. Given a certain set of criteria, a lake is classified into one of four hazard categories.

Earth remote sensing data is most often used to the outburst hazard assessment of a large number of lakes (Agarrwal et al, 2016; Rounce et al, 2016). However, from satellite images it is not possible to determine the water volume of the studied lakes, on which the dam stability depends. The work (Konovalov, 2009) outlines a method that makes it possible to determine the characteristics of the regime of outburst high-mountain lakes in the Pamirs (area and volume of lakes, maximum discharge of the outburst wave) using remote information. Formulas for calculating the lake volume were obtained based on the morphometric characteristics of 141 high-mountain lakes and have the following form:

$$V_1 = a_1 H_{max} + b_1 F + c_1, \tag{1.1}$$

$$V_2 = a_2 H_{mean} + b_2 F + c_2, \tag{1.2}$$

where V – lake volume, million m^3; H_{max} и H_{mean} – the maximum and average lake depths, respectively, m; F – lake area, km^2; a_1, b_1, c_1 – the coefficients given in (Konovalov, 2009) are determined depending on the size of the lake area.

Determination of the maximum depth using Earth remote sensing data is carried out on the basis of the statements that: the maximum depth is located near the middle of the lake, the longitudinal vertical profile of the lake depth from its beginning to the dam can be approximated by a semi-ellipse inscribed in a right triangle. The maximum depth of the lake is calculated according to the expression:

$$H_{max} = \frac{L}{2} \frac{1}{tg\left(arctg(L/H_2)\right)}, \tag{1.3}$$

where L – lake length, m; H_2 – the difference between the absolute height of the water edge at the dam and the lower elevation of the dam, m.

The determination of the outburst flood maximum discharge was carried out according to the formula (Costa, 1985):

$$Q_{max} = 3.8(\Delta ZV)^{0.61}, \tag{1.4}$$

where ΔZ – dam height; V – lake volume.

In (Agarrwal, 2016), the lake volume is determined using empirical dependencies.

The work (Viskhadzhieva, Chernomorets, 2015) is aimed at danger assessment of the mudflow processes development that arise as a result of glacial lakes outbursts in the Shakhimardan River basin (the Alai Ridge, Kyrgyzstan and Uzbekistan) and the province of Badakhshan (Hindu Kush, Afghanistan). For the assessment, an inventory of lakes in the study areas was first carried out using Landsat-8 satellite images, followed by compiling a catalog of lakes, and then their outburst hazard was assessed. The parameters influencing the lakes outburst hazard were determined using a method developed by a team of authors (Dokukin M.D., Savernyuk E.A., Chernomorets S.S.). The results of the assessment showed that for the study territory more than half of the basins with lakes are potentially hazardous.

The advantage of the outburst hazard assessment using Earth remote sensing data is that it is quite simple and can be used to analyze the outburst hazard of a large number of lakes. However, the disadvantage is that it is not possible to determine from satellite images the lake volume needed to complete the assessment. Calculation of the water mass volume using empirical formulas can have significant discrepancies with real data, since often the ratios for determining the water volume are obtained as a result of statistical analysis of morphometric data of a certain group of lakes located within the specific region, thus the empirical formulas are regional. Thus, in a scientific study presented in (Rasputina et al., 2021a), potentially outburst hazardous moraine-dammed lakes were identified in the area of the Mongun-Taiga mountain ridge (South-Eastern Altai, Russia, Tyva Republic) using a scoring method, which was supplemented with taking into account regional features based on Earth remote sensing data and field data. When comparing the calculated volume using empirical formulas and real data, it was found that the error in determining the water volume using empirical expressions reaches 216%. The authors of the article (Huggel et al, 2004) point out errors in determining the water volume calculated using formulas: the large lakes volume may be underestimated, and small lakes volume, on the contrary, may be overestimated. This allows us to conclude that ranking lakes according to the outburst hazard degree, performed using remote data, is not always effective, so it is necessary to use other approaches to assess the outburst hazard. For example, Kidyaeva V.M. in her thesis (Kidyaeva, 2014) to assess the lakes outburst hazard proposed an integral scale of five classes for zoning the potential hazard of an outburst, which depends on the integral index of outburst hazard (is a function of the lake volume, the shear stability coefficient and the ratio of the dam height to the water edge to the dam height) and the intensity of the resulting floods. The results of the performed assessment are comparable with field data. And in the work (Pryakhina et al., 2022) the typification of lakes by outburst hazard is carried out using the method of constructing composite indices based on territorial determinants for lakes of the Antarctic oasis Larsemann Hills based on the following criteria: the type of the flow through the dam, the dam type, cascading, frequency of occurrence of outbursts, the infrastructure of settlements in the coverage area, the sum of air temperatures above 0^0C, the sum of precipitation for the warm period and for the previous cold period. The typification of lakes performed using the proposed method is consistent with actual observation data. This approach includes data that can be obtained from satellite images, and data on air temperature and precipitation from the nearest meteorological stations and seems to be more effective compared to those previously considered and can be used to assess the outburst hazard of periglacial and moraine-dammed lakes.

1.3. Identification and study of trigger mechanisms influencing outburst

When studying the formation of the outburst flood process resulting from a lake outburst, it is necessary to establish what trigger mechanism can lead to the dam destruction. According to published scientific works (Awal et al, 2011; Liu et al, 2013; Wastoby et al, 2014; Gurung et al, 2017; Begam et al, 2018; Chernomorets et al, 2018; Neupane et al, 2019; Zheng et al, 2020; Dokukin et al., 2020; Dokukin et al., 2022) triggers leading to a decrease in the dam stability are:

1. intensive inflow of melted glacial waters into the lake or precipitation, which will result in an increase in the water volume, an increase in the water level of the lake, which can lead either to overtopping of the lake and subsequent overflow, or to an increase in pressure on the moraine dam and intensive filtration through the dam body, its weakening

and outburst; if there is a filtration drainage channel, its expansion may occur with subsequent drainage of the lake;

2. in the case of a cascade arrangement of periglacial and moraine-dammed lakes, the overflow of the lake located below and its subsequent outburst can occur due to the inflow of a large amount of water as a result of the lake outburst located higher in the cascade;
3. melting of ice cores in the moraine dam, which leads to a decrease in its stability and subsequent destruction;
4. calving parts of the glacier, ice blocks movement, snow avalanches and landslides, collapses of moraine material and large boulders can weaken the moraine dam and lead to its destruction and further the lake outburst.

An analysis of published scientific studies has shown that the most common trigger mechanisms for outburst are the formation of a filtration channel in the moraine dam body and the water overflow over its crest as a result of overtopping the lake (Grabs, 1993; Liu et al, 2013).

1.4. Calculation of outburst flood characteristics

The most important direction in the study of moraine-dammed lakes outbursts is the mathematical modelling of outburst floods. Mathematical modelling is carried out both to obtain an outburst flood hydrograph at the site of the breach, and to assess the characteristics of mudflows formed during catastrophic descents of lakes, as well as to establish the boundaries of territories exposed to the effects of the outburst flood and the associated mudflow.

Most often, to calculate the outburst floods characteristics and associated mudflows, predictive calculations of the transformation of wave movement and determination of flood zones, as well as measures to prevent and minimize the consequences of floods and mudflows, mathematical models are used, which, depending on the method for determining flow velocities through the breach, can be divided into two groups. The first group includes models based on systems of hydrodynamic equations (systems of Navier-Stokes and Saint-Venant equations): FLO-2D (O'Brien et al., 1993; Nie et al., 2020; Kidyaeva et al., 2021; Raimbekov and al., 2021; Kurovskaia et al., 2022; Yudina, 2022), RAMMS (Christen et al., 2010), HEC-RAS, STREAM-2D model (Belikov, Militeev, 1992; Kidyaeva et al., 2017), STREAM- 2D CUDA (Aleksyuk, Belikov, 2017). The second group includes models in which the flow velocity through a breach is calculated using the broad-crested weir formula (a broad crested weir and an ogee-crested weir) depending on the stage of the breach formation, for the calculation of which equations of erosion and soil mechanics are used (Fread, 1988; Mohamed et al, 2002; Zagongolli, 2007; Osti, Egashira, 2009; Chang, Zhang, 2010; Zhong et al, 2018).

To estimate the maximum discharge during the destruction of moraine dams, empirical formulas are often used, which are obtained as a result of regression analysis of data on historical dam outbursts (Wahl, 2010). These formulas are also used to estimate the construction of a complete outburst hydrograph, given the known hydrograph shape and the outburst flood volume that can pass through the breach. The most common hydrograph shape is triangular (Zhang at al, 2021). As empirical relationships for calculating the maximum discharge of an outburst flood, its functional dependences on the lake volume or on the dam height are used. Using empirical formulas, it is also possible to determine the time it takes for an outburst flood to pass, depending on the lake volume and the height of the resulting breach. In (MacDonald, Langridge-Monopolis, 1984; Evans, 1986; Costa, Shuster, 1988; Froehlich, 1995) provide various empirical relationships for calculating the maximum discharges and the period of passage of an outburst flood, which are most often used in calculations.

Thus, according to (Froehlich, 1995), the value of the maximum discharge and the time of passage of the outburst are determined as:

$$Q_p = 0.607V^{0.295}h_w^{1.24} \tag{1.5}$$

$$T_p = 0.00254V^{0.53}h_b^{-0.9}. \tag{1.6}$$

According to (MacDonald, Langridge-Monopolis, 1984), the outburst flood maximum discharge is calculated using the following formula:

$$Q_p = 1.154(Vh_w)^{0.412}. \tag{1.7}$$

In (Evans, 1986) the relationship for maximum discharge is:

$$Q_p = 0.72V^{0.53}, \tag{1.8}$$

where Q_p – maximum discharge, m^3/s; T_p – outburst flood time period; V – water volume, m^3; h_w – water depth above the breach at the moment of destruction, m; h_b – depth breach, m.

In the study (Costa, Shuster, 1988), depending on the dam type, different empirical relationships are given for calculating the outburst maximum discharge. When a moraine dam is destructed, the discharge is calculated as:

$$Q_p = 0.0000069(PE)^{0.73}, \tag{1.9}$$

and when an ice dam is destructed:

$$Q_p = 0.0000055(PE)^{0.59} \tag{1.10}$$

Q_p – maximum discharge, m^3/s; PE – potential energy (J).

The advantage of empirical formulas is the simplicity of calculating maximum discharges, which makes it possible to quickly estimate their values for a large number of outburst hazardous moraine-dammed lakes. For example, an assessment of the outburst floods discharge in lakes of the Bolivian Andes based on the empirical relationships proposed in (Evans, 1986) was carried out in (Kougkoulos et al, 2018). However, the main disadvantage of this approach is that the calculation equations do not include parameters related to the erodibility of the material from which the dams are made, and which affect the time of erosion of the dam and, accordingly, the time of passage of the outburst flood and the discharge value. Also, the formulas do not take into account the trigger mechanisms for lake outburst.

Most often, empirical formulas are regional ratios, that is, they can be used to estimate water discharge and outburst time only for lakes in the region for which the formula was developed.

Despite these disadvantages, empirical relationships have found wide application in modelling lake outbursts. In particular, when using such well-known models as MIKE-11, HEC-RAS, FLO-2D, RAMMS to simulate the outburst wave movement along the valley and subsequent construction of flood maps. The mentioned models do not simulate the dam destruction, therefore, data obtained using empirical relationships on the cross-sectional area of the flow, the breach width, and the outburst time are used as the initial and boundary conditions (Froehlich, 1995; Cook, Quincey, 2015; Aggarwal et al, 2016; Zhang et al, 2021).

Note that the outburst flood hydrographs specified in this case as initial information for modelling have a simplified triangular shape and are set under the assumption of the possible the outburst flood volume and the time of the outburst, which does not always reflect the real conditions of the process (Raimbekov et al, 2021; Zhang et al, 2021).

The work (Wang et al, 2008) for previously outburst periglacial moraine lakes located in the Chinese Himalayas compares the results of water discharges calculations performed using the BREACH model (Freed, 1998) and using empirical formulas of different authors (Popov, 1991; Evans, 1986; Walder, O'Connor, 1997; Huggel et al, 2002; Costa, Shuster, 1988; Clague, Evans, 2000), which made it possible to establish which empirical formulas are best used to calculate the outburst flood hydrograph. The error in calculating the maximum discharges using the BREACH model was the smallest compared to the water discharge values obtained using empirical formulas. A similar approach was used in studies by German scientists (Mergili et al, 2011) when modelling the outburst floods movement of potentially outburst hazardous lakes of the Pamirs (Tajikistan). Modelling was carried out taking into account different scenarios for the development of outburst events using the RAMMS and FLO-2D models. As initial conditions, the RAMMS model was set to the maximum water discharge, calculated on the basis of empirical formulas according to (Evans, 1986; Costa, 1988; Costa, Schuster, 1988; Manville, 2001; Huggel et al, 2004), and the outburst volume at this discharge , and in the FLO-2D model - the calculated input outburst flood hydrograph. When comparing the simulation results with each other, it was concluded that the FLO-2D model better reproduces the outburst process.

In a number of works, the outburst flood hydrograph is first modeled, and then the movement of the flow (mudflow) through the valley is simulated using another model. For example, in (Maskey et al, 2020), the modelling of the outburst flood hydrograph was carried out using the NWS-BREACH model, and the construction of flood maps was carried out in the two-dimensional HEC-RAS model. In the work of Chinese and English scientists, the outburst flood modelling of the moraine lake Chongbaxia Tsho (the Eastern Himalayas) is carried out using a physically-based numerical model DL Breach. The resulting outburst hydrograph was used as the initial conditions in a mathematical model based on the shallow water equation to simulate the movement of the outburst wave (Nie et al, 2020).

The article (Yudina, 2022) discusses the use of a chain of mathematical models (lake outburst model, transport-shear model of mudflow formation and FLO-2D model) to calculate the mudflow for the case of an outburst of Lake Bodomdara Nizhneye (Tajikistan). For mathematical modelling, the FLOVI programme is first used, developed by the author of the article, which combines a model for calculating the lake outburst hydrograph through an intraglacial channel, developed by Yu.B. Vinogradov, and a transport-shear model of mudflow formation. The FLOVI programme allows you to obtain an outburst hydrograph and a mudflow wave hydrograph, which are used as input data for calculating the characteristics of a mudflow in the FLO-2D hydrodynamic model.

In some scientific works, mathematical modelling of the outburst flood hydrograph formed during lake outbursts is carried out using the model of Yu.B. Vinogradov (Vinogradov, 1977), which is based on equations describing the formation of an intraglacial channel. The model is designed to simulate outbursts of glacier-dammed lakes. Based on the model of Yu.B. Vinogradov calculated a hypothetical outburst of Lake Bashkara through an intraglacial tunnel in that part of the lake that is dammed by a glacier (Gnezdilov et al., 2007). The maximum modeled outburst flood discharge was 123.5 m^3/s 4.5 hours after the start of the outburst. During the real outburst of Lake Bashkara on September 1, 2017, the estimated maximum discharge was 600 m^3/s, which is much higher than the modeled discharge. Limitation of the use of the model by Yu.B. Vinogradov is that a lake cannot always be dammed by a glacier or a dam, within which a large amount of ice cored, is distributed. If the dam is composed of loose moraine material, then this mathematical model cannot be used to simulate an outburst.

Let us note the STREAM-2D CUDA software package (Aleksyuk, Belikov, 2017), which is based on a two-dimensional system of Saint-Venant equations and models the outburst of a soil dam taking into account the heterogeneous composition of the soil (an arbitrary number of fractions is specified). The mathematical model was tested using the results of laboratory experiments, which showed that the modelling results are in good agreement with experimental data. The software package has proven itself well in performing calculations of outburst floods of artificial soil dams (Vasilieva, 2021). However, this mathematical model has not been used to calculate the characteristics of outburst floods during outbursts of moraine-dammed lakes.

In the work (Begam et al, 2018), an integrated model is used to simulate the outburst flood of a moraine-dammed lake as a result of overflow, the verification of which was first carried out on physical experiments of soil dam outbursts, after which the modelling was carried out on a real moraine lake located in the mountains of Tajikistan.

1.5. Chapter Conclusions

The analysis of published Russian and foreign scientific works showed the lack of methods for calculating the characteristics of an outburst flood wave formed during outbursts of moraine-dammed lakes, which would include several mechanisms of a lake outburst and take into account the heterogeneous composition of the moraine dam.

The hydrodynamic models FLO-2D, RAMMS and HEC-RAS are currently most used to simulate the movement of outburst flood waves, in which the input the outburst flood hydrograph at the dam site is introduced as the initial and boundary conditions. However, in these models the outburst hydrograph is not calculated, but is specified schematically or calculated using simplified formulas that do not take into account the process of dam destruction, which is their limitation. The schematization of the hydrograph does not take into account the morphometric characteristics of lakes, the characteristics of the moraine from which the dam are made, the erodibility of the moraine and the trigger mechanisms that resulted in the outburst, which reduces the physical validity of the calculations. The Russian hydrodynamic model STREAM-2D CUDA (Aleksyuk, Belikov, 2017) simulates an outburst wave taking into account the heterogeneous composition of the soil and has proven itself well in calculating the outburst wave during accidents on artificial dams, but this model has not been used to simulate a outburst flood resulting from the moraine-dammed and periglacial lakes outbursts.

It was also found that very little attention is paid to the study of the development of high-mountain moraine-dammed and periglacial lakes, as well as to the description of their hydrological regime due to insufficient knowledge of mountain areas, and, consequently, the lack of observational data. At the same time, a description of the stages of development of moraine lakes, and mainly the features of the level regime of lakes of different stages, would make it possible to obtain more detailed information about the lake and assess its further development, including determining its potential outburst hazard, information about which is necessary in the conditions ongoing climate change and intensive development of mountainous areas.

Chapter 2. Methodology for calculating the outburst flood characteristics resulting from a moraine-dammed lake outburst

2.1. Formation of an outburst flood resulting from moraine-dammed lakes outbursts

Moraine dams that dammed periglacial and moraine lakes are among the weak natural dams. The material, which most moraine dams is consisted, sand, and boulders with minimal clay content. Most moraine dams have steep slopes (some exceeding 40°) (Awal et al, 2011).

The moraine lake maintains a balance between the flow of meltwater into the lake and the water filtration through the dam body. In the warm season, when the amount of meltwater entering the lake increases, the water level in the lake increases due to the fact that the water does not have time to filter through the moraine at the same velocity as the meltwater entering the lake (Liu et al, 2013). In addition, ice blocks or stone boulders entering the lake may cause an increase in the water level in the lake. The most common causes of outbursts are the overflow of the lake and the water filtration through the dam body (Costa, Schuster, 1988).

The outburst flood that occurs when lakes outburst through poses a serious hazard to the downstream territory, often causing mudflows.

Common triggers for triggering a moraine-dammed lake outburst mechanism can be:

- The presence of an ice core in the moraine dam, the melting of which will lead to a decrease in the dam stability.
- Intensive inflow of glacial meltwater or large amounts of precipitation, which will result in an increase in the lake volume. An increase in the water volume will be accompanied by an increase in water level. An increase in the water level in the lake to the level of the moraine dam crest can lead to overtopping of the lake and subsequent water overflow over the dam crest, or to intensive water filtration through the body of the moraine dam.
- A large water volume entering the lake due to a moraine-dammed lake outburst located upstream (in the case of a lakes cascade) can lead to overtopping of the lake.
- Dynamic movement of ice blocks, snow avalanches and landslides, collapses of moraine material and large boulders can affect the moraine dam stability.
- Loose moraine material from which the dam is constructed.

An analysis of published scientific studies has shown that the most common trigger mechanisms for outburst are the formation of a filtration channel in the moraine dam body and the overflow of water over its crest as a result of overtopping of the lake (Grabs, 1993; Liu et al, 2013), so they are considered in detail in this study.

The process of a moraine dam erosion during overflow

The process of the moraine dam destruction during overflow occurs as follows: a water flow is formed along the moraine dam body (Fig. 2.1). If the velocity of the resulting flow is greater than the non-erosion velocity, then the flow will begin to erode the damming dam and carry out moraine material, which will indicate the beginning of an outburst (Liu et al. 2013). As a result of a moraine dam erosion by water, its destruction begins and an initial small breach is formed in the place where the moraine material is most loose. The profile of the breach when a moraine lake outbursts through will depend on the duration of the water overflow and the characteristics of the material from which dam is composed. According to the experimental results presented in (Zhong-xin et al, 2004; Liu et al, 2013), it was revealed that the initial breach is formed in the upper part of the dam, in the middle of the crest, where the maximum water pressure is observed. If the duration of overflow is short, then erosion will be weak and the breach development will occur slowly.

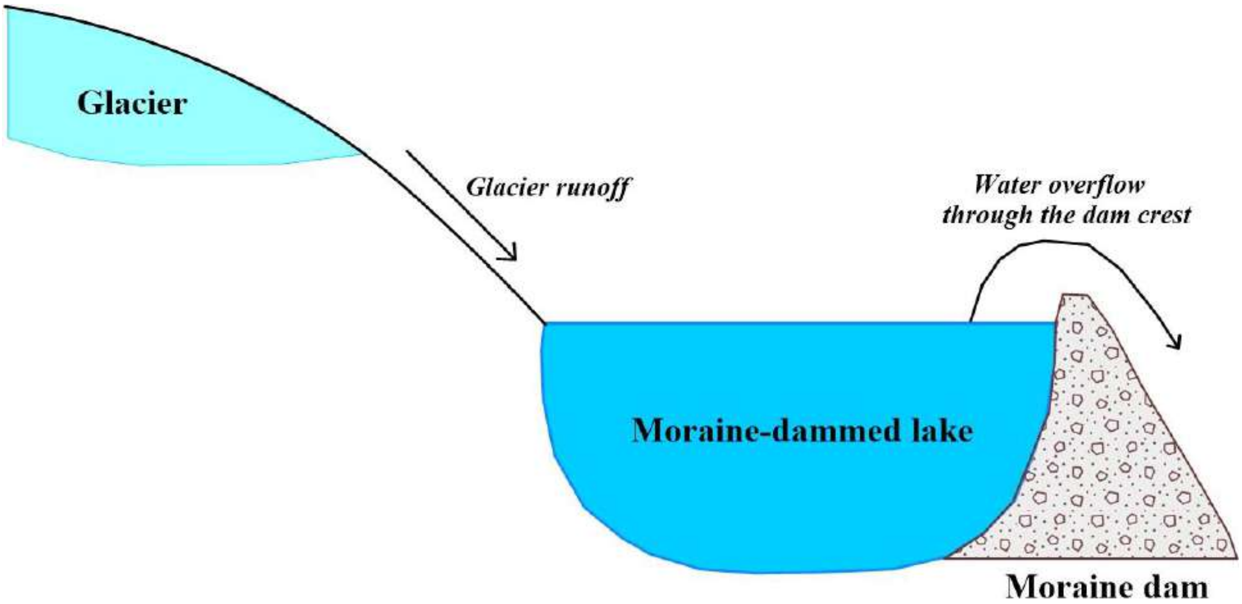


Fig. 2.1. A moraine-dammed lake outburst due to water overflow through the dam crest.

The process of a moraine dam erosion during the formation of a filtration channel

When a filtration channel is formed in the moraine dam body, the process of its destruction is as follows (Fig. 2.2): the seepage of water into the moraine dam body causes wetting of the moraine material and a gradual weakening of the adhesion forces of the particles of the material from which the dam is composed. This causes internal erosion of the dam, resulting in the formation of drainage channels filled with lake water. Water will accumulate in the dam body until a breach is formed and a subsequent outburst occurs. During an outburst, water will begin to flow out of the lake through the formed drainage channel and erode the dam body, carrying out moraine material along with the flow. The part of the moraine dam located above the breach will become unstable as a result of erosion, which will lead to its sliding or collapse and the subsequent formation of an outburst flood (Liu et al, 2013, Neupane et al, 2019).

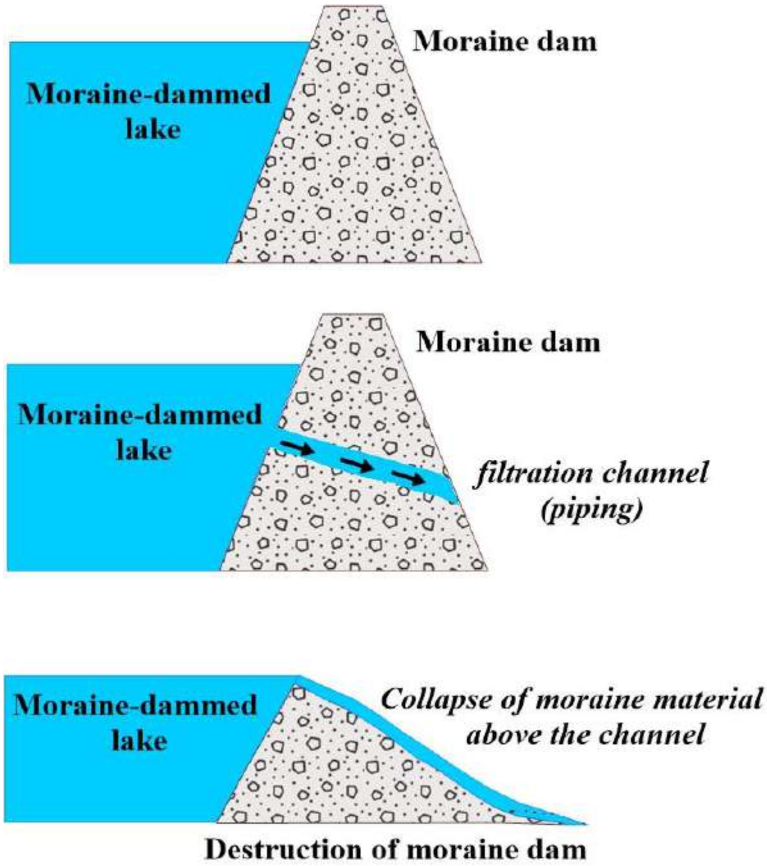


Fig. 2.2. Stages of a moraine-dammed lake destruction as a result of erosion of the filtration channel.

2.2. Heterogeneous composition of moraine dams

The investigation of moraine deposits and their changes over time is of significant interest from the point of view of geology, paleogeography, glaciology and hydrology. The granulometric composition of moraines is characterized by multi-fractionation, unsorted material, expressing the absence of mechanical differentiation of the constituent parts. In general, moraines are composed of unsorted loose rock fragments, most often boulders, sandy loams, and loams.

From a hydrological point of view, the most interesting is the analysis of the structure and composition of moraine deposits which compose of damming dams of periglacial and moraine lakes, because the internal structure of a moraine dam is an important link in the study of outburst floods and their prediction, since the composition and structure of the dam the process of its possible destruction depends. In all scenarios for the outburst development, it is necessary to obtain detailed information about the internal structure of the dam, the granulometric composition of particles, and the depth distribution of particles of different sizes, since the time and erosion rate of the dam, which affect the values of water discharge, depends on this. The particle size of the moraine material ranges from coarse sands (0.5–1 mm) to large boulders (>1000 mm).

Most often, the moraine dam damming the lake is the terminal moraine. The terminal moraine usually takes the form of a ridge that contours the glacier margin in a regular arc, and which is formed when the glacier margin stabilizes or moves slowly. In mountain glaciers, the accumulation of fragmental material before the glacier margin by shedding determines the lack of elementary orientation in the location of moraine fragments. The fragmental material has no layering or sorting; large blocks are mixed with glacial deposits of various shapes and sizes (Ivanovsky, 1981).

To study the internal structure of a moraine dam, the method of ground penetrating radar and electrical sounding is often used, which make it possible to find out what the moraine dam is made of based on resistivity values. The work (Ohashi et al., 2012) presents the results of electrical sounding of moraine lakes dams. The results show that different materials (wet, dry, including buried ice cores) have different resistivity. Thus, buried ice has the highest resistivity value.

Terminal moraines of Altai are characterized by the difference in morphology and moraines composition of ancient stages from younger moraines (Holocene ones). Young moraines have a short length, the height of the moraine lines does not exceed 20-30 m. Young moraines are composed of large fragments, rubble and loam.

The small amount of glacial silt in young moraines may depend on the small size of the glacier, which does not have time to grind a large amount of rock. Also, a small amount of finely dispersed material is observed in glaciers that do not have noticeable bends in the subglacier floor (Ivanovsky, 1962). Small glaciers with a steep fall or squeezed into very narrow valleys provide much more fine-grained material. If we compare small glaciers with each other, then those glaciers that are located in very narrow rocky valleys with a steep fall supply much larger quantities of fine-grained material.

In Little Ice Age moraines, the distal slopes of the frontal lines are steep and straight, the bases are clear and uneroded. This case is typical for terminal-moraine complexes, in which the frontal line is not eroded by a glacial stream; runoff occurs by filtration through the moraine (Parzhayuk, 1997).

Since the moraine dam damming the lake may contain buried ice cores, it becomes an important question to establish the presence of a core in the dam body. An indirect sign of the presence of dead ice in the dam is the hilly-moraine relief. When ice cores melt, a redistribution of moraine material occurs, as a result of which an inversion relief is formed (Markov, 1955).

Since there is no clearly expressed structure and division into fractions in the moraine dam, a new approach is proposed to take into account the heterogeneous composition of the dam during calculating the characteristics of an outburst flood formed due to a moraine lake outburst.

The approach is based on the results obtained within the framework of complex geographical expeditions of the Institute of Earth Sciences of St. Petersburg State University. In 2019, 2021, 2022 and 2023 the author of the thesis took part in field research. As part of the field work, a visual survey of the moraine deposits from which the dams are composed, and soil samples were taken to determine the granulometric composition. Unstable moraine lakes, which have active temporal dynamics, are young lakes formed during glacier retreat on young moraine deposits and on the Little Ice Age moraines, which differ from older and more ancient moraines in their lack of stability (Fig. 2.3, 2.4).

Fig. 2.3. Photos of moraine dams of Lake Barsovo (a), Gachy-Kol (b) and moraine deposits of the northern slope of Tavan-Bogdo-Ola (c). Photo by *Rasputina V.A.* and *Bantcev D.V.*

Fig. 2.4. Photos of the Little Ice Age moraine deposits (young moraines). Photo by *D.V. Bantcev*.

According to the analysis of the young moraine deposits structure (Fig. 2.3 and 2.4), it was revealed that the main part of the dam is an embankment composed of fine-grained material (sandy loam, loam). The crest and front of the moraine dam is covered with large boulders of various sizes (10-100 cm) (Fig. 2.3a, b). A similar structure of moraines is shown in other photographs (Fig. 2.3c, 2.4a, b, c).

Thus, it can be assumed and accepted that almost the entire moraine dam consists of mixed fine-grained material (sandy loam, loam, gravel). The dam crest may be covered with boulders. For this case, a new scheme for erosion of the moraine dam was proposed (Fig. 2.5).

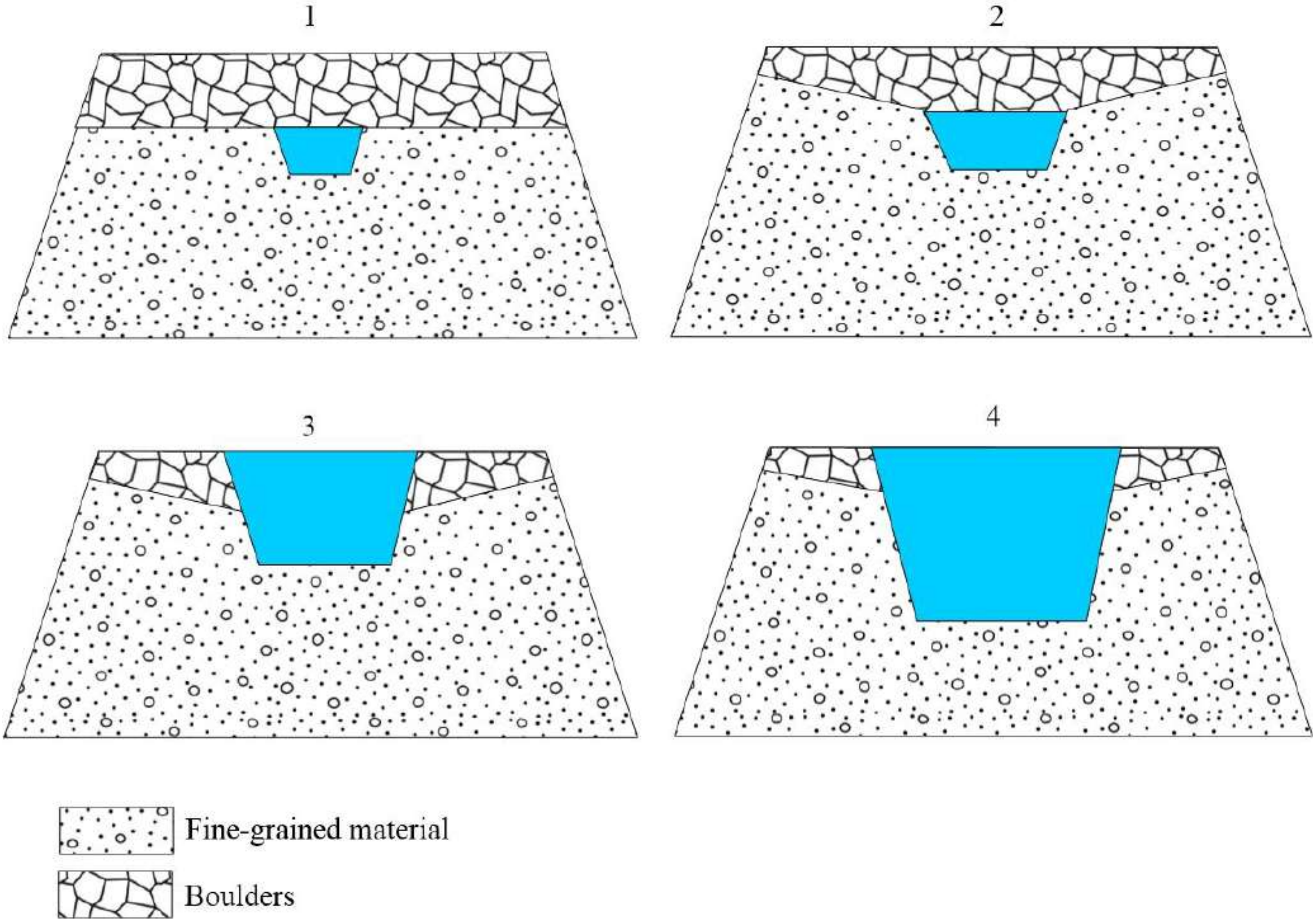


Fig. 2.5. Stages of formation of a breach in the moraine dam body in the case when the crest is blocked by large boulders.

When the lake is overtopped, water begins to overflow over the dam crest. Since the crest is covered by boulders, between which there are vast spaces and cracks, the water begins to seep through these cracks between the boulders until it reaches the fine-grained fraction. In this case, classic erosion as a result of water overflow, as in artificial soil dams, does not occur, but the dam destruction occurs through the formation of a channel under boulder piles (another variation of destruction as a result of the formation of a filtration channel (piping)).

Then the fine-grained material is eroded and carried away, which leads to the formation of a breach. In this case, the boulders that are located above this breach, at the beginning of erosion, settle at the bottom of the breach, and then, when high flow velocities are reached, the water flow can carry them out.

Since the fine fraction of moraine deposits may contain loam, sandy loam, gravel, etc. each individual fraction has its own erosion rate *E(t)* (Hanson, Simon, 2001; Attal et al., 2011), which depends on the value of the shear stress *τ(t)* initiated by the water flow and on the value of the critical shear stress τ_c.

The content of sandy loam, loam, and gravel in a moraine dam can be in different percentage ratios; in this case, it is necessary to take a soil sample to determine the granulometric composition at different points of the dam in order to obtain the average content of each fraction in the dam body in fractions of 1 (C_{cons}). By entering its soil characteristics for each fraction (specific gravity γ_s, plasticity index ξ, roughness coefficient n_s and Stickler coefficient *n*, porosity ς and clay content N), shear stresses initiated by water flow *τ*, critical shear stresses τ_c, and erosion coefficients *K* are determined. These characteristics determine the shear stress of water and the erosion rate for each fraction (the number of fractions can be from 1 to N):

$$\tau(t)_{i=1} = \rho_w g R(t) S(t)_{i=1}$$

$$.$$

$$.$$

$$\tau(t)_{i=N} = \rho_w g R(t) S(t)_{i=N},$$

since the specific gravity is $\gamma = \rho g$, the formula can be rewritten as:

$$\tau(t)_{i=1} = \gamma_w R(t) S(t)_{i=1} \tag{2.1}$$

$$.$$

$$.$$

$$\tau(t)_{i=N} = \gamma_w R(t) S(t)_{i=N}$$

γ – specific gravity of water, $S(t)$ - energy slope, which is also determined for each individual fraction.

Also, for all fractions in moraine material, the critical shear stress is calculated:

$$\tau_{c_{i=1}} = 6.8 {\xi_{i=1}}^{1.68} {\aleph_{i=1}}^{-1.73} {\varsigma_{i=1}}^{-0.97} \tag{2.2}$$

$$.$$

$$.$$

$$\tau_{c_{i=N}} = 6.8 {\xi_{i=N}}^{1.68} {\aleph_{i=N}}^{-1.73} {\varsigma_{i=N}}^{-0.97},$$

after which the erosion rate value is determined for each fraction:

$$E(t)_{i=1} = K_{i=1}\left[\tau(t)_{i=1} - \tau_{c_{i=1}}\right] \tag{2.3}$$

$$.$$

.

$$E(t)_{i=N} = K_{i=N}\left[\tau(t)_{i=N} - \tau_{c_{i=N}}\right].$$

The resulting erosion rate and the subsequent increase in breach are then calculated. The resulting erosion rate is expressed from the sum of the erosion rates for each fraction:

$$E_{sum}(t) = E(t)_{i=1} + \ldots + E(t)_{i=N} \qquad (2.4).$$

At the initial moments of time, the water flow velocities are small, at which not all soil particles can be carried out, but only those whose critical shear stress is less than the shear stress of water. And what proportion of these particles carried away by water is contained in the moraine dam, the expansion and deepening of the breach occurs to the same extent.

2.3. Description of the methodology for calculating the characteristics of an outburst flood, taking into account the heterogeneous composition of the moraine dam as a result of erosion of the filtration channel and overflow over the crest

This methodology is based on the following ideas about the outburst flood formation. Prolonged high water levels can cause water filtration through the moraine dam body. Water seeping through the dam body is leading to a weakening of the adhesion forces of the material from which the dam is made. The moraine dam has a heterogeneous structure, which affects erosion and the maximum water discharge. The seepage of water through the soil layer leads to the removal of particles by this flow, forming a filtration channel and initiating the beginning of a dam outburst. Moreover, at the initial moment of time, the water flow velocities have small values, at which not all soil particles can be washed out, but only those whose critical shear stress is less than the shear stress of water. And what fraction of these particles carried away by water is contained in the moraine dam, this fraction relative to unity is what causes the expansion and deepening of the channel. The channel is formed in the central part of the dam, and the channel is assumed to have a circular shape. At the initial moment of time, the channel diameter has a small value. As destruction occurs, the size of the resulting channel increases, resulting in an increase in its discharge capacity and, as a consequence, an increase in water discharge. With an increase in flow velocities and, accordingly, an increase in the erosion rate, a gradual expansion of the channel occurs until the width (diameter) of the channel reaches a critical value equal to 1/5 of the water height, since the formed arch cannot withstand the upper arch of the soil (Protodyakonov, 1931). When this critical value is reached, the part of the dam that is located above the channel will collapse, and this collapsed soil will be further removed by the water flow. After which the calculation is carried out as for overflow.

The subsequent destruction of the moraine dam is carried out by overflowing water from the moment when the soil collapse occurred. The water flow is concentrated at the point where the breach is formed, and the water rushes into it. Water from the lake begins to flow through the open channel.

The dam destruction and the breach development occurs unevenly from top to bottom due to the uneven distribution of flow velocities along the depth.

The proposed methodology differs from those previously developed by other authors in that with a simple approach to calculating flow velocities (surface spillway formula), the authors nevertheless take into account the distribution of velocities in depth, which significantly affects the process of dam destruction during overflow, and also takes into account heterogeneous composition of moraine deposits.

Water balance equation

Water balance equation for a reservoir in case of an lake outburst:

$$\Delta V = \Delta t(Q_{IN} - Q_B - Q_S),$$

or, moving to infinitesimal quantities,

$$\frac{\partial V}{\partial t} = Q_{IN}\Delta t - Q_B\Delta t - Q_S\Delta t, \tag{2.5}$$

where $Q_B(t)$, $Q_{IN}(t)$ и $Q_S(t)$ – these are the time-varying discharge through the breach, the discharge of the inflow entering the lake, and the discharge through spillways, respectively, $\Delta V(t)$ – change in the volume of a lake over time.

Calculation through the filtration channel

Water discharge through the filtration channel

It is assumed that the filtration channel has a circle shape and is completely filled with water. The water discharge through the channel over time will be calculated as:

$$Q_f(t) = \omega_f(t) v_f(t) \tag{2.6}$$

where $\omega_f(t)$ – cross-sectional area of the filtration channel, which is equal to $\frac{\pi D(t)^2}{4}$, where *D(t)* – channel diameter. The flow velocity is calculated according to (Chen et al., 2019) as $v_f(t) = \sqrt{\frac{2g(z_w(t) - z_{pip})}{h_f(t)}}$, where g – acceleration of gravity, $z_w(t)$ - flow water surface elevation, z_{pip} – channel center elevation, $h_f(t)$ - head loss along the length, which is calculated as $h_f(t) = \sqrt{1 + \frac{f(t)L}{4R(t)}}$, where *L* – channel length, *R(t)* – hydraulic channel radius, *f(t)* – parameter that depends on friction and is calculated as $f(t) = \frac{8g{n_s}^2}{R(t)^{1/3}}$, where n_s – roughness coefficient.

Calculation of erosion rates and channel development

Calculation of the erosion rate and sediment transport by water flow was carried out according to approaches (Hanson, Simon, 2001; Chang, Zhang, 2010; Attal et al., 2011), in which the erosion rate *E(t)* is determined by the shear stress on the eroded surface *τ(t)*, initiated by a water flow, and erosion occurs only when the critical value of the shear stress τ_c of the erosion rate is exceeded:

$$E(t) = K[\tau(t) - \tau_c], \tag{2.7}$$

where K – erosion coefficient,

$$K = \frac{10\rho_W}{\rho_S} exp\left\{-0.121\aleph^{0.406}\left(\frac{\rho_S}{\rho_W}\right)^{3.1}\right\}, \tag{2.8}$$

where ρ_S– density of dam material, ρ_W– water density, ℵ - proportion of clay content in the dam material.

To take into account the structure heterogeneity of the moraine dam during calculating the outburst, it is necessary to first determine how many fractions are contained in the moraine composition, and what proportion of each fraction C_{cons} is contained in the moraine dam (set this content in fractions). By entering its soil characteristics for each fraction (specific gravity γ_s, plasticity index ξ, roughness coefficient n_s and Stickler coefficient n, porosity ς and clay content N), shear stresses initiated by water flow τ, critical shear stresses τc, erosion coefficients K are determined, which in turn determine the shear stress of water and the erosion rate for each fraction (the number of fractions can be from 1 to N):

$$\tau(t)_{i=1} = \rho_w g R(t) S(t)_{i=1}$$

.

.

$$\tau(t)_{i=N} = \rho_w g R(t) S(t)_{i=N}$$

since the specific gravity $\gamma = \rho g$, then the formula can be written as:

$$\tau(t)_{i=1} = \gamma_w R(t) S(t)_{i=1} \tag{2.9}$$

.

.

$$\tau(t)_{i=N} = \gamma_w R(t) S(t)_{i=N}$$

γ – the water specific gravity, $S(t)$ - energy slope, which is determined for the average velocity and is calculated according to the following relationship also for each fraction:

$$S(t)_{i=1} = \bar{v}^2 {n_{i=1}}^2 [R(t)]^{-4/3} \tag{2.10}$$

.

.

$$S(t)_{i=N} = \bar{v}^2 {n_{i=N}}^2 [R(t)]^{-4/3}$$

where $\bar{v}$ – average water flow velocity, which is defined as $\bar{v} = \sqrt{2g(z_W - z_B)}$; n – The Stickler coefficient, which depends on the size of soil particles, is characterized by values in the range from 0.01 to 0.05 and is determined by the relation $n = (0.15/\sqrt{g})k^{1/6}$, where k – soil particle size.

To determine the critical shear stress τ_c, calculated for each soil fraction, we will use the relationship proposed in (Attal et al, 2011):

$$\tau_{c_{i=1}} = 6.8{\xi_{i=1}}^{1.68}{\aleph_{i=1}}^{-1.73}{\varsigma_{i=1}}^{-0.97} \tag{2.11}$$

.

.

$$\tau_{c_{i=N}} = 6.8\xi_{i=N}{}^{1.68}\aleph_{i=N}{}^{-1.73}\varsigma_{i=N}{}^{-0.97}$$

where ξ –plasticity index of dam soil, % (a characteristic reflecting the ability of the soil to retain water, for sandy loams will change within 1-7%, for loams 7-17%, for clays more than 17%), ς – porosity.

The calculation of the erosion rate was determined for each allocated N amount of fraction:

$$E(t)_{i=1} = K_{i=1}\left[\tau(t)_{i=1} - \tau_{c_{i=1}}\right] \tag{2.12}$$

.

.

$$E(t)_{i=N} = K_{i=N}\left[\tau(t)_{i=N} - \tau_{c_{i=N}}\right].$$

The resulting erosion rate is expressed from the sum of the erosion rates for each fraction:

$$E_{sum}(t) = E(t)_{i=1} + \ldots + E(t)_{i=N} \qquad (2.13).$$

The values of increments in the linear dimensions of the channel *l(t)* were determined by the formula (2.14):

$$l(t) = E_{sum}(t)\Delta t \tag{2.14}$$

The channel diameter is calculated as:

$$D(t)_i = D(t)_{i-1} + l(t)_i. \tag{2.15}$$

After the new channel diameter is determined, the new cross-sectional area of the channel is determined $\omega_{f\,i+1}$.

The water mark $z_w(t)$ is determined by the volumetric curve of the reservoir, which is assumed to be known, for example, from the results of a bathymetric survey, taking into account the leaked water and taking into account the possible replenishment of the lake:

$$z_W(t) = \mathbb{F}\left(\int_{t_0}^{t}[Q_{IN}(t) - Q_B(t) - Q_S(t)]dt\right) \qquad (2.16).$$

As soon as the channel width (diameter) reaches a critical value equal to 1/5 of the water height, the material located above the channel will collapse and be carried away by the water flow, after which the calculation will be carried out as for an overflow.

Overflow calculation

Water discharge through the breach

As an assumption, we assume that the water flow through the breach is close in parameters to the water flow through a broad crested weir and the initial cross-section of the breach after the collapse of the soil above the channel has a rectangular shape. Based on this, to determine the water flow through the breach at each time t, t > t_0, where t_0 is the initial time, the following equation is used:

$$Q_B(t) = \mu\omega(t)\sqrt{2gH(t)}, \tag{2.17}$$

where $\omega(t)$ - cross-sectional area of flow in the breach; μ - the flow coefficient, depending on the type of weir and its operating conditions, varies over a wide range (μ= 0,3÷0,6); g - acceleration of gravity; H - water height equal to the difference in water surface elevation in the flow $z_W(t)$ and the bottom of the breach $z_B(t)$ (fig. 2.6):

$$H(t) = z_W(t) - z_B(t). \tag{2.18}$$

Substituting expression (2.18) into equation (2.17), we obtain an equation for determining the water discharge through the breach at each moment in time:

$$Q_B = M\omega(t)\sqrt{z_W(t) - z_B(t)}, \text{ where } M \equiv \mu\sqrt{2g}\,. \tag{2.19}$$

The ratio for the calculation $\omega(t)$ depends on how the cross-sectional shape of the flow through the breach will be approximated, in other words, how the breach will develop. When modelling, its shape is most often approximated by a triangle or trapezoid (Zhong et al, 2018).

If D_T and D_B are the breach width in the upper and lower parts, and z_C is the dam crest elevation, then the cross-sectional area of the flow $\omega(t)$ and the breach $\Omega(t)$ at each moment of time can be represented as:

$$\omega(t) = \frac{D_T(t)+D_B(t)}{2}(z_W - z_B), \tag{2.20}$$

$$\Omega(t) = \omega(t) + D_T(z_C - z_W), \tag{2.21}$$

Then,

$$Q_B = M\frac{D_T(t)+D_B(t)}{2}(z_W - z_B)^{3/2},$$

or

$$Q_B = M\frac{D_T(t)+D_B(t)}{2}(\mathbb{F}(V(t)) - z_B)^{3/2}. \tag{2.22}$$

The increment in the linear dimensions of the hole caused by bottom erosion $\Delta l_B(t)$ is less than that of its side parts $\Delta l(t)$, since the velocity in the bottom layer is lower than the average value used in the calculation $\Delta l(t)$. To calculate the area of the cross-section of the flow $\omega(t)$ at an arbitrary moment of time t, t>t$_0$, its shape is approximated by a trapezoid, as the most often encountered when describing the shapes of breaches during outbursts (Fig. 2.6a). At the same time, in the process of deepening the breach, the side walls are undermined and collapse, as a result of which the cross section of the breach takes on a more complex shape (Fig. 2.6b). In practice, this means that the breach profile within the wetted perimeter remains trapezoidal, and rectangular at the top.

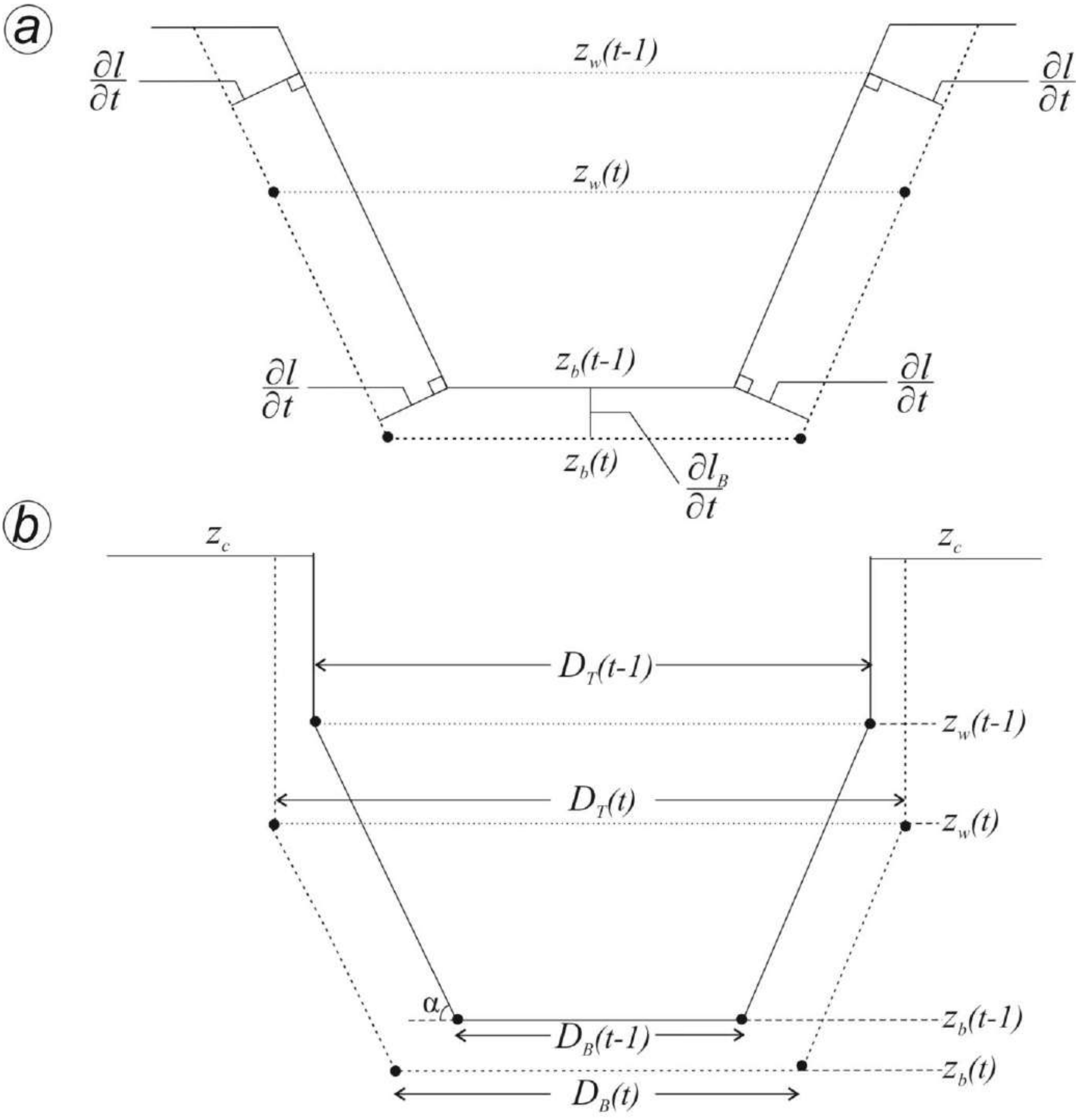


Fig. 2.6. Scheme for calculating the cross-sectional area of the flow (a) and the breach area (b). *Designations*: $D_T(t)$ and $D_B(t)$ - the breach width in the upper and lower parts respectively, $\frac{\partial l}{\partial t}$ - denudation rate corresponding to the average flow velocity, $\frac{\partial l_B}{\partial t}$ - denudation rate corresponding to bottom flow velocity, $z_W(t)$ and $z_B(t)$- water surface elevation and breach bottom elevation.

Thus, taking into account (2.20), (2.21) and (2.22), the rate of increase in the breach area can be written as follows:

$$\frac{\Delta\Omega}{\Delta t} = \left[2(z_C - \mathbb{F}(V(t))) + \sqrt{(D_T(t) - D_B(t))^2 + 4(\mathbb{F}(V(t)) - z_B(t))^2}\right]\frac{\Delta l}{\Delta t} + D_B(t)\,\frac{\Delta l_B}{\Delta t}. \quad (2.23)$$

The rate of increase in the linear dimensions of a breach formed in a heterogeneous dam is equal to the erosion rate $\boldsymbol{E(t)}$, which is determined similarly to formulas (2.9) - (2.13) and is the resulting value of the erosion rates for each fraction composing the moraine dam.

The energy slope $S(t)$, determined by formula (2.10) during water flows through a breach during overflow, is calculated both for the average flow velocity and for the bottom velocity v_B, which is calculated using the Karaushev equation (Bykov, Vasiliev, 1970), $v_B = \bar{v}\sqrt{1-\frac{z}{R(t)}\left(0.57+\frac{3.3}{C}\right)}$, where z - point immersion depth, C - коэффициент Шези, $\boldsymbol{R(t)}$ – hydraulic flow radius, calculated as:

$$R(t) = \frac{\omega(t)}{D_B(t)+\sqrt{(D_T(t)-D_B(t))^2+4(z_W-z_B)^2}},$$

or

$$R(t) = \frac{0.5(D_T(t)+D_B(t))(\mathbb{F}(V(t))-z_B)}{D_B(t)+\sqrt{(D_T(t)-D_B(t))^2+4(\mathbb{F}(V(t))-z_B)^2}} \quad (2.24).$$

Thus, the expression for the breach increment is:

$$\frac{\partial l}{\partial t} = K\eta(\mathbb{F}(V(t)-z_B)\left[\frac{D_B(t)+\sqrt{(D_T(t)-D_B(t))^2+4(\mathbb{F}(V(t)-z_B)^2}}{0.5(D_T(t)+D_B(t))(\mathbb{F}(V(t)-z_B)}\right]^{1/3}-\phi, \quad (2.25)$$

where $\eta \equiv 2\rho_w g^2 n^2$ и $\phi \equiv K\tau_c$

$$\begin{gathered}\frac{\partial l_B}{\partial t} = K\eta[\mathbb{F}(V(t)-z_B(t)]\left[\frac{D_B(t)+\sqrt{(D_T(t)-D_B(t))^2+4(\mathbb{F}(V(t)-z_B(t))^2}}{0.5(D_T(t)+D_B(t))(\mathbb{F}(V(t)-z_B(t))}\right]^{1/3}\times \\ 1-0.95[\mathbb{F}(V(t)-z_B(t)]\left[\frac{D_B(t)+\sqrt{(D_T(t)-D_B(t))^2+4(\mathbb{F}(V(t))-z_B(t))^2}}{0.5(D_T(t)+D_B(t))(\mathbb{F}(V(t))-z_B(t))}\right]\times \quad . \\ \left[0.57+3.3n_s\left(\frac{0.5(D_T(t)+D_B(t))(\mathbb{F}(V(t))-z_B)}{D_B(t)+\sqrt{(D_T(t)-D_B(t))^2+4(\mathbb{F}(V(t))-z_B)^2}}\right)^{-1/6}\right]-\phi\end{gathered} \quad (2.26)$$

The rates of change in the elements of the breach configuration $\frac{\partial l}{\partial t}$ and $\frac{\partial l_B}{\partial t}$ depend on constant values for each object K, η, ϕ и z_C, and are determined by relations (2.25) and (2.26), its changing linear dimensions D_T, D_B, z_B,, and also the water level z_W. The rate of change of values D_T and D_B is determined through $\frac{\partial l}{\partial t}$ and $\frac{\partial l_B}{\partial t}$ as:

$$\frac{\partial D_T}{\partial t} = 2\frac{\partial l}{\partial t}, \quad (2.27)$$

$$\frac{\partial D_B}{\partial t} = \frac{\partial l_B}{\partial t}. \quad (2.28)$$

The rate at which the water level falls and the water level z_W is determined by the volumetric curve $z_W = \mathbb{F}(V)$.

Substituting the obtained relations into (2.20) and numerically solving the resulting equation, we will find the configuration of the channel profile at each moment of time, and taking into account (2.22) we will obtain the time-varying discharge through it.

The proposed relations (2.5) – (2.28) were used as the basis for a computer program written in the MatLab environment. The block diagram for calculating an outburst flood during the development of a filtration channel is presented in Appendix 1, and the block diagram for calculating an outburst flood during an overflow is in Appendix 2.

The programme for calculating the outburst flood formed by the erosion of a filtration channel with the subsequent collapse of the soil above the channel, and the outburst flood resulting from the water overflow through the dam crest, is registered in the Register of Computer Programs (Rasputina and Pryakhina, 2022). A description of the methodology for calculating a reservoir outburst as a result of water overflow through the dam crest was published in (Rasputina et al., 2021c).

To test the calculation methodology for adequacy, as well as to establish to which parameters the mathematical model is most sensitive, a number of numerical experiments were carried out. Verification and testing of the proposed calculation algorithm was carried out using the results of physical experiments on the outburst of a soil dam and published data on real moraine lakes outbursts.

2.4. Chapter Conclusions

The methodology for calculating the characteristics of outburst floods developed as part of the thesis is based on the principles of hydraulics, erosion and soil mechanics and, according to the classification given in (Zhu et al, 2004), refers to physically based models of the formation of outburst floods. The main advantages of the developed calculation algorithm, in contrast to similar existing mathematical models, are:

1. taking into account the heterogeneous composition of the moraine dam (the approach to taking into account the moraine heterogeneity is based on the results of existing published studies and our own field materials);
2. taking into account the two main trigger mechanisms for the lake outburst (overflow of water over the dam crest and the formation of a filtration channel in dams body);
3. taking into account changes in flow velocity in the bottom part of the breach (calculation of bottom velocity is carried out using the Karaushev equation);
4. a more complex approximation of the breach cross-sectional shape: when the breach is washed out, the soil collapses from its sides, as a result of which the breach shape within the cross-section of the flow remains trapezoidal, and rectangular on top (the proposed approximation of the breach shape, in the opinion of the author, is more accurate than traditional used (triangular and trapezoidal), reflects the process of its formation).

The proposed calculation algorithm was used as the basis for a computer programme written in the MatLab, which has a convenient interface for entering input characteristics and parameters. The result of the calculation is the derivation of the main characteristics of an outburst flood: the outburst hydrograph, the change over time in the velocity and cross-sectional area of the flow, the volume of water in the lake and the dimensions of the breach (bottom elevation, width and area of the breach).

Chapter 3. Approbation of the calculation methodology based on the results of numerical and physical experiments

3.1. Numerical experiments

Since the developed model does not allow calculating the initial breach in the dam body, and it is specified initially, it was necessary to evaluate how the size of the specified initial breach, as well as some parameters of the soil composing the dam, influence the beginning of the process of its destruction. For this purpose, numerical experiments were carried out: with a constant geometry of the dam and lake, different sizes of the initial breach (outburst due to water overflow) and the initial diameter of the channel (with an outburst as a result of the filtration channel formation) in the dam and different soil characteristics were specified with other equal model parameters. The characteristics of the dam and lake that were used for numerical experiments corresponded to the periglacial lake «Gachy-Kol», which is located on the northern slope of the Tavan-Bogdo-Ola mountain massif (a more detailed description of the lake is in section 3.3 of this thesis). The dam length is 80 m, the dam height is 2.5 m, the lake volume is 5144 m^3. The dam soil material was specified to be heterogeneous (30% sand, 70% loam).

In Fig. 3.1. a series of calculated hydrographs is presented for different initial depths and widths of the breach when water overflows over the crest. The depth of the initial breach in the numerical experiment varied from 2.5 to 20 cm. The range of width values was from 10 to 80 cm, which corresponds to from 0.12% to 1% of the dam length.

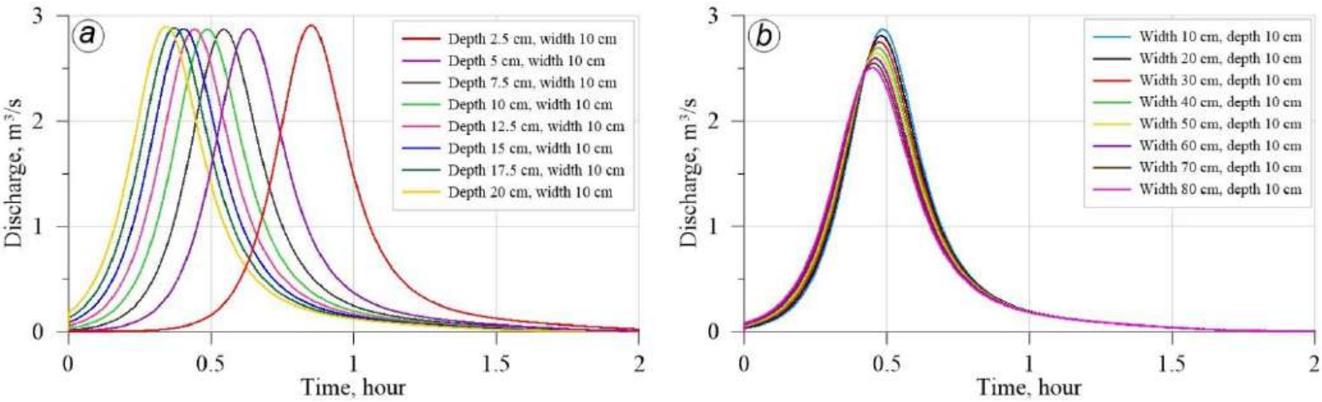


Fig. 3.1. Hydrographs of outburst floods at different initial depths (a) and width (b) of the breach.

According to the calculations performed, an increase in the depth of the initial breach has virtually no effect on the value of the maximum discharge, the shape of the outburst hydrograph and the time of passage of the outburst flood wave (Fig. 3.1a). Changing the depth from 2.5 cm to 20 cm leads to a change in the maximum discharge by only 0.4%. However, there is a significant increase in the outburst time from the beginning of the water outflow through the crest to the descent of the lake. Increasing the depth from 2.5 cm to 20 cm reduced the outburst time by 30 minutes. The smaller the initial depth of the breach, the longer the process of erosion of the dam occurs over a longer period of time and, accordingly, the water discharge later reaches its maximum value.

Changing the breach width at a constant depth does not affect the time of passage of the outburst flood, the time of the beginning of the outburst and the shape of the hydrograph. As for the maximum water discharge, the larger the initial breach width, the lower the maximum discharge (Fig. 3.1b). This is explained by the fact that in this case there is a more intense increase in discharge, which leads to a faster outflow of water from the lake. A rapid water outflow leads to a decrease in water height and, accordingly, a decrease in flow velocity, and, as a consequence, a decrease in the maximum outburst discharge. Changing the breach width by 2 times (from 10 cm to 20 cm) leads to a decrease in the maximum discharge consumption by 2.1%, and increasing the breach width from 10 cm to 80 cm leads to a decrease in water discharge by 15.3%.

With different values of the initial diameter of the channel (Fig. 3.2), the same picture is observed as when changing the depth of the initial breach: the smaller the diameter of the channel, the slower the erosion of the channel occurs and, accordingly, the longer the flow of water through the filtration channel until the soil above it collapses. An increase in depth from 1 cm to 10 cm leads to a reduction in the time interval for water movement through the channel by almost 1 hour. In this case, the shape of the outburst flood hydrograph, the duration of the outburst wave and the value of the maximum discharge do not change when the diameter of the initial channel changes.

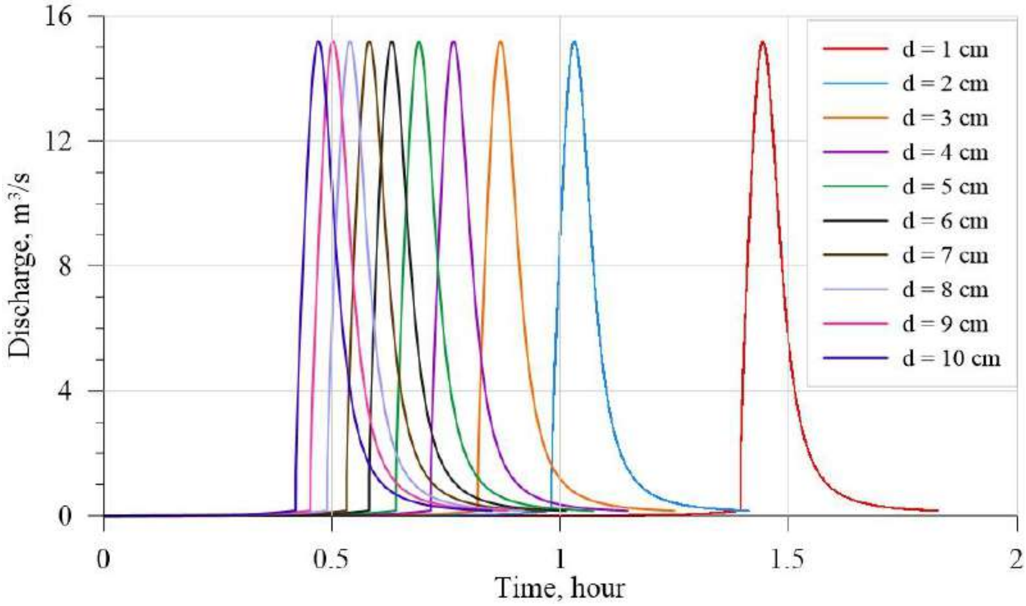


Fig. 3.2. Hydrographs of outburst floods for different initial diameters of the channel in the moraine dam body.

Because the specific gravity of the material that makes up moraine dams varies widely, and moraine material can contain different clay contents, numerical experiments were carried out for specific gravity values and clay contents that correspond to soils containing particles greater than 200 mm (GOST 25100-2011 Soils. Classification; Westoby et al, 2015), since the dams damming the moraine lakes of the selected study area contain boulders. Analysis of the results of numerical experiments showed that the model is most «sensitive» to such input parameters as the specific gravity of the material from which the moraine dam is constructed and the percentage of clay content in it, since the value of the erosion coefficient, which affects soil erosion rate. In Fig. Figure 3.3 shows the dependence of the maximum discharge on the specific gravity of the material and the percentage of clay for soils that are most often found in moraine dams, according to (Westoby et al, 2015; Zheng et al, 2021).

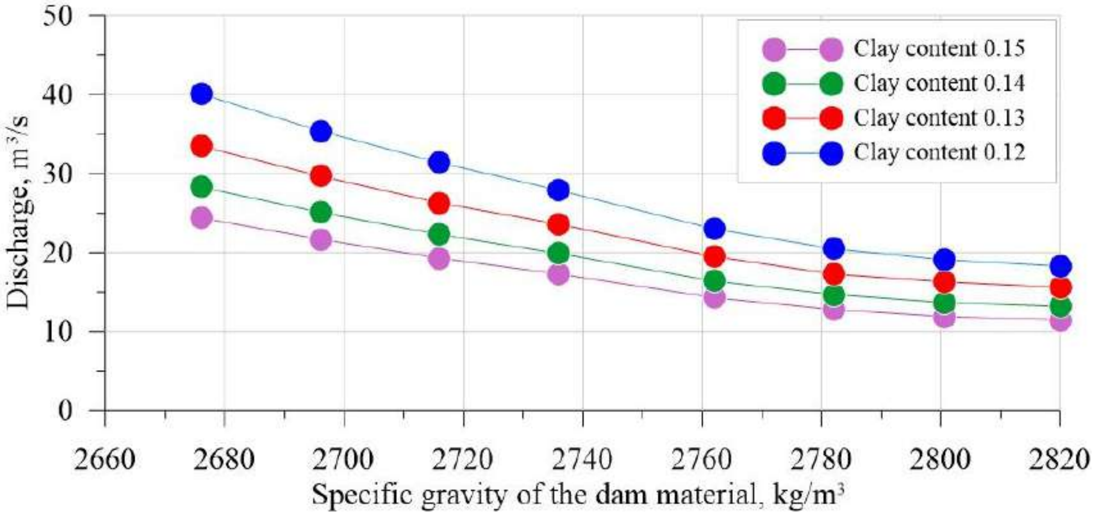


Fig. 3.3. Dependence of the maximum discharge on the specific gravity of the dam material and the percentage of clay in it.

As can be seen from the graphs, a change in clay content for soils with different granulometric compositions can lead to a significant change in the maximum discharge. So, for example, when the clay content is reduced by 7% (from 15% to 14% in a sample at any specific gravity), discharge increases by 15%-16%. The obtained dependencies (Fig. 3.3) are due to the influence of clay content on the erosion rate and, consequently, on the rate of the dam destruction.

The specific gravity of moraine material can vary widely and depends on the composition of rocks, soil moisture, granulometric compositions, the presence of large boulders, clay content, therefore the selection of parameters (specific gravity, clay content) for modelling must be carried out more carefully, using both literature data, as well as the results of special field research. To date, published sources contain scant data on soil characteristics, so conducting detailed laboratory or field studies related to determining the granulometric composition of the material of moraine dams seems relevant. Particularly important is the generalization of the characteristics of the granulometric composition and specific gravity in areas with similar geological and geomorphological conditions.

Analysis of the results of numerical experiments made it possible to identify a quantitative criterion for choosing the initial dimensions of the breach and the filtration channel diameter. The length of the initial breach should be no more than 1% of the dam length, and the breach depth should not be more than 20 cm, since within these limits the geometric characteristics of the initially depression do not affect further calculations. The value of the initial diameter of the filtration channel up to 10 cm does not affect the shape of the outburst flood hydrograph, the duration of the outburst wave and the value of the maximum discharge and can be taken as a guideline for setting the initial condition in the model. In general, the methodology for calculating the characteristics of an outburst flood does not contradict the nature of the outburst process, which provided the basis for further testing of the model on the results of physical experiments.

3.2. Physical experiments on the outburst of soil dams taking into account two trigger mechanisms of outburst

Due to the fact that the outburst process occurs suddenly and in a very short period of time (minutes, hours), observational data on lake outbursts are extremely scarce. Most often, the verification information for mathematical modelling is an expert assessment of the time of passage of a outburst flood and the size of the resulting breach, therefore, to test mathematical models, the method of physical modelling is often used, since it allows a more detailed phenomenological description of the process of a moraine dam outburst, identifying the factors influencing it in natural conditions, obtain the observed outburst flood hydrograph and the necessary parameters for mathematical models. In this regard, to test the developed mathematical model, a number of physical experiments were carried out on outburst soil dams, which were carried out by students and staff of the departments of Land Hydrology and Geophysics of the Institute of Geosciences of St. Petersburg State University (the author of this study was directly involved in conducting physical experiments and desk processing of the obtained materials).

A nature experiment (experiment No. 1) was carried out in July 2018 in the Caucasus in the coastal zone of Lake Bashkara, which repeatedly outbursted (Seynova, 1997; Chernomorets et al., 2018). An artificial lake was created by blocking the flow of a stream with a dam, which consisted of moraine material (Fig. 3.4). The experiment is unique in that it was carried out in conditions of the formation of dangerous hydrological phenomena (Pryakhina et al., 2019).

Fig. 3.4. Conducting a nature experiment (photo by *A.S. Boronina*).

Physical experiments No. 2, No. 3 and No. 4 were carried out at an experimental installation on the territory of the Priladozhskaya educational and scientific base of the St. Petersburg State University (Kuznechnoye village, Priozersky district, Leningrad region) in 2020, 2021 and 2023.

The experimental reservoir was a container made of monolithic polycarbonate measuring 1×1×1.5 m, consisting of two compartments.

The first compartment measuring 1×1×0.6 m was filled with water. A dam was built in the second compartment. A partition with a rectangular hole (0.05×0.15 m) for water flow was installed between the compartments. During the filling of the first container before the start of the experiment, the hole was closed with a shutter. To fix the water level, a measuring scale was installed on the wall of the second container (Fig. 3.5).

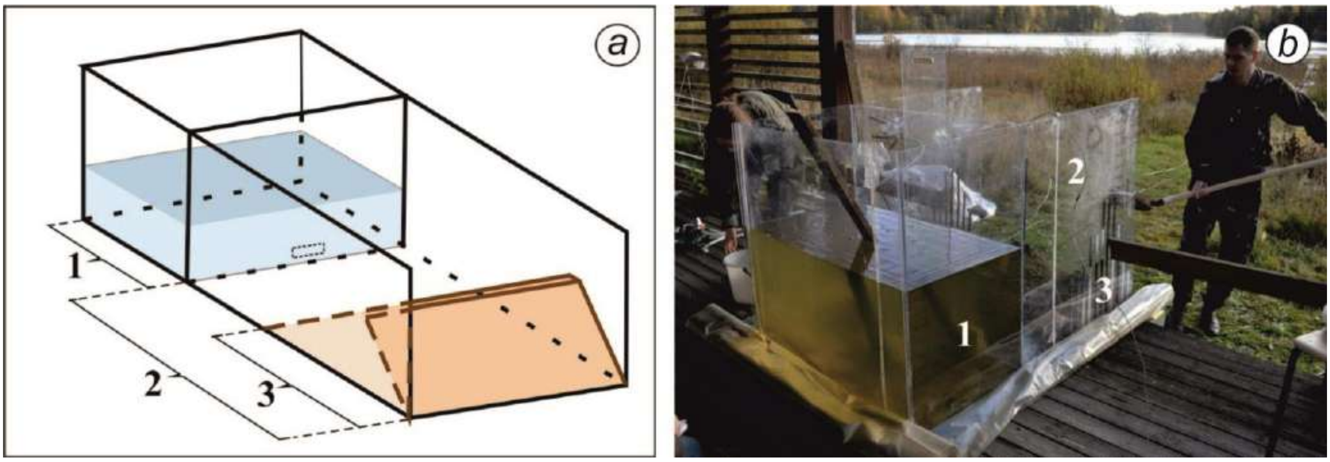


Fig. 3.5. Experimental installation: diagram (a) and photo (b). Photo by *A.S. Boronina.*
Designations: 1 – compartment for water, 2 – compartment for the construction of a dam, 3 – dam.

Based on the results of experiments, water discharge through the breach was determined by the formula:

$$Q = \frac{W_1 - W_2}{T}, \tag{3.1}$$

where Q – water discharge through the breach, l/s; W_1 and W_2 – reservoir volumes at different water levels (discreteness 1 cm), T – time during which the water level decreased by 1 cm. To assess the convergence of hydrographs calculated from the model and obtained as a result of the experiment, the Nash-Sutcliffe criterion (NS) was used, recommended by the American Association of Civil Engineers for assessing the consistency of runoff models, and also used by the World Meteorological Organization for comparative analysis of models (Nash, Sutcliffe, 1970). The range of criterion values is from -∞ to 1; in general, modelling is considered satisfactory when NS > 0.5. As an example, we present the results of experiments with the best, satisfactory and worst NS values (the dimensions of the dams and soil characteristics are presented in Table 3.1).

Table 3.1.

Characteristics of experimental dams and reservoirs

№ п/п	Experiment No. 1 (nature)	Experiment No. 2	Experiment No. 3	Experiment No. 4
Soil type	Moraine	Sandy loam	Sandy loam	Sandy loam
Specific gravity of soil, kg/m^3 / clay percentage, %	2630 / 5%	2730 / 16%	2590 / 6.9%	2610 / 7.7%
Height, m	0.17	0.2	0.35	0.16
The dam thickness at the base, m	0.4	0.46	0.71	0.7
The dam length along the crest, m	1.2	1	1	1
The crest width, m	0.05	0.1	0.05	0.05
The dam slope length, m	0.3 and 0.3	0.29 and 0.33	0.55 and 0.55	0.48 and 0.38
The initial breach depth, m	0.005	0.005	0.01	0.01
The reservoir volume, m^3	0.203	0.183	0.312	0.162

The purpose of the physical experiments was to test the developed calculation methodology. In experiments No. 1-3, physical models (dams) had arbitrarily specified dimensions and were not reduced copies of known dams, and in experiment No. 4 geometric similarity was maintained (constancy of the ratio of the linear dimensions of the physical model and the original), and the real object for physical modelling was moraine Lake Nurgan (North-Western Monogolia) was selected.

The observed and modeled hydrographs of artificial reservoirs outbursts obtained as a result of the experiments (Fig. 3.6) are characterized by an asymmetrical shape (with the exception of experiment No. 1 (Fig. 3.6a)): a rapid increase in water discharge and a smoother decrease in their values after reaching a maximum. The modelling does not take into account the spontaneous collapse of soil from the breach sides, which leads to the appearance of local increases in water discharges on the observed hydrographs (Fig. 3.6a, b, d). In physical experiments No. 1, No. 3 and No. 4, the outburst of soil dams occurred when water overflowed over the crest, and in experiment No. 2 - as a result of the formation of a filtration channel in the dam body (piping), thus, two outburst mechanisms were taken into account in the experiments.

Analysis of modeled hydrographs and hydrographs, which obtained as a result of physical experiments showed: the onset of the peaks of outburst floods practically coincides in time; the discrepancy in the onset of maximum water discharges ranges from 5 (experiment No. 1, Fig. 3.6a) to 22 seconds (experiment No. 4, Fig. 3.6d). The largest deviation of the values of the simulated maximum discharges from those obtained as a result of the experiments was 6% (experiment No. 2, Fig. 3.6b and experiment No. 4, Fig. 3.6d). During experiment No. 1 (Fig. 3.6a), a spontaneous collapse of the soil occurred at 19 seconds, which led to a mismatch of hydrograph peaks. It is for this case that the NS criterion takes the smallest value – 0.42. It is also worth noting that for experiment No. 2, in which the dam destruction occurred as a result of the formation of a filtration channel, the time of channel erosion calculated by the mathematical model (102 seconds) is comparable to the observed value (93 seconds). For experiments No. 2 and No. 4, NS was 0.61 and 0.58, which indicates satisfactory convergence, for experiment No. 3 - 0.8, which indicates good convergence of hydrographs, and, therefore, high quality of modelling.

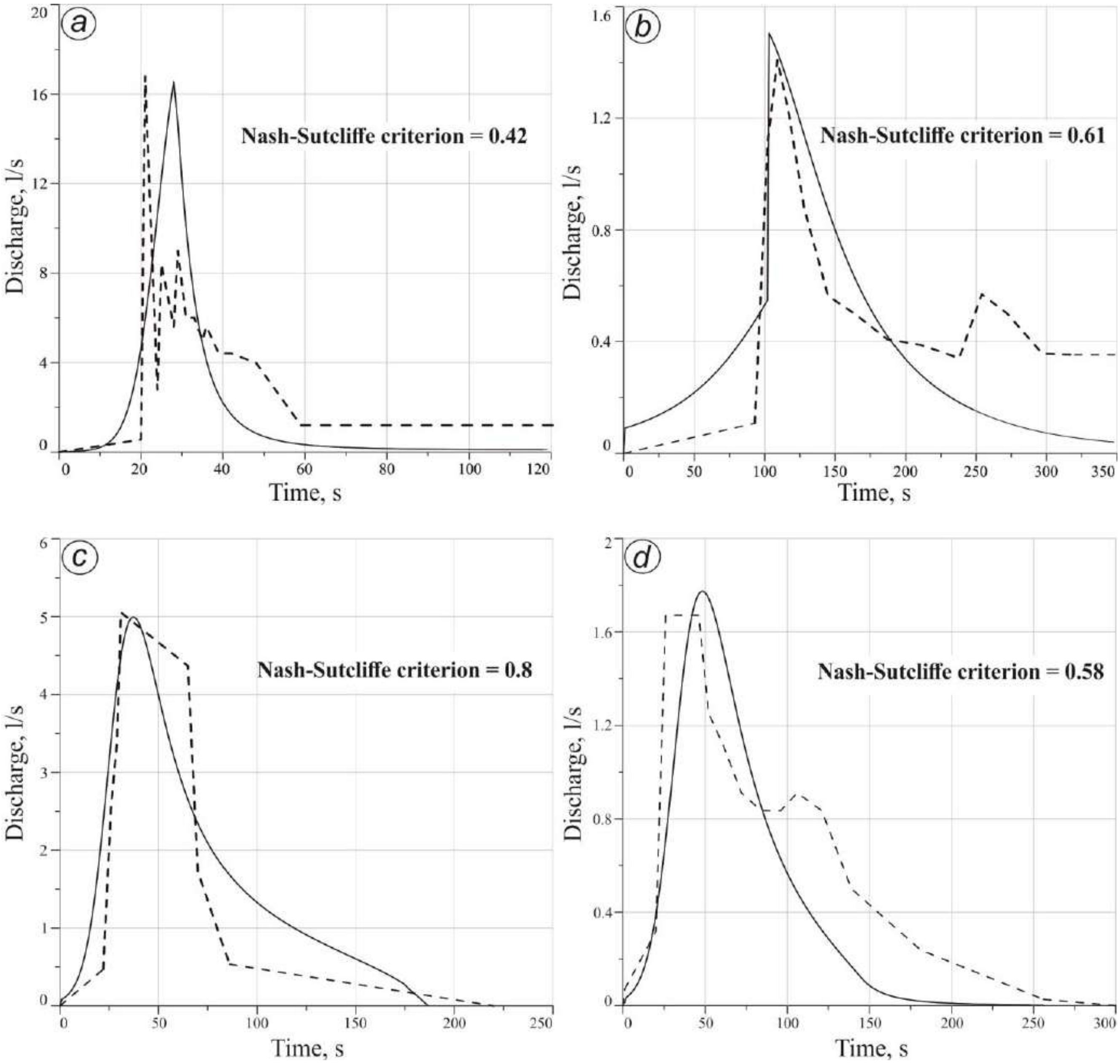


Fig. 3.6. Observed (dashed line) and simulated (solid line) outburst flood hydrographs obtained from the results of physical experiments No. 1 (a), No. 2 (b), No. 3 (c) and No. 4 (d).

Thus, a comparison of the results of mathematical modelling with the results of physical modelling showed their satisfactory convergence, which indicated the adequacy of the proposed calculation methodology. This made it possible to use it for mathematical modelling of outburst floods formed during the outburst of real moraine and periglacial lakes.

3.3. Approbation of the calculation methodology on real cases of outbursts of moraine lakes

Satisfactory results of verification of the developed calculation methodology, obtained during numerical and physical experiments, made it possible to use the method for calculating real cases of outbursts of moraine lakes. To test the methodology, published data on outbursts of moraine lakes Jinwuco (Zheng et al, 2021) and Tam Pokhari (Osti, Egashira, 2009) were used.

Lake Jinwuco was a periglacial lake and was located near the Jinwu Glacier in the Nidou Zangbo River basin (Tibetan Plateau) at an altitude of 4450 m above sea level. Before the outburst, the lake length was 1800 m, the lake width was 330 m. The lake volume was 13900000 m^3. The outburst of lake occurred in June 2020 as a result of intense precipitation and high air temperatures. The width of the resulting breach, according to studies published in (Zheng et al, 2021), is 80 m along the crest and 40 m along the bottom. The breach depth is 45 m. The volume of the outburst flood formed when the lake outburst was 10 million m^3. There are no expert estimates of the maximum water discharge, but the authors of the study (Zheng et al, 2021) simulated the resulting outburst flood, according to which the maximum water discharge was about 5000 m^3/s.

Based on the data obtained, a lake volume curve was constructed (Fig. 3.7), which was used as input information for mathematical modelling.

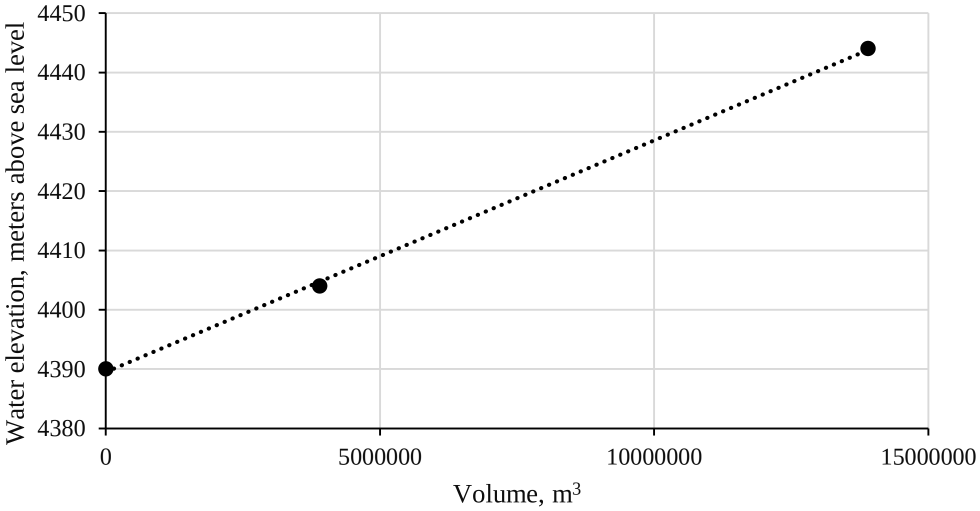


Fig. 3.7. Volume curve of the Jinwuco periglacial lake.

The results of mathematical modeling are presented in Fig. 3.8-3.10.

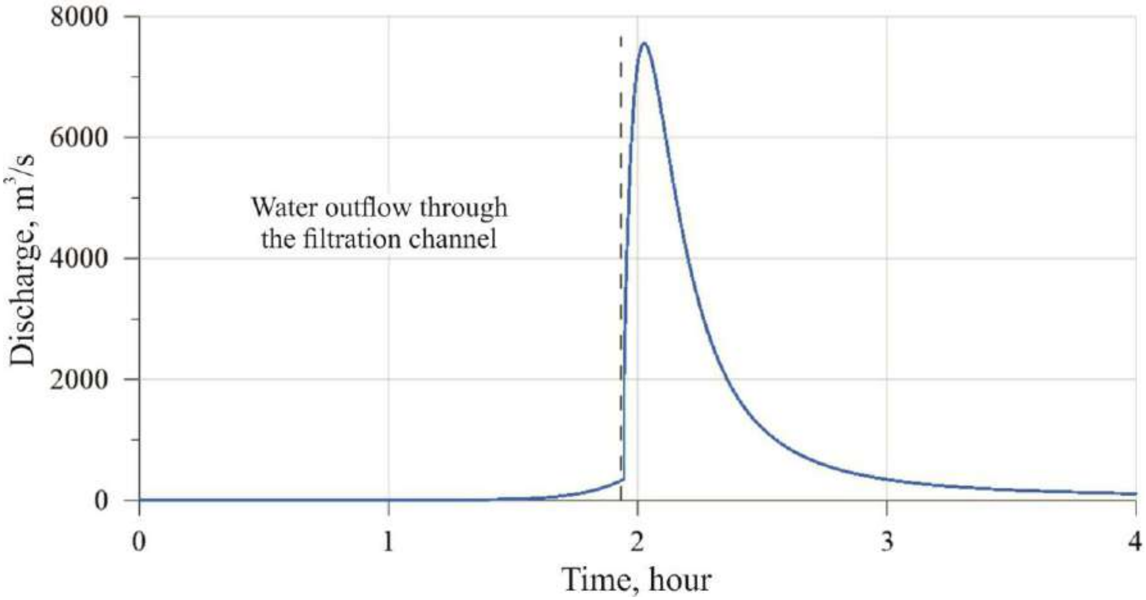


Fig. 3.8. Simulated hydrograph of the outburst flood during the outburst of Lake Jinwuco.

According to the simulation, the time of water outflow through the filtration channel was about 2 hours. Then the soil collapsed above the breach, and an outburst flood wave formed. The maximum discharge (7550 m^3/s) was reached 5 minutes after the soil collapse, after which there was a decrease in discharges. The time period for the outburst wave to pass was about 1 hour. The flow velocity varied from 0.4 to 12 m/s.

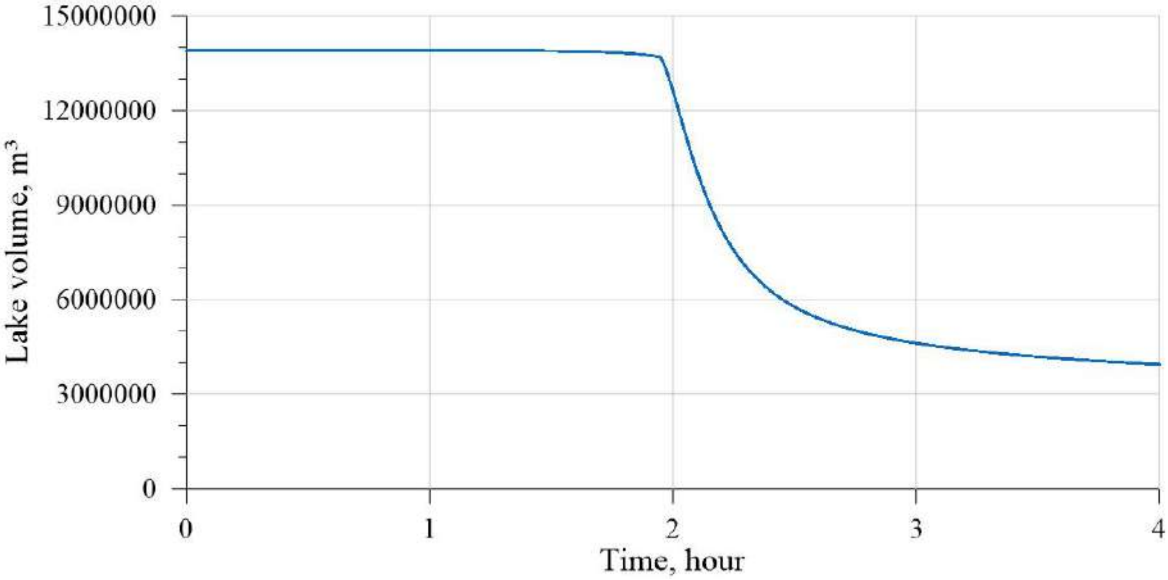


Fig. 3.9. Change in the volume of Lake Jinwuco during outburst.

According to the calculation results, the lake was not completely emptied during the outburst. The bulk of the water volume was released after the soil collapsed above the channel. The volume of the outburst flood was 9.96 million m^3, which corresponds to published data (10 million m^3). The error was less than 1%.

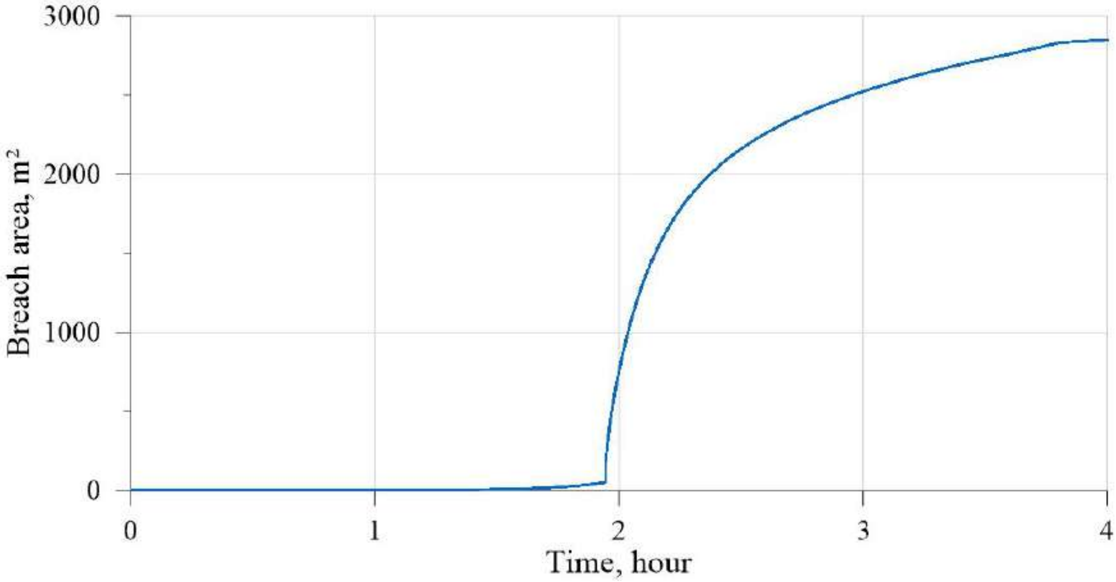


Fig. 3.10. Change in the breach area in the moraine dam during an Lake Jinwuco outburst.

The estimated area of the breach formed when the lake outburst is 2850 m^2. The breach width along the crest was 70 m, and along the bottom 38 m. The breach depth was 41 m. The quality of the modelling was also assessed by comparing the calculated and measured dimensions of the breach. The discrepancy between the calculated the breach width along the crest and the observed width (80 m) was 12.5%; the discrepancy between the modeled breach width along the bottom and the measured value (40 m) was 5%.

Lake Tam Pokhari was a moraine-dammed lake and was located in the upper reaches of the Hinku River (Himalayas, Nepal) near the Sabai glacier at an altitude of 4420 m above sea level. Before the outburst, the lake length was 1000 m and the breach width was 350 m. The lake volume was 21.3 million m^3. The destruction of the dam damming the lake with the subsequent outburst of the lake and the formation of a mudflow occurred in September 1998. The volume of the outburst flood according to (Osti, Egashira, 2009) was 18 million m^3. The breach formed as a result of the outburst was trapezoidal in shape and had the following dimensions: the width along the crest was 100 m, along the bottom 25 m, the breach depth was 50 m. The lake volume curve is shown in Fig. 3.11.

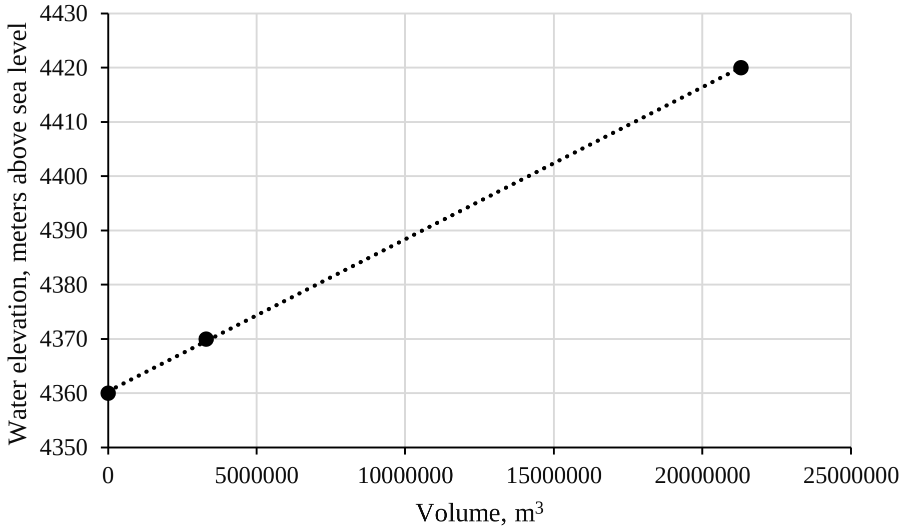


Fig. 3.11. Volume curve of the Tam Pokhari moraine-dammed lake.

There is no information about what the trigger mechanism for the outburst was and what the maximum discharge was. However, according to the calculations performed, the convergence of the modeled breaches sizes with the observed values is better if the calculation of the lake outburst is performed for the case of erosion of the filtration channel (Fig. 3.12-3.14).

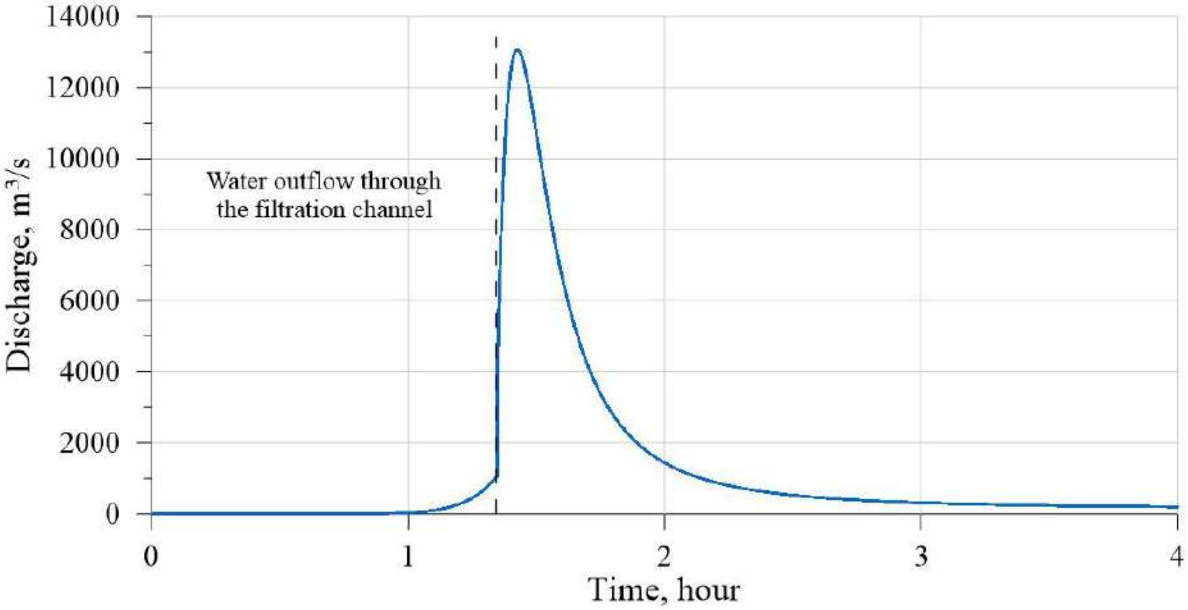


Fig. 3.12. Simulated hydrograph of the outburst flood during the outburst of Lake Tam Pokhari.

According to the calculations performed, the outflow of water through the filtration channel occurred for about 1 hour 20 minutes, after which the soil above the channel collapsed and the overflow of water began (Fig. 3.12). The maximum calculated discharge is 13000 m^3/s. The period of passage of the outburst flood wave was about 1 hour. Flow velocities according to the calculation varied from 0.4 to 14 m/s.

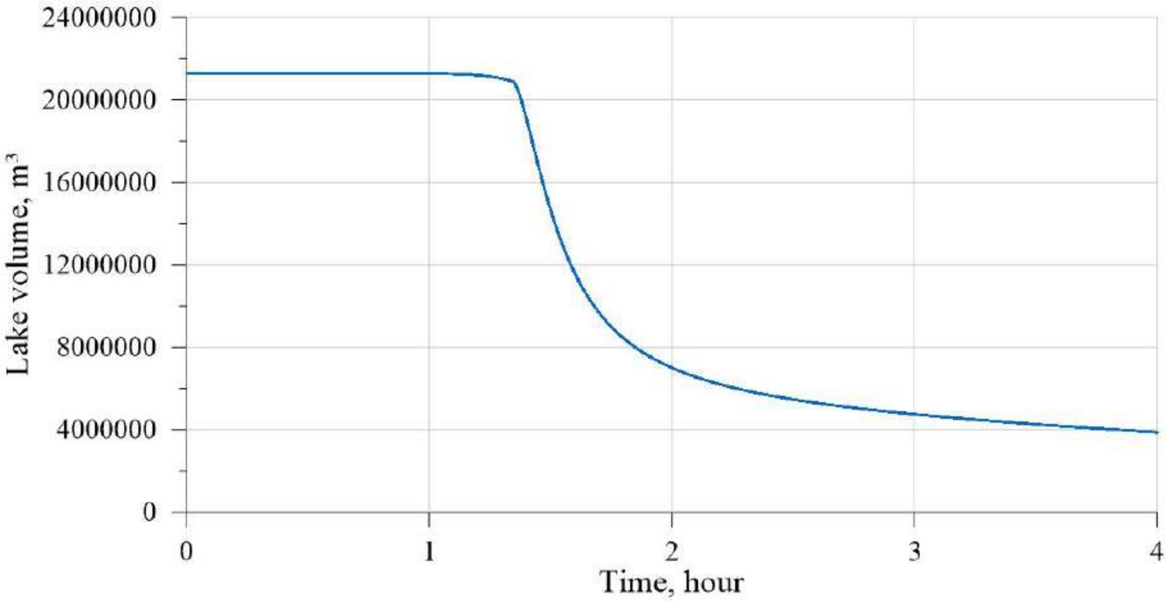


Fig. 3.13. Change in the volume of Lake Tam Pokhari during outburst.

According to the modelling results (Fig. 3.13), the lake was not completely emptied; the volume of the outburst flood was 17.3 million m^3, which is consistent with existing estimates. The discrepancy between the calculated value and published data was 4%.

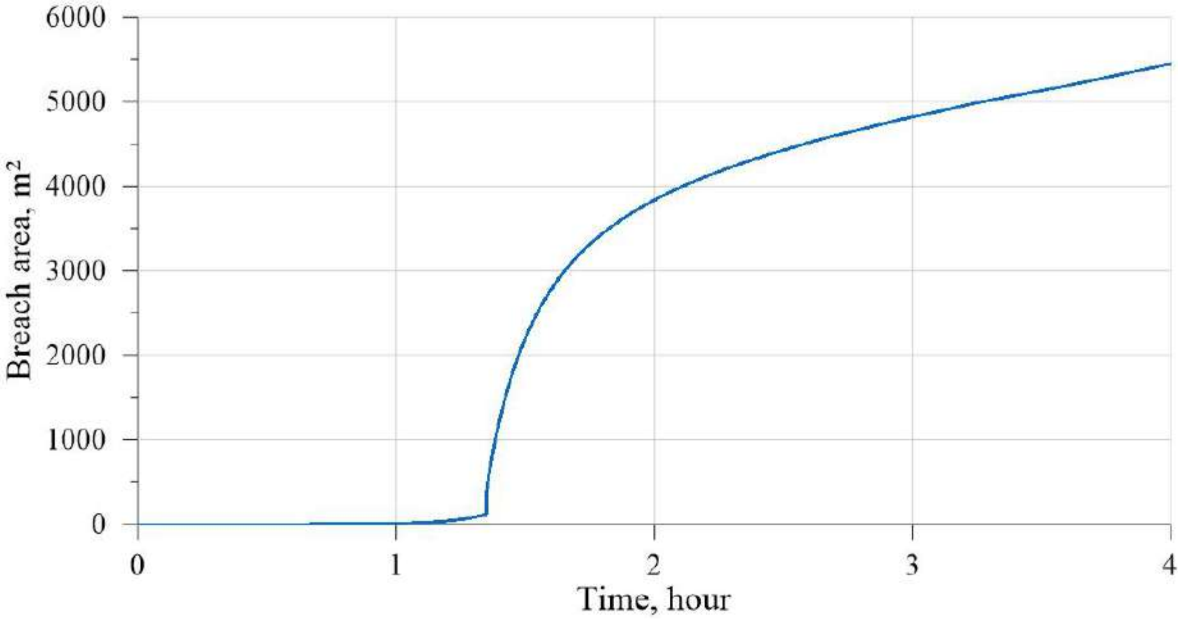


Рис. 3.14. Change in the breach area in the moraine dam during an Lake Tam Pokhari outburst.

The breach area formed during the outburst was 5448 m^2. The breach width along the crest was 102 m, and along the bottom 58 m. When compared with the observed data, the discrepancy between the observed and calculated breach width along the crest is practically absent (the observed width is 100 m), however, the calculated width along the bottom is almost 2 times larger observed, which may be due to the fact that during the period of time from the outburst to the moment of measuring the size of the breach, shedding of soil from its sides could have occurred, as a result of which the measurement result could have been underestimated. The calculated breach depth was 53 m and is comparable to the measured depth of 50 m (the discrepancy is 6%).

3.4. Chapter Conclusions

Comparison of the results of mathematical modelling, performed on the basis of the developed calculation algorithm, with the results of physical modelling showed their satisfactory convergence in terms of the time to reach the maximum discharge, its value and the time of passage of the outburst flood, with the exception of cases where spontaneous collapse of soil from the sides of the breach was observed, since in the algorithm this is not taken into account in the calculation. The values of the Nash-Sutcliffe criterion varied in the range from 0.5 to 0.8 and averaged 0.63, which corresponds to a satisfactory convergence of model and observed results, and, therefore, indicates the adequacy of the proposed calculation method.

Approbation of the developed calculation methodology on published data on real outbursts of moraine lakes also showed satisfactory results. The quality of the modelling was assessed by comparing the calculated dimensions of the breach (width and depth) with published measured values, and also comparing the simulated volumes of the outburst flood with the volumes calculated from the difference in lake volumes before and after the outbursts. Based on the comparison results, it was found that the discrepancy between the actual and calculated volumes of water in the lakes that went into the formation of the outburst flood is minimal (up to 4%). As for the size of the outburst, in the case of calculating the characteristics of the periglacial lake Jinwuco outburst, it did not exceed 12.5%, which indicates a satisfactory quality of modelling. The calculated the breach depth is also comparable with the actual depth (the discrepancy was 5%). In the case of modelling performed for Lake Tam Pokhari, it was found that there is practically no discrepancy between the measured and calculated the breach width along the crest, however, the value of the breach width along the bottom calculated using the methodology is overestimated compared to the observed width. This may be due to the fact that during the period of time from the outburst that occurred (1998) to the moment of measuring the size of the breach (2000), soil shedding from its sides could have occurred, as a result of which the result of the measurement could have been underestimated. The results of calculating the breach depth are comparable with the actual depth (the discrepancy was 6%).

Numerical experiments have shown that the mathematical model is most «sensitive» to such parameters as the specific gravity of the material from which the dam is made and the percentage of clay in it, since these parameters affect the value of the erosion coefficient, on which the erosion rate of the dam depends. The selection of these parameters (specific gravity and clay content) for modelling must be carried out on the basis of the experience gained, the developed methodology and the results of special field studies. Based on the results of numerical experiments, a quantitative criterion for choosing the initial breach size and the filtration channel diameter during modelling was proposed: the initial breach length should be no more than 1% of the dam length, and the breach depth should not be more than 20 cm, since the initial geometric characteristics are within these limits outburst floods have virtually no effect on the calculation and characteristics of the outburst flood. The value of the initial diameter of the filtration channel up to 10 cm does not affect the shape of the outburst hydrograph, the duration of the outburst flood wave and the value of the maximum discharge and can be taken as the initial condition for modelling.

Thus, the results of numerical experiments and approbation of the methodology on the results of physical experiments and on published data of real outbursts showed the adequacy and efficiency of the proposed calculation algorithm, and the possibility of its use for assessing the characteristics of outburst floods of possible outbursts of periglacial and moraine-dammed lakes. In addition, the calculated outburst flood hydrograph can be used as input information for mathematical modelling of mudflows.

Since it makes sense to use the developed methodology for calculating the characteristics of a outburst flood for lakes that have the prerequisites for the formation of an outburst, the next urgent task was to identify such lakes and carry out calculations. The territory of the Altai mountains was chosen as the study area (Katunsky, North-Chuya, South-Chuya ridges, Tavan-Bogdo-Ola and Mongun-Taiga mountain massifs and the Tsambagarav ridge). The choice was due to little hydrological knowledge, on the one hand, and the availability of data from long-term expeditionary research at St. Petersburg State University, in which the author took part for 4 years, on the other. We also note that, despite the relatively calm situation with outbursts in the Altai, such phenomena occurred here periodically, and taking into account the non-stationary climate situation and the intensification of economic activity and tourism, research is becoming increasingly relevant in order to reduce risks from dangerous hydrological phenomena.

Chapter 4. Features of the hydrological regime of high mountain lakes in the Altai

Despite the fact that the Altai mountainous country is one of the world's centers of glaciation and is influenced by the ongoing climate warming, the hydrological knowledge of the Altai Mountains is very weak, in particular, the hydrological regime of modern periglacial and moraine-dammed lakes, which can be potentially hazardous, has been practically unstudied compared to other mountainous areas.

This chapter is devoted to identifying the features of the level regime of moraine-dammed and periglacial lakes of the Altai, which are at different stages of development, based on field observation data obtained during long-term complex expeditions of the Institute of Earth sciences of St. Petersburg State University. Identification of the features of the level regime of each stage of development will make it possible to detect potentially outburst-hazardous lakes in conditions of poor hydrological knowledge and reduce the degree of information uncertainty in the area under consideration.

4.1. Exploration and physicogeographical description of the study area

The study of outburst-hazardous mountain lakes (glacial, periglacial, moraine-dammed and landslides) is carried out all over the globe and is carried out in almost all directions: analysis of the variability and dynamics of periglacial and moraine-dammed lakes, outburst hazard assessments are carried out using Earth remote sensing data; field expeditionary research is carried out to obtain the necessary data on the hydrological regime of lakes, morphometric characteristics of the lake and the dam; mathematical modelling of lake outbursts, both hypothetical and real, is carried out. The most studied areas are the highlands of the Himalayas (Chikita et al, 2004; Khanal et al, 2015), the Tibet (Osti, Egashira, 2009), the Tien Shan (Torgoev et al, 2013), the Pamir (Raimbekov et al, 2021), the Andes (Anacona et al, 2015). In Russia, from the point of view of the study of lakes, the most studied area is the highlands of the Caucasus (Dokukin et al., 2022; Adzhiev et al., 2023). The periglacial and moraine-dammed lakes of the Altai Mountains (the Altai Mountains are the second largest mountain glaciation region in Russia) have been poorly studied in this regard, although in the high mountain areas of the Altai Mountains in recent decades both an increase in the number of periglacial lakes and an increase in existing ones have been recorded (Rasputina et al., 2022). Quite a lot of scientific research is devoted to the analysis of the dynamics of Altai paleolakes and the formation of superfloods (Rudoy, 1981; Butvilovsky, 1985; Rudoi, Korolev, 1984; Rudoi, Kiryanova, 1994; Borodavko, Akhmatov, 2006), but there is practically no work related to the development of modern periglacial and moraine lakes.

Currently, a team of researchers from St. Petersburg State University is studying moraine-dammed lakes in the Altai highlands from the point of view of their outburst hazard (Pryakhina et al., 2021; Rasputina et al., 2021a; Rasputina et al., 2021b; Rasputina et al., 2022). To date, the team has examined the periglacial and moraine-dammed lakes of South-Eastern Altai (the Mongun-Taiga mountain massif, the Russian part of the Tavan-Bogdo-Ola mountain massife, the Tsambagarav ridge

(North-Western Mongolia)) and Central Altai (North-Chuya and South-Chuya ridges). In view of the growing tourist attractiveness of the Altai Mountains, studying the development of outburst-hazardous periglacial and moraine-dammed lakes, assessing their outburst hazard and mathematical modelling of outbursts will reduce the risks and damages from the development of dangerous hydrological phenomena.

To analyze the spatiotemporal variability of moraine-dammed lakes, high-mountain territories of Altai were selected, located in different meteorological conditions: Central Altai (Katunsky, North-Chuya and South-Chuya ridges) and South-Eastern Altai (Tavan-Bogdo-Ola and Mongun- Taiga mountain massifs, Tsambagarav ridge) (fig. 4.1).

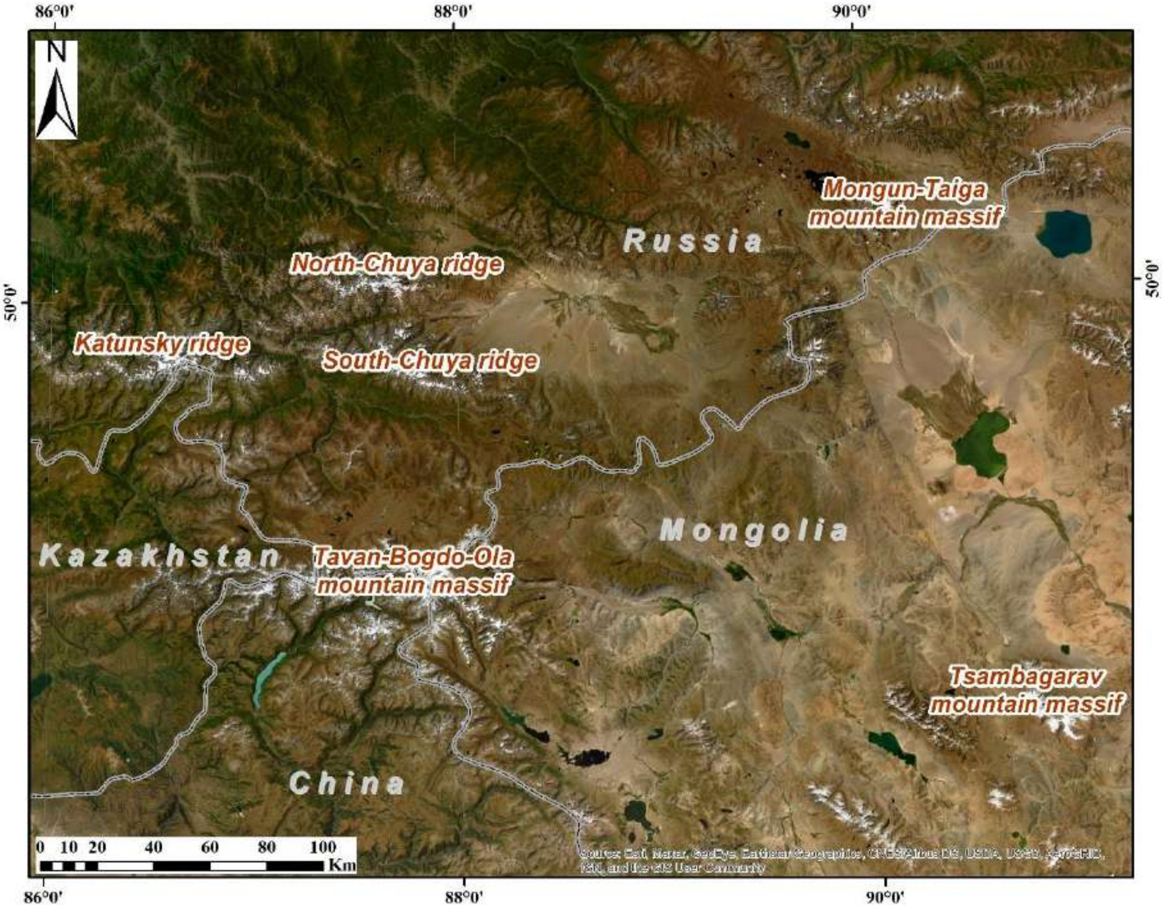


Fig. 4.1. Scheme of the study area.

Climate change in the study area

The climatic features of the study area are determined by the location of the area in the central part of Asia at a great distance from the oceans. The three main factors that determine the climate of Altai are: the position in the temperate latitudes of the Northern Hemisphere, the dominance of the westerly transport of air masses from the Atlantic, and the influence of the powerful Asian anticyclone in winter (Kotlyakov et al., 2015). At the junction with the front ridges, the movement of cyclones slows down, rising air currents increase, resulting in a sharp increase in the amount of precipitation. The difference in the provision of precipitation to the interior regions of the Altai and the slopes of the front ridges and high-mountain ranges exposed to moisture-carrying westerly winds determines one of the main features of the climate of the Altai Mountains, which makes it possible to divide the territory of Altai into two parts: with sharply continental and more temperate types of climate (Nenasheva, 2013).

The increase in the number of periglacial and moraine-dammed lakes located on modern moraines and Little Ice Age moraines is the result of deglaciation of the Altai territory as a result of ongoing climate warming, which, according to (Third Assessment Report..., 2022) began at the end of 1970. The non-stationary climate situation is confirmed by positive statistically significant trends in average annual air temperatures for the period 1980-2020 (Fig. 4.2, 4.3) for a significance level of 5%, identified by the author based on data from weather stations Bertek (21 km north-west of the Tavan-Bogdo-Ola massif, altitude is 2146 m), Kara-Turek (16 km north of Katunsky ridge, altitude is 2596 m), Akkem (Akkem river valley, Katunsky ridge, altitude is 2040 m), Mugur-Aksy (25 km east of the Mongun-Taiga mountain massif, altitude is 1850 m), Khovd (100 km south-east of the Tsambagarav ridge, altitude is 1395 m) and Bayan-Ulgii (60 km north-west of the Tsambagarav ridge, altitude is 1710 m). The Bertek weather station was closed in 1981, so the series of average annual air temperatures after 1980 were restored using data from the Kosh-Agach weather station (the correlation value between the series of air temperature values at the Bertek and Kosh-Agach weather stations for the joint observation period was 0.9) (Ganyushkin et al., 2017).

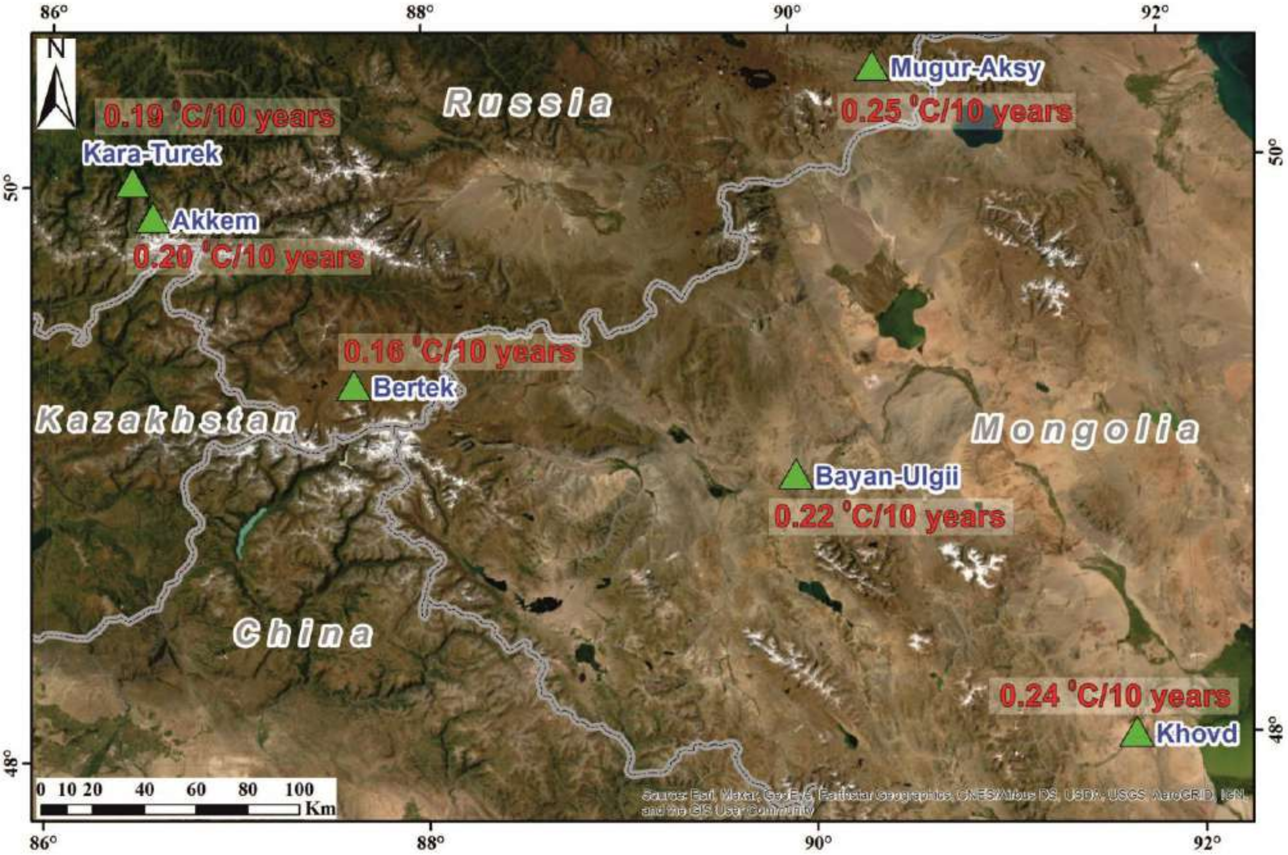


Fig. 4.2. Location of weather stations in the study area and the magnitude of air temperature changes over 10 years at weather stations.

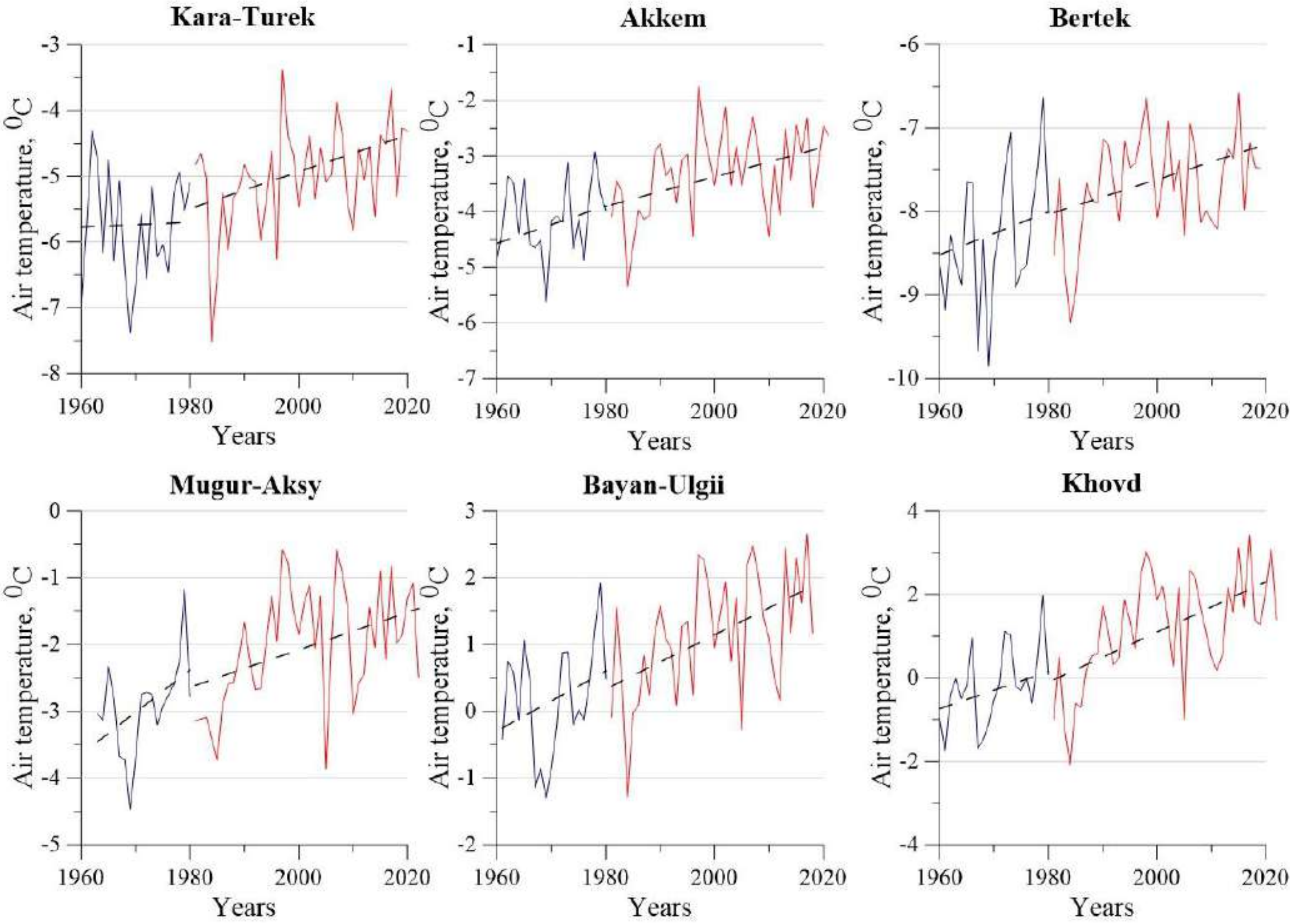
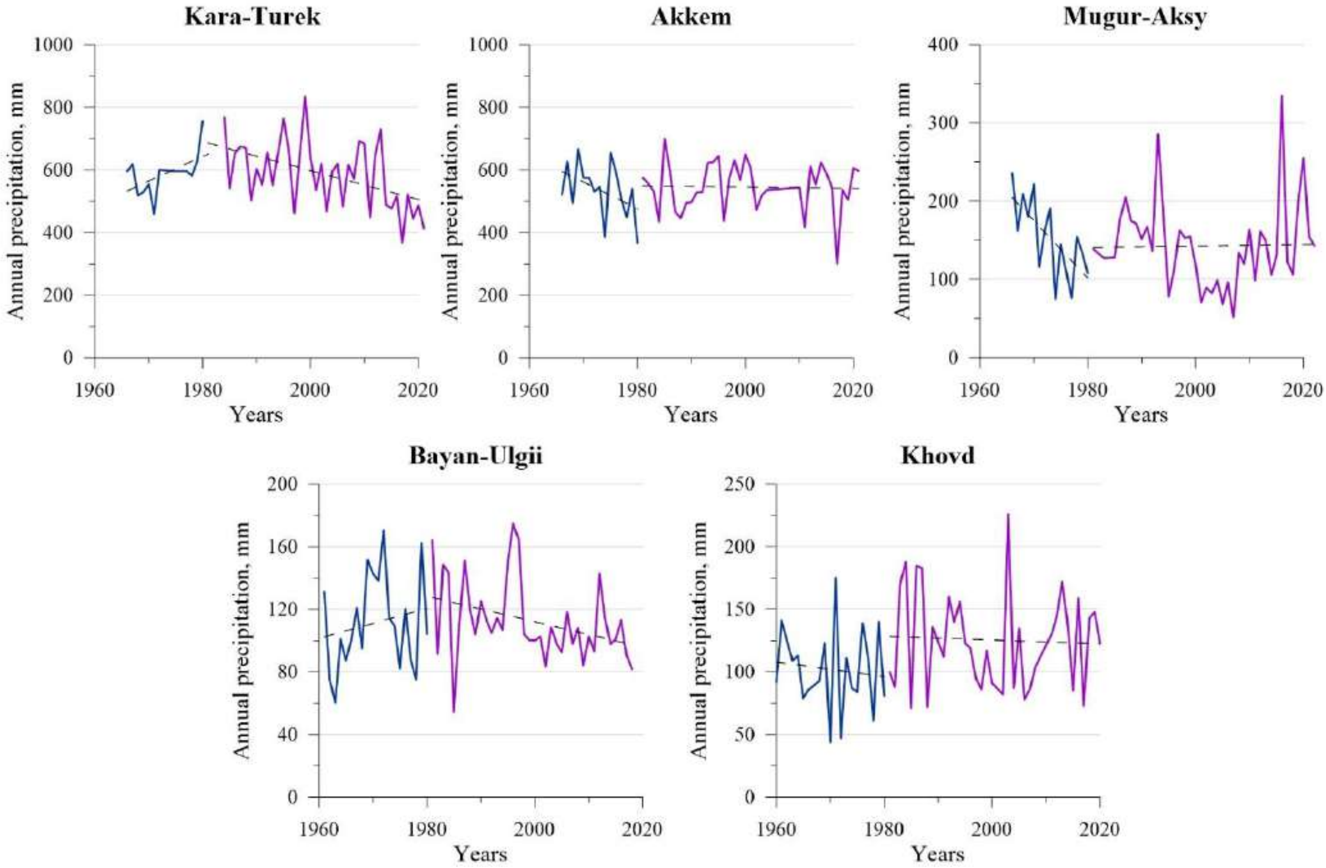


Fig. 4.3. Changes in average annual air temperatures at weather stations located in the study area (blue color – air temperature trend before 1980, red color – air temperature trend after 1980, dotted line shows air temperature trends).

It has been established that in the territory of the Central Altai the increase in average annual air temperature since 1980 has reached 0.2^{0}C/10 years, and for the territory of the South-Eastern Altai the average annual air temperature has increased by 0.25^{0}C/10 years.

For the time period under consideration, annual precipitation amounts were analyzed for those weather stations for which data were available (Fig. 4.4). A statistically significant reduction in annual precipitation since 1980 was detected for the Kara-Turek and Bayan-Ulgii weather stations. The amount of annual precipitation at the Akkem, Mugur-Aksy and Khovd weather stations has remained practically unchanged since 1980.



Kara-Turek

Akkem

Mugur-Aksy

Bayan-Ulgii

Khovd

Fig. 4.4. Changes in the annual amount of precipitation at weather stations in the study area (blue color - the amount of precipitation before 1980, purple color - the amount of precipitation after 1980, dotted line shows precipitation trends).

Thus, there is no clear trend in changes in the annual amount of precipitation according to weather stations in the study area, which is also noted in studies previously carried out for the Altai Mountains (Toropov et al., 2020). This indicates that the main reason influencing the reduction of glaciation in the high mountain areas of the Altai is an increase in air temperature.

Glaciation of the study area

The thesis examines moraine-dammed and periglacial lakes of large centers of glaciation in the Altai Mountains. Modern glaciation of the Altai occupies more than 1500 km^2 (Galakhov and Mukhametov, 1999; Kotlyakov et al., 2012). Within Russia, the Altai glaciation occupies about 800 km^2 (Kotlyakov, 2015). About 78% of the Altai glaciation area is located on the territory of the Central Altai (Nikitin, 2009; Kotlyakov et al., 2015). About 1% of the glaciation area is located to the west in the Ivanovsky, Kholzun and Listvyaga ridges. About 1% is located to the north-east of the central group – between it and Shapshal ridge (Catalog of Glaciers..., 1980). About 3% of glaciation is located on the Shapshalsky ridge and the Tsagan-Shibetu ridge (Catalog of Glaciers..., 1973). About 4% – to the south of them on the territory of the Sailyugem and Chikhacheva ridges and the Mongun-Taiga mountain massif (Catalog of Glaciers..., 1978) and 13% of the glaciation of the Russian Altai is located within the Tavan-Bogdo-Ola mountain massif and the Southern Altai ridge (Catalog of Glaciers ..., 1977).

The greatest glaciation is observed on the Katunsky Ridge and currently amounts to 198 km^2. The North-Chuya and South-Chuya ridges have approximately equal glaciation areas of 112.9 km^2 and 118 km^2, respectively. The Tavan-Bogdo-Ola mountain massif is the largest glaciation center in South-Eastern Altai with a glaciation area of 192.4 km^2 (Ganyushkin et al, 2023). The glaciation of the Mongun-Taiga and Tsambagarav mountain massifs is significantly smaller compared to the glaciation area of the above-described mountain massifs and amounts to 17.8 km^2 and 68.1 km^2, respectively (Ganyushkin et al, 2023).

The mountain areas under consideration combine various forms of glaciation. There are three main types of glaciers: valley, ridge, hanging, and their combinations. In addition, there are flat-top and slope glaciers. In areas with good moisture, depending on the morphology of the peaks and slopes, all forms of glaciation are found, among which valley, corrie-valley, and corrie glaciers predominate (the Central Altai), and in areas with less moisture, only small forms are found: corrie-hanging and flat-top glaciers (Mongun-Taiga and Tsambagarav mountain massifs) (Surface water resources..., 1969; Toropov et al., 2020).

In the Altai, the exposure of slopes occupied by glaciers is dominated by northern slopes. The glaciers margins are located at altitudes from 2000 to 3500 m. The glacier height feeding boundary from west to east increases from 2200 to 3200 m (Kotlyakov et al., 2015).

4.2. Temporal variability and distribution of moraine-dammed and periglacial lakes in the Altai

Of greatest interest for research are young periglacial and moraine-dammed lakes that form on modern moraines and the Little Ice Age moraines. These moraines differ from moraines of the historical stage in their lack of stability. Lakes formed on young moraines as a result of glacial retreat have active temporal variability due to the fact that they are connected to a glacier, and, accordingly, are unstable and outburst hazardous (a rapid increase in lakes can lead to weakening of the moraine dam, its destruction and subsequent outburst). In this regard, catalogs of lakes of the Katunsky, North-Chuya, South-Chuya ridges, the Tavan-Bogdo-Ola, Mongun-Taiga and Tsambagarav mountain massifs were compiled. Catalogs of high-mountain lakes were compiled on the basis of visual interpretation of satellite images for two time sections of 1998-2001 (Landsat-7 July 2000) and 2020-2022 (Sentinel-2-L2A July 2022) to assess lake dynamics over the past 22 years. Changes in the number of lakes and their areas were determined in the ArcMap 10.4.1 programme (ESRI Inc., USA) by manual interpretation using a combination of «natural colors» channels (for all satellite images). The spatial resolution of Landsat-7, 8 and 9 satellite images was improved by combining with panchromatic images (15 m resolution), and Sentinel images with a resolution of 10 m were interpreted without improvement.

Analysis of Landsat satellite images for 2000 and 2022 (Appendix 3) for the high mountain areas of Altai showed that over the past 22 years the number of lakes has increased on the territory of the

North-Chuya ridge by 114% (from 28 to 60 lakes), on the territory of the South-Chuya ridge by 87% (from 39 to 73 lakes), on the territory of the Katunsky ridge by 56% (from 57 to 89 lakes), on the territory of the Tavan-Bogdo-Ola mountain massif by 54% (from 44 to 68 lakes), on the territory of the Mongun-Taiga mountain massif by 50% (from 8 up to 12 lakes), and on the territory of the Tsambagarav mountain massif (North-western Mongolia) the number of lakes remained virtually unchanged (from 7 to 8 lakes) (Fig. 4.4). As a result of using the SRTM digital elevation model, a distribution of lake heights was obtained for all the studied mountain massifs (Fig. 4.5).

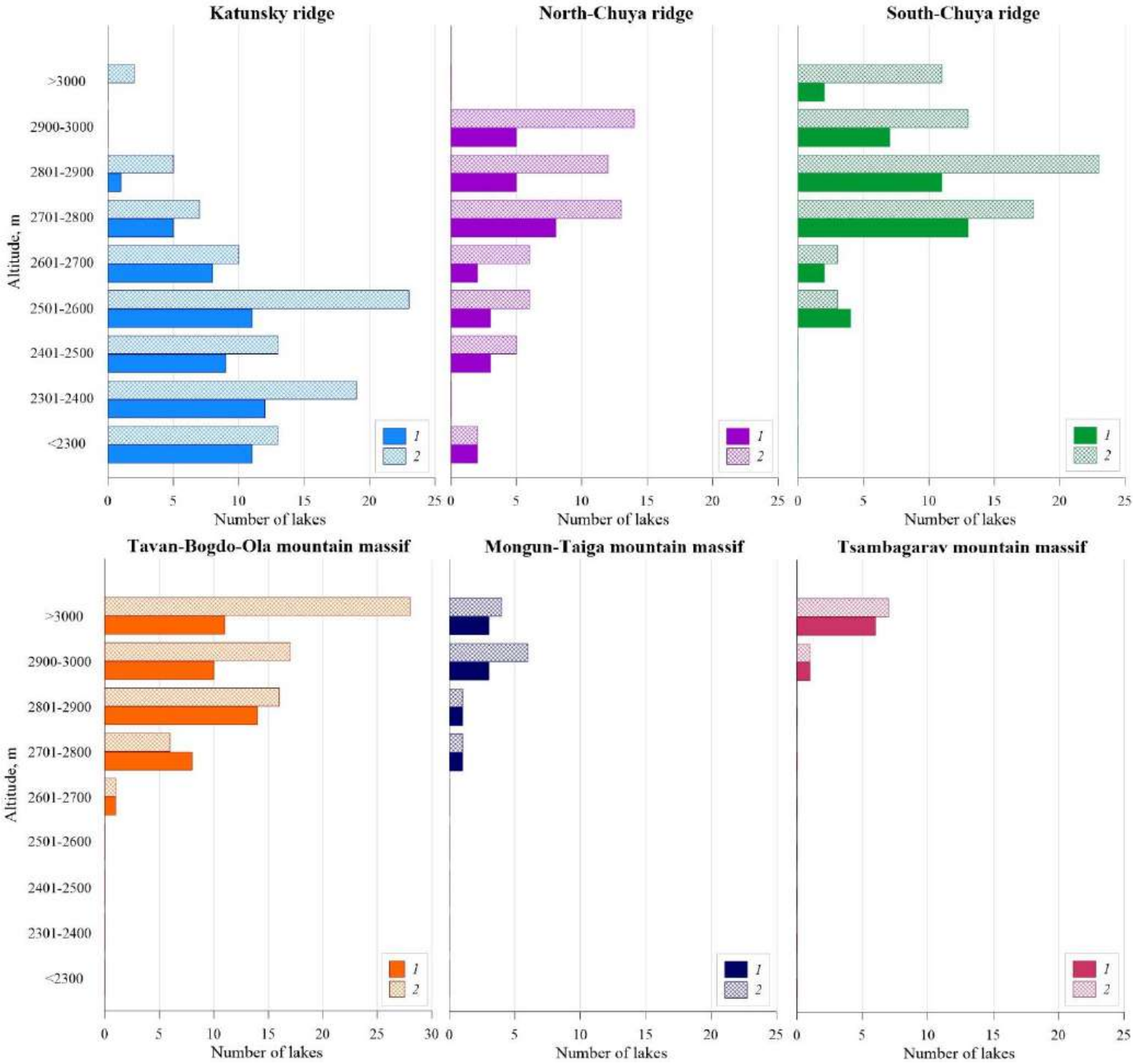


Fig. 4.5. Distribution of the number of moraine-dammed and periglacial lakes by altitude for 2000 (1) and 2022 (2) on the territory of the Central Altai (Katunsky, North-Chuya and South-Chuya ridges) and South-Eastern Altai (Tavan-Bogdo-Ola, Mongun-Taiga and Tsambagarav mountain massifs).

An analysis of the distribution of lakes by altitude showed that there is a difference in the nature of the distribution of lakes between the Central and the South-Eastern Altai. For example, with a slight difference in the glaciation area, altitude and number of lakes, on the territory of the Tavan-Bogdo-Ola mountain massif (South-Eastern Altai) the lakes are located in higher altitude intervals (starting from 2600 m), compared to the ridges of the Central Altai, where lakes are located at lower altitude intervals (from 2200 m). This is due to the fact that in the territory of the Central Altai, due to more humid climatic conditions (the annual precipitation amount is 2-4 times greater than the amount of precipitation in the territory of the South-Eastern Altai), the glaciers margins are located lower than in the territory of the South-Eastern Altai, thereby conditions are created for the formation of lakes in lower altitude intervals.

Also, the distribution of moraine-dammed and periglacial lakes by altitude showed that in most of the mountain massifs there was a shift in the interval of the area of greatest distribution of lakes (Table 4.1).

Table 4.1.

Altitudinal intervals of the greatest distribution of moraine-dammed and periglacial lakes in the study territory.

Mountain massifs /ridge	**Altitudinal intervals of the greatest distribution of lakes, m**	
	2000	**2022**
Katunsky	2301-2400	2501-2600
North-Chuya	2701-2800	2900-3000
South-Chuya	2701-2800	2801-2900
Tavan-Bogdo-Ola	2801-2900	>3000
Mongun-Taiga	2801-3000	2801-3000
Tsambagarav	>3000	>3000

Until 2000, on the North-Chuya and South-Chuya ridges territory, most of the lakes were in the range of 2701-2800 m, in the Katunsky ridge territory - in the range of 2301-2400 m, in the Tavan-Bogdo-Ola mountain massif territory most of the lakes were located in the range of 2801-2900 m. The largest number of lakes for 2022 are located in the marginal parts of modern glaciers: in the altitude range of 2900 - 3000 m above sea level, for the North-Chuya ridge, in the range of 2800-2900 m - for the South-Chuya ridge, in the range of 2500- 2600 m – for the Katunsky ridge, and at an altitude of more than 3000 m – for the Tavan-Bogdo-Ola mountain massif. Thus, the upper limit of the interval of the area of maximum distribution of periglacial and moraine-dammed lakes at present (2022) is located 100-200 m higher in altitude compared to 2000, which is associated with the ongoing retreat of the glaciers margins. However, for the Mongun-Taiga and Tsambagarav mountain massifs, there is no tendency to shift the area of maximum distribution of lakes. This is due to the fact that the glaciated area of these massifs is much smaller compared to the mountain massifs described above, that is, the volume of glacial melt water is not enough to form new periglacial and moraine-dammed lakes. It is also clear that the total number of existing lakes located in these mountain massifs is significantly lower than in the other study high-mountain areas. That is, there is a close connection between the retreat of glaciers and the changes occurring in moraine-dammed and periglacial lakes. Thus, on the territory of mountain massifs with a large area of glaciation, when glaciers retreat, new lakes form in areas freed from ice, with an associated shift in the area of the greatest distribution of lakes, and in territories with a small area of glaciation, practically no changes occur in the number of lakes and their location. Thus, we can conclude that lakes are indicators of the process of mountain glaciation degradation and reflect its changes.

Also, analysis of satellite images made it possible to establish how the ratio of lake surface to drainage area changed from 2000 to 2022, as well as how the total area of lakes by altitude changed (Fig. 4.6). The ratio of lake surface to drainage area was calculated within the boundaries of the Little Ice Age moraine.

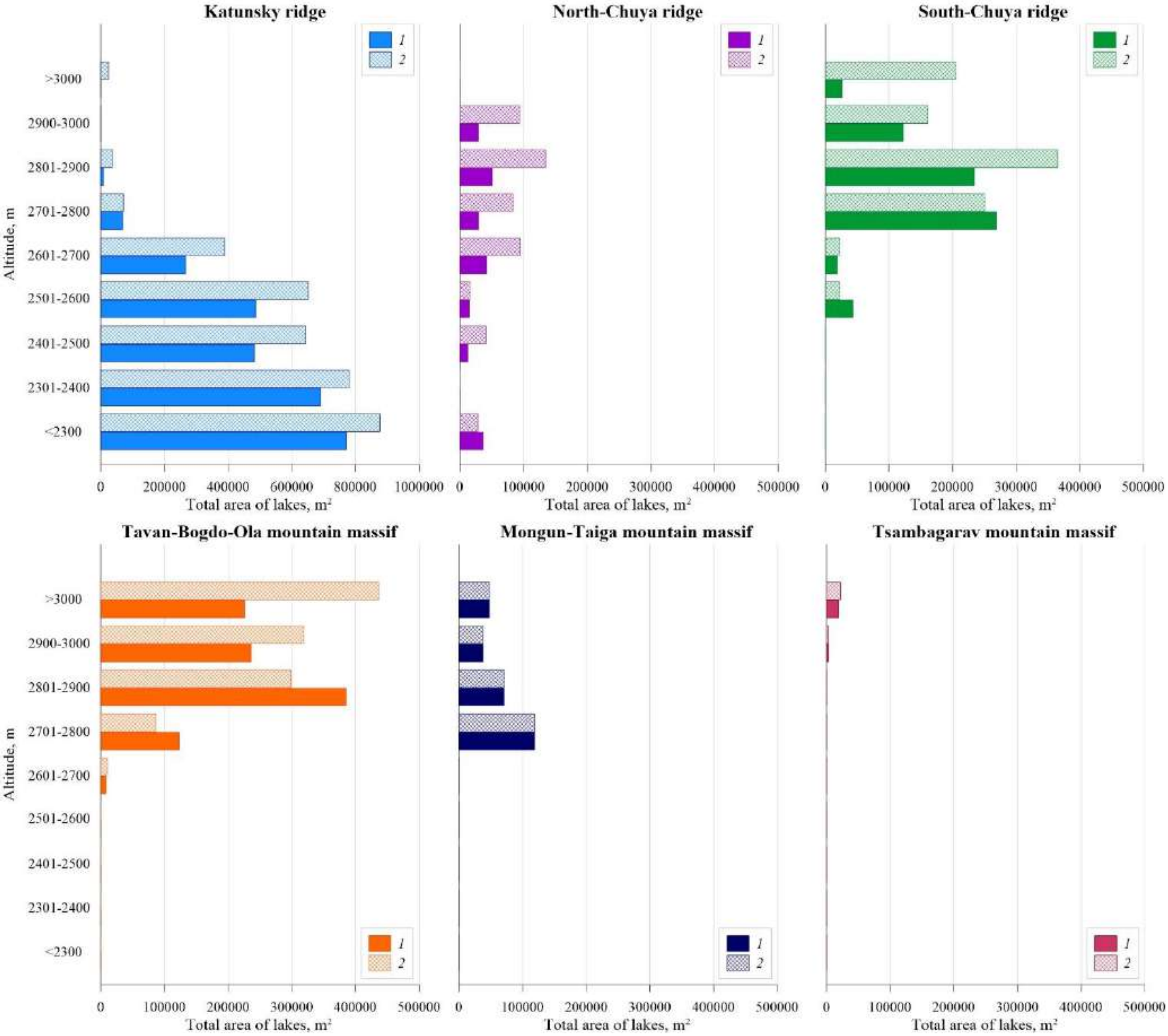


Fig. 4.6. Distribution by altitude of the total area of moraine-dammed and periglacial lakes for 2000 (1) and 2022 (2) on the territory of the Central Altai (Katunsky, North-Chuya and South-Chuya ridges) and South-Eastern Altai (Tavan-Bogdo-Ola, Mongun-Taiga and Tsambagarav mountain massifs).

According to the distribution of the total area of lakes by altitude, it was revealed that the trend of changes in the areas of lakes is similar to the trend of changes in their number. That is, in the study territory there is an increase in the total area of periglacial and moraine-dammed lakes and the ratio of lake surface to drainage area (Table 4.2). The ratio of lake surface to drainage area was calculated as the ratio of the total surface area of lakes to the total area of the territory limited by the Little Ice Age moraine for each mountain massif (in %). The total area of mountain massifs limited the Little Ice Age moraines was taken from published works (Okishev, 2011; Ganyushkin et al, 2022).

Table 4.2.

Changes in the total area of moraine-dammed and periglacial lakes and the ratio of lake surface to drainage area in the study territory.

Mountain massif/ridge	**The total area of lakes, thousand m^2**			**the ratio of lake surface to drainage area**	
	2000	**2022**	**Changing, %**	**2000**	**2022**
Katunsky	2773	3470	25	0.84	1.05
North-Chuya	213	491	130	0.07	0.16
South-Chuya	714	1028	44	0.23	0.33
Tavan-Bogdo-Ola	978	1149	17	0.28	0.32
Mongun-Taiga	274	290	6	0.8	0.85
Tsambagarav	22	25	14	0.017	0.019

It has been established that on the Katunsky and South-Chuya ridges territory, as well as on the Tavan-Bogdo-Ola massif territory, the largest total area of lakes is observed. Moreover, the most significant changes in the total area of lakes from 2000 to 2022 occurred on the ridges of the Central Altai (from 25 to 130%), while the total area of lakes located on the South-Eastern Altai territory changed slightly (from 6 to 17%). For the Mongun-Taiga and Tsambagarav mountain massifs, minor changes in the lakes areas are due to the fact that the glaciation area of these massifs is small compared to other territories, and the amount of meltwater runoff is not enough to increase the lakes. If we compare the Tavan-Bogdo-Ola mountain massif with the ridges of the Central Altai, then with a similar total lakes area, the lakes area changed by only 17%. This is due to the moisture regime of the territory and the altitude of the marginal parts of the glaciers. When the glacier retreats and, accordingly, when the connection between the lake and the glacier is reduced against the backdrop of a small annual precipitation amount, the area of lakes decreases. It is this trend that is characteristic of lower altitude intervals for the Tavan-Bogdo-Ola mountain massif, and this also takes place (only to a lesser extent) for low altitude intervals of the South-Chuya ridge, since it is located further east than the Katunsky and North-Chuya ridges.

Thus, in the study territory over the past 22 years, the following trend has been noted: in the territory of the Central Altai there is an increase in both the number of periglacial and moraine-dammed lakes and their total area. As for the South-Eastern Altai territory, the Mongun-Taiga and Tsambagarav mountain massifs, due to their small glaciated area, are characterized by a small number of moraine-dammed lakes, which change little over time. The total area of lakes on the territory of these mountain massifs also remains virtually unchanged. However, for the Tavan-Bogdo-Ola mountain massif, a different trend is observed: in higher altitude intervals there is both an increase in the number of lakes and an increase in their total area, but in lower altitude intervals there is a decrease in the number and lakes total area. This indicates that in the South-Eastern Altai territory, which is characterized by a more arid climate, the existence of lakes is completely determined by the presence of sufficient supply of melted glacial waters to the lakes. The ongoing retreat of glaciers leads to a reduction in the connection of moraine-dammed lakes located in lower altitude intervals with glaciers, resulting in the lakes degradation up to their complete extinction.

4.3. Description of the level regime of periglacial and moraine-dammed lakes at different stages of development, based on field studies and Earth remote sensing data

An important issue related to the study of outburst-hazardous moraine-dammed lakes is the study of the process of lakes formation, their evolution and stages of development. Currently, very little attention is paid to this area, which was confirmed by a review of published scientific works (Chapter 1 of this thesis). It should be noted scientific studies (Zimnitsky, 2005; Pryakhina et al., 2021; Rasputina et al., 2022), which examined and described the stages of lake development.

In this thesis, based on a generalization of the available published material on this issue, long-term data from field hydrological observations (in which the author took part) on the periglacial and moraine-dammed lakes of the Altai, which are at different stages of development, and data obtained from the analysis of satellite images, we introduced characteristics according to which it seems possible to attribute the study lake to one or another stage of development.

According to the classification proposed in (Zimnitsky, 2005) and supplemented in (Pryakhina et al., 2021), three stages of development of moraine-dammed and periglacial lakes can be distinguished: transgressive, regressive and quasi-stable.

4.3.1. Transgressive stage of development

The transgressive stage (growth phase) is characterized by the filling of the moraine-dammed lake basin with melted glacial waters with an increase in water level, an increase in the surface area and the lake depth.

Almost all young (up to 15-20 years old) periglacial lakes are at the transgressive stage of development. Such lakes are most often small in size (area is up to 6000 m^2), located at the glacier margin or in close proximity to it, and are partially surrounded by modern moraine deposits. The main source of feed is melted glacial waters. Examples of lakes that are at the earliest stage of development, and on which field hydrological studies were carried out, are lakes «Maloe» (Mongun-Taiga mountain massif), «Gachy-Kol» (Tavan-Bogdo-Ola mountain massif), «Chill» and «HB» (South-Chuya Ridge).

Observations of the water level in lakes showed that the level regime of lakes during the transgressive phase is characterized by intra-daily dynamics due to different intensities of ablation, and repeats the daily variation of air temperature with some delay (Fig. 4.7a, b). The amplitude of water level fluctuations can reach 150-170 cm.

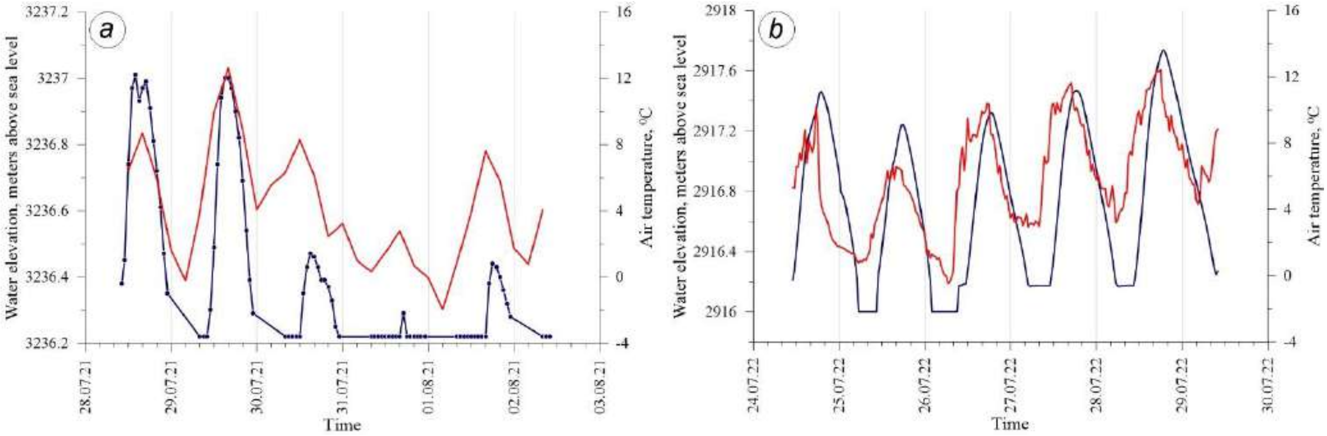


Fig. 4.7. Combined variation of the water level on Lake «Gachy-Kol» and air temperature at the weather station installed at the site of field work (3260 m above sea level) (a). Combined variation of the water level on Lake «Chill» and air temperature at the weather station installed at the site of field work (3000 m above sea level) (b).

Periglacial lakes have a complex level regime not only in the daily, but also in the annual cycle (Fig. 4.8). Thus, analysis of changes in area based on satellite images of Lake «Gachy-Kol» (Tavan-Bogdo-Ola mountain range), located in the marginal part of glacier No. 12 (Catalogue of Glaciers..., 1977; Ganyushkin et al., 2022) showed that the lake existed only during the period of glacier ablation: in mid-June the lake basin was filled, and at the end of September the water was completely drained through filtration channels. At the same time, at the end of the warm period of each subsequent year, the volume and the lake surface area became larger (Fig. 4.8). A similar trend in changes in surface areas was noted for Lake «Maloe», adjacent to glacier No. 24 (Mongun-Taiga massif) (Rasputina et al., 2021a): the lake area increased by 74% from 2016 to 2022 (Fig. 4.8). Lake «Chill», located on the South-Chuya ridge territory, has the same seasonal and interannual changes in area (Fig. 4.8).

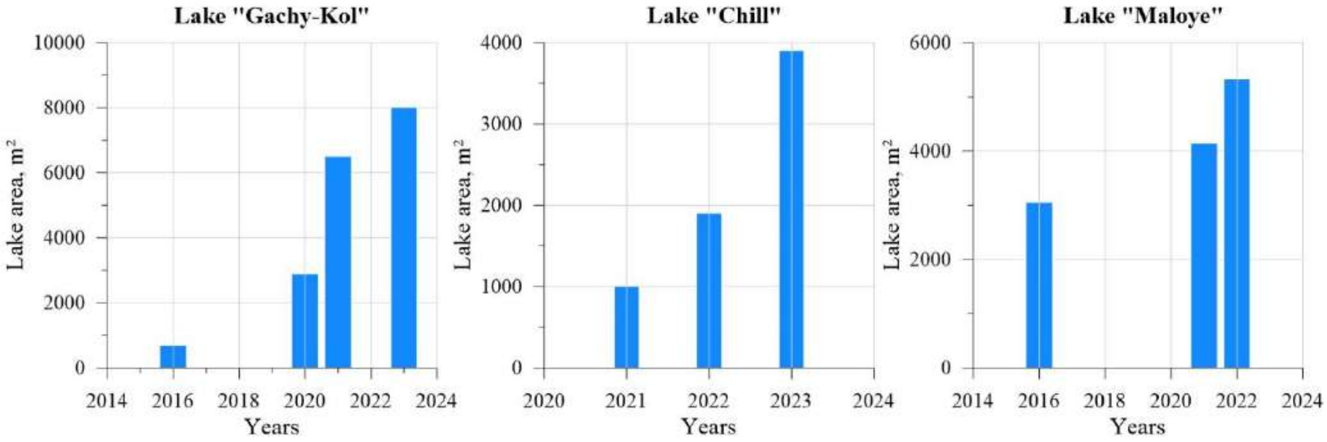


Fig. 4.8. Changes in the areas of the periglacial lakes «Gachy-Kol», «Chill» and «Maloye», which are in a transgressive stage of development. The lake area was determined at the end of the ablation period.

Of interest are the «retreating» lakes, which, while maintaining a connection with the retreating glacier, change their configuration. An example of a «retreating» lake is a periglacial lake located in the Khovd river basin on the Kharkhiraa mountain massif territory (North-western Mongolia) (Fig. 4.9). With a visual reduction in area, the lake volume may increase: most likely, the territory freed from ice has a deeper incision, and the lake waters «flow» closer to the glacier. Despite the absence of an increase in the lake surface area in a long-term perspective, «retreating» lakes that have a direct connection with the glacier, in our opinion, should be attributed to the transgressive stage of development.

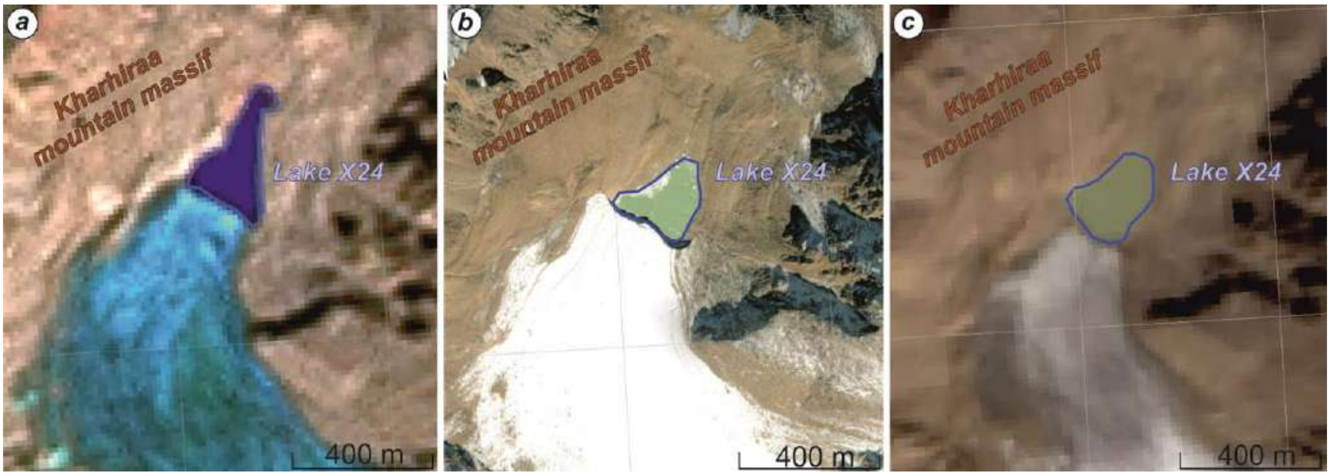


Fig. 4.9. Changing the configuration of the «retreating» lake H24 in the Khovd river basin (Kharhiraa mountain massif, North-western Mongolia) from 2000 to 2022: a – June 2000; b – August 2012; c – August 2022 (the name is given according to the emerging catalog of lakes).

4.3.2. Regressive stage of development

The regressive stage of development of a lake is characterized by a reduction in the size of the lake and a decrease in its volume at the end of the ablation period in a long-term period. This stage can proceed quickly (from several hours to several months) when the dam is destroyed or lake water is released through filtration channels inside the dam, or it can last for a long period (years). When the connection between the lake and the glacier is reduced, i.e. a gradual decrease in glacier feed, the process of regression stretches over years. For example, the moraine-dammed lakes «Khoinur» and «Verkhnee» (Mongun-Taiga mountain massif), the surface area of which, due to the loss of direct connection with retreating glaciers, began to decline in 2012 and 2014 accordingly, the state of stability (quasi-stable stage) has not yet been reached (Fig. 4.10a, b).

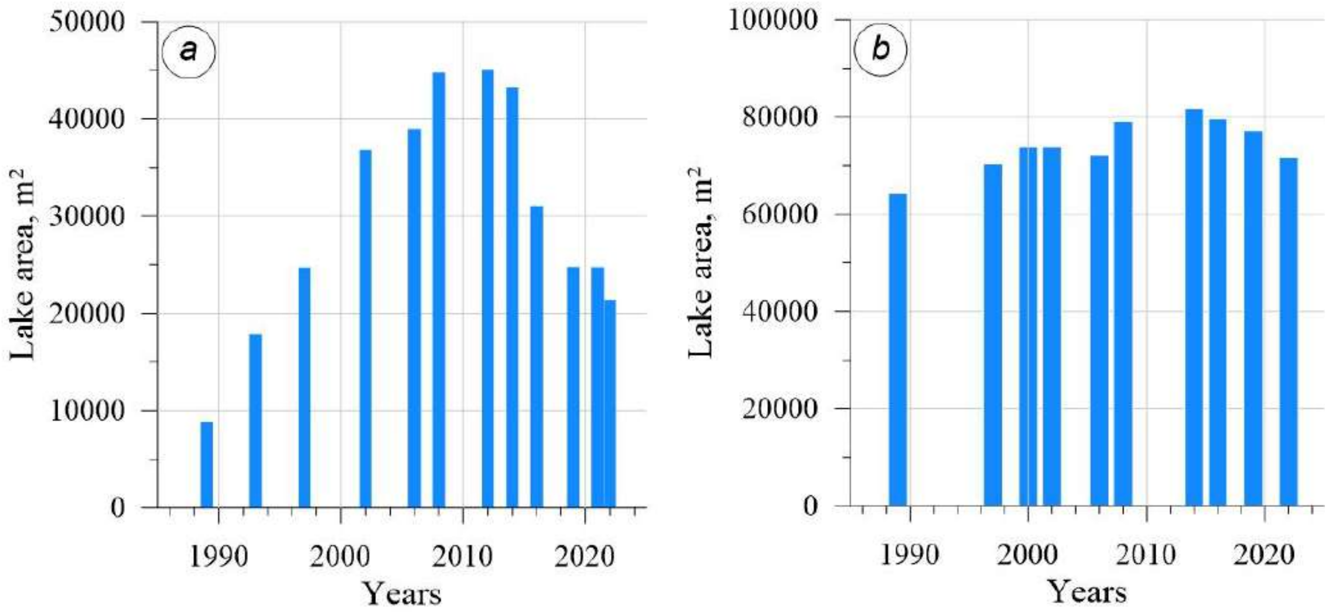


Fig. 4.10. Changes in the area of Lake «Khoinur» (a) and Lake «Verkhneye» (b) over a long-term period.

4.3.3. Lake outburst as a special case of a regressive stage of development

A special case of the development of moraine-dammed lakes is a lake outburst associated with the destruction of the lake moraine dam, as a result of which the lake basin is quickly emptied (in this case, the duration of the regressive stage can be several hours) with the formation of an outburst flood. Or the emptying of lake water through filtration channels without destroying the moraine dam (in this case, the duration of the reduction in the lake size can be several months). The lake's outburst occurs as a result of the weakening of the moraine dam. The weakening of the dam is due to an increase in the lake size (that is, when the moraine-dammed lake is in a transgressive stage of development). An increase in the water level in the lake can lead to its overtopping and subsequent overflow of water over the crest, or to the erosion of the filtration channel in the dam body (the formation of an outburst flood as a result of a lake outburst in the case of the two most common outburst trigger mechanisms is described in detail in Section 2.1 of this thesis).

An example of a lake outburst is the outburst of Lake Maashey (North-Chuya Ridge) as a result of the dam destruction. The lake outburst was preceded by a long increase in its size (transgressive stage), and the impact of an external trigger in the form of prolonged intense precipitation led to a rise in the water level in the lake and watering of the dam, its weakening, erosion and subsequent lake outburst with the formation of an outburst flood and associated mudflow (a detailed description of the development of the lake and its outburst is described in section 4.4).

The emptying of the lake through filtration channels can be considered using the example of Lake «Barsovo» (the Russian part of the Tavan-Bogdo-Ola mountain massif). During a visual survey of the lake in 2021, a surface water outflow from the lake was revealed, which, when the water level in the lake decreased, passed from surface to underground and was recorded on the outside of the damming moraine in the form of seepage. This allowed us to suggest a high probability of the lake emptying (Rasputina et al., 2022). Analysis of satellite images at different times over a long-term period showed that in the period of time preceding the emptying, Lake «Barsovo» was also in a transgressive stage of development (Fig. 4.11).

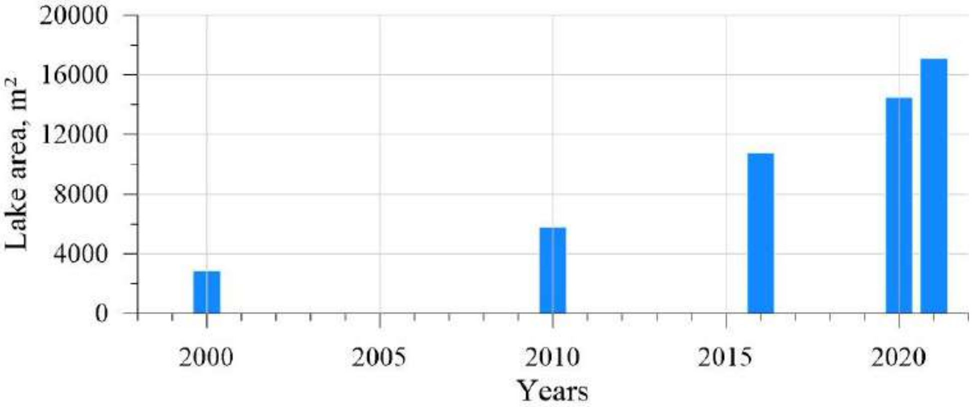


Fig. 4.11. Change in the area of Lake «Barsovo» over time.

At the end of June 2022, according to the analysis of satellite images, the outflow process began, and by September 3, the reservoir was completely emptied (Fig. 4.12). Based on bathymetric and tacheometric surveys completed in 2021, the lake volumes during the period of its emptying were calculated (Fig. 4.13). The uniform lake emptying indicates that the channel through which the water outflow occurred did not change in size and was located in the lower part of the lake basin.

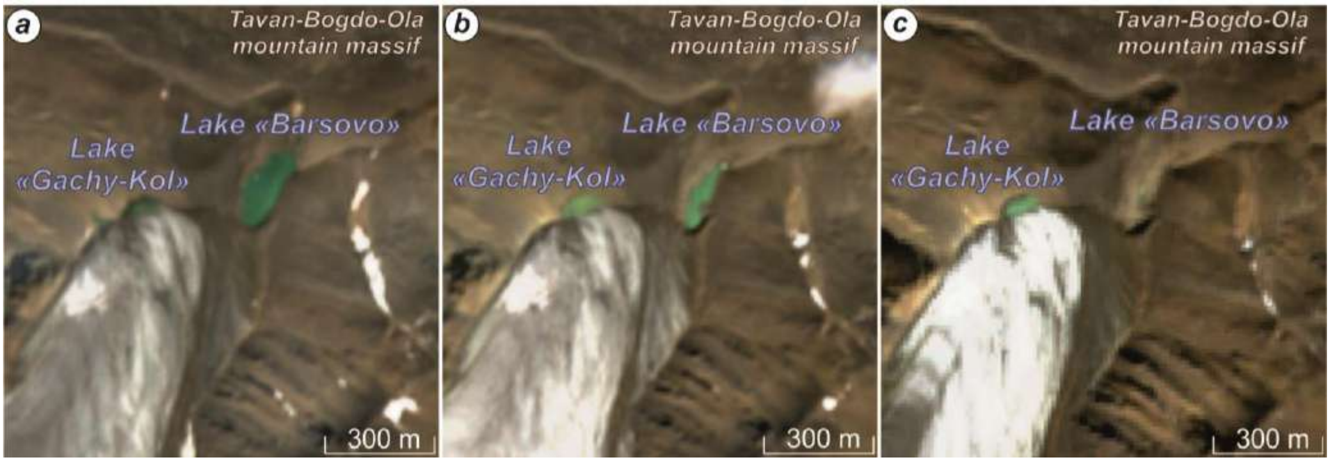


Fig. 4.12. Changes in the area of Lake «Barsovo» during its emptying.

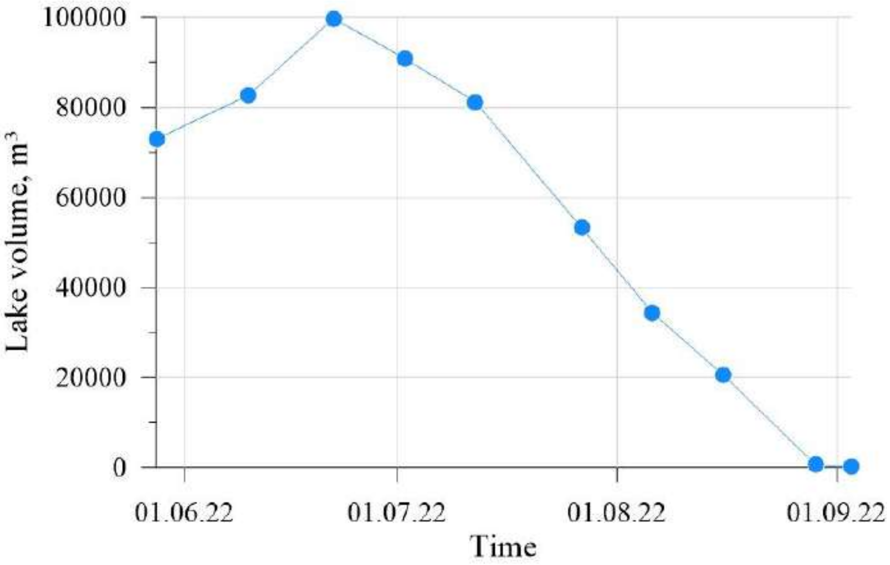


Fig. 4.13. Changes in the volume of Lake «Barsovo» during its emptying through filtration channels.

Since Lake «Barsovo» was a periglacial lake, and its main source of feed was melted glacial waters, in the summer the lake had its maximum size, and from September the water level began to decrease. With the complete emptying of the lake in the summer of 2022, the decrease in water level and the corresponding reduction in the lake area began in June 2022. Thus, the shift in the emptying of the water mass to an earlier warm period for moraine-dammed and periglacial lakes is a sign of a high outburst hazard of the lake and the need for monitoring observations. The volume and maximum discharge of an outburst flood depend on the height and size of the resulting filtration channel.

Thus, the outburst of the lake dam and the emptying of the lake through filtration channels lead to a decrease in the lake size until its complete emptying. In a situation where partial emptying of a lake basin occurs as a result of an outburst or emptying of a water through channels, the lake continues to exist and can enter a quasi-stable stage of development. If the surface flow is blocked or the filtration channels are blocked after an outburst has occurred, the lake may again begin to increase in size and enter the transgressive stage of development. In this case, a repeated lake outburst may occur (regressive stage of development). Thus, if the lake continues to exist after the outburst, then with further development the lake can move to any stage of development depending on the exogenetic processes occurring in its catchment area, changes in the climatic situation and trigger mechanisms that can lead to a repeated outburst.

4.3.4. Quasi-stable stage of development

The quasi-stable stage is characterized by a stable state of the lake, that is, over a long-term period, the lake area and its volume practically do not change in size.

Intra-annual and long-term variability of levels can be indirectly judged by changes in the lake area. For example, Lake «Tamozhennoye» has entered a quasi-stable stage (South-Chuya Ridge), as evidenced by the long-term reduction in the surface area that has ceased since 2014 (Fig. 4.14a). Also, a quasi-stable state is characteristic of the corrie Lake «Lagernoe» , dammed by a rock riegel, the surface area of which did not change significantly from 1987 to the end of the ablation period (Fig. 4.14b).

The daily regime of the levels of lakes that are in a quasi-stable stage is significantly influenced by the runoff of liquid precipitation from the part of the catchment area not occupied by the glacier. During the rainy period, the rise and fall of the level extends over several days, and in the absence of precipitation, the water level has a pronounced intra-daily variation, repeating the variation of air temperature taking into account the travel time (in our example - 8-10 hours) (Fig. 4.15a, b).

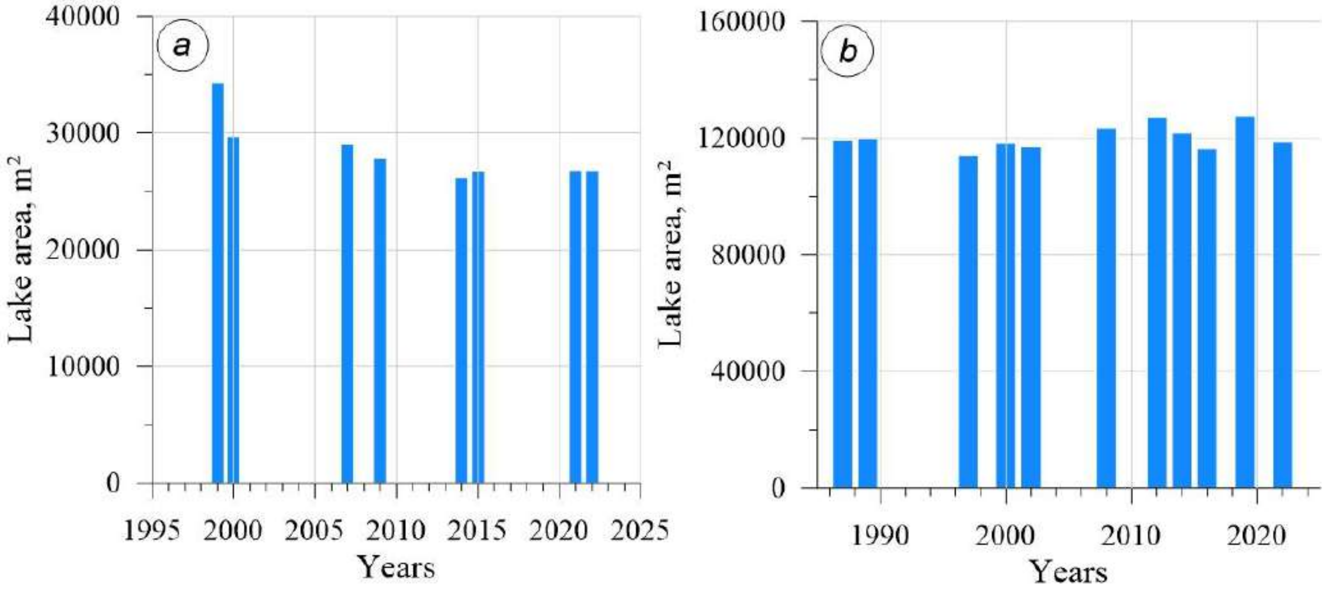


Рис. 4.14. Changes in the area of Lake «Tamozhennoye» (a) and Lake «Lagernoye» (b).

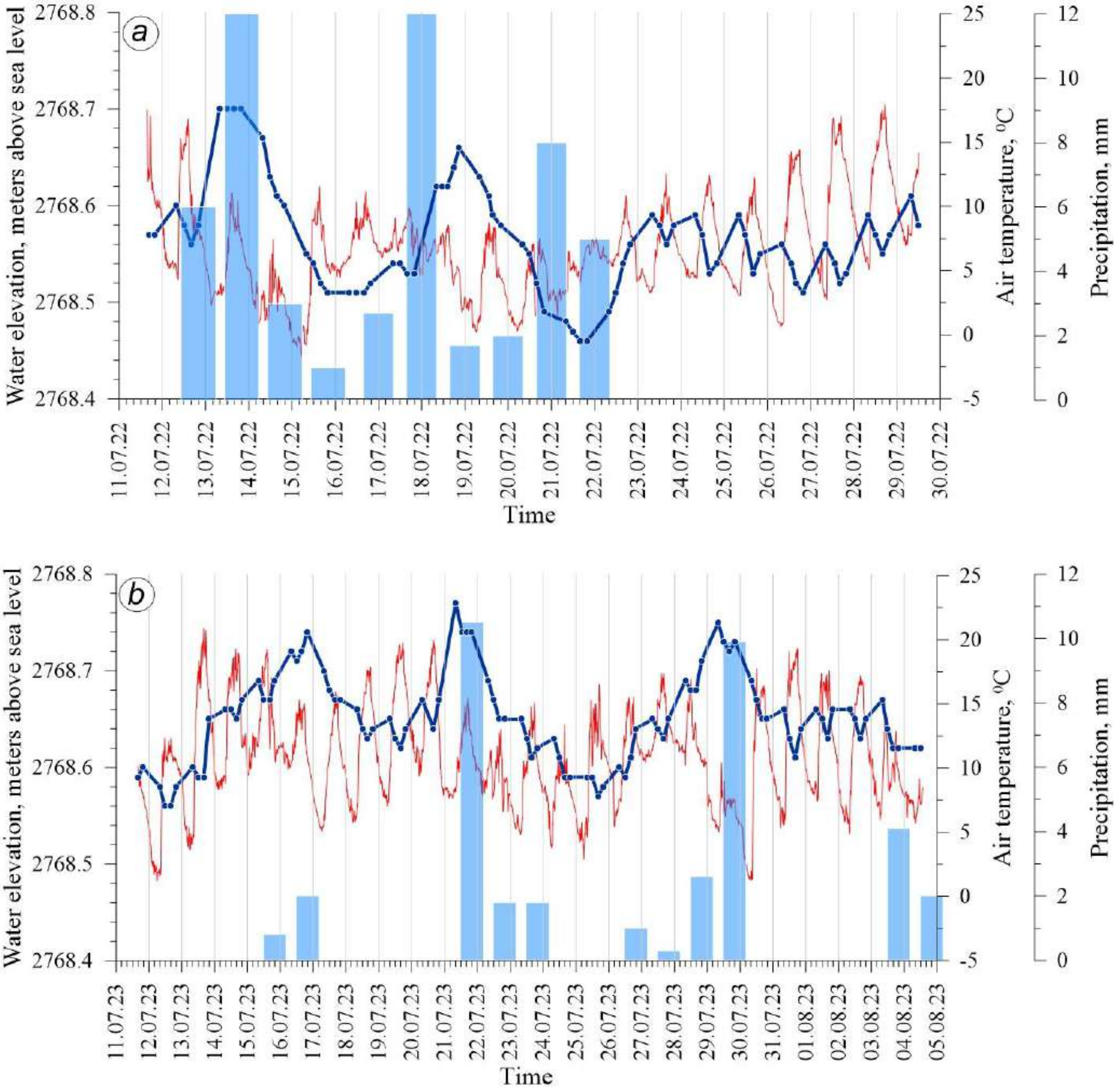


Fig. 4.15. Water level courses on Lake «Tamozhennoye» in 2022 (a) and 2023 (b).

In most cases, moraine-dammed lakes in their development successively go through the stages of transgression, regression and pass into a quasi-stable state. In some cases, the trend of lake development may change. For example, Lake Nurgan, located on the territory of the Tsambagarav mountain massif (Mongolia), has gone through the main phase of the regressive stage, as evidenced by traces of changes in the volume and direction of the lake’s flow preserved in the relief. Destruction of the moraine line between 1948 and 1968 (Pryakhina et al., 2021) caused a partial emptying of the lake, and the loss of direct connection with the retreating the Eregtiin glacier led to the transition from a periglacial lake to a moraine-dammed one. During field work in 2019, an area with active melt-out and soil collapse was discovered in the north-eastern part of the slope of the lake basin (Pryakhina et al., 2021). Due to the intensification of thermal erosion in recent years in the Altai Mountains (Chistyakov, Ganiushkin, 2015), monitoring of the process was continued using Sentinel satellite images. It was revealed that thermal erosion collapse of the dam has led to a displacement of the lake contour in the northeastern part over the past 2 years by approximately 10-15 m. At the same time, over four years the lake area practically did not change: 62100 m^2 – in 2019 (obtained from field data); 62200 m^2 and 61900 m^2 in 2020 and 2022, respectively (according to remote sensing data). The increase in the lake area at the end of the ablation period in 2023 by 5.5% compared to 2022 may indicate the beginning of the next transgressive stage. The continued retreat of the edge of the moraine dam can lead to its destruction and possible the lake outburst and transition to a regressive stage.

Based on the results of the completed descriptions of the stages of development of lakes and the generalization of hydrographic descriptions, field observation data and the results of interpretation of satellite images, the characteristics of lakes at various stages of development were detailed (Table 4.3).

Table 4.3.

Generalized characteristics of lakes at different stages of development

Stage of the lake development	Morphological characteristics	Hydrological characteristics	Temporal variability of morphometric characteristics
transgressive	time of formation no more than 20 years ago; small sizes (up to 6000 m^2); location in close proximity to the glacier	pronounced daily and long-term variations in water levels; predominance of glacial feeding	gradual increase in the area and depth of the lake at the end of the ablation season of each subsequent year
regressive	partially emptied basin, sometimes the presence of lake terraces; the presence of a breach in the dam; presence of an outflow stream	a decrease in water level over a long-term/seasonal period as a result of a reduction in glacier feeding during glacier retreat or during partial emptying through filtration channels; sometimes a sharp fall in level in case of a dam outburst	a gradual decrease in the area and depth of the lake at the end of the ablation season of each subsequent year, sometimes a sharp reduction in the lake as a result of the dam destruction
quasi-stable	partially emptied basin, sometimes the presence of lake terraces; the presence of a breach in the dam; presence of an outflow stream	absence of significant changes in water level over many years; during the ablation season during the period of precipitation, intraday fluctuations in water level are not pronounced	changes in the lake size over a long-term period are weakly expressed

The distribution of modern periglacial and moraine lakes by stages of development was carried out on the basis of an amended classification (Table 4.3). Due to the lack of information about the level regime of lakes according to field research, the distribution of lakes in the studied mountain ridges by stages of development (Fig. 4.16) was carried out based on the results of the analysis of satellite images. In this case, to classify lakes, the criteria «Morphological characteristics» and «Temporal variability of morphometric characteristics» of the proposed classification were used (Table 4.3).

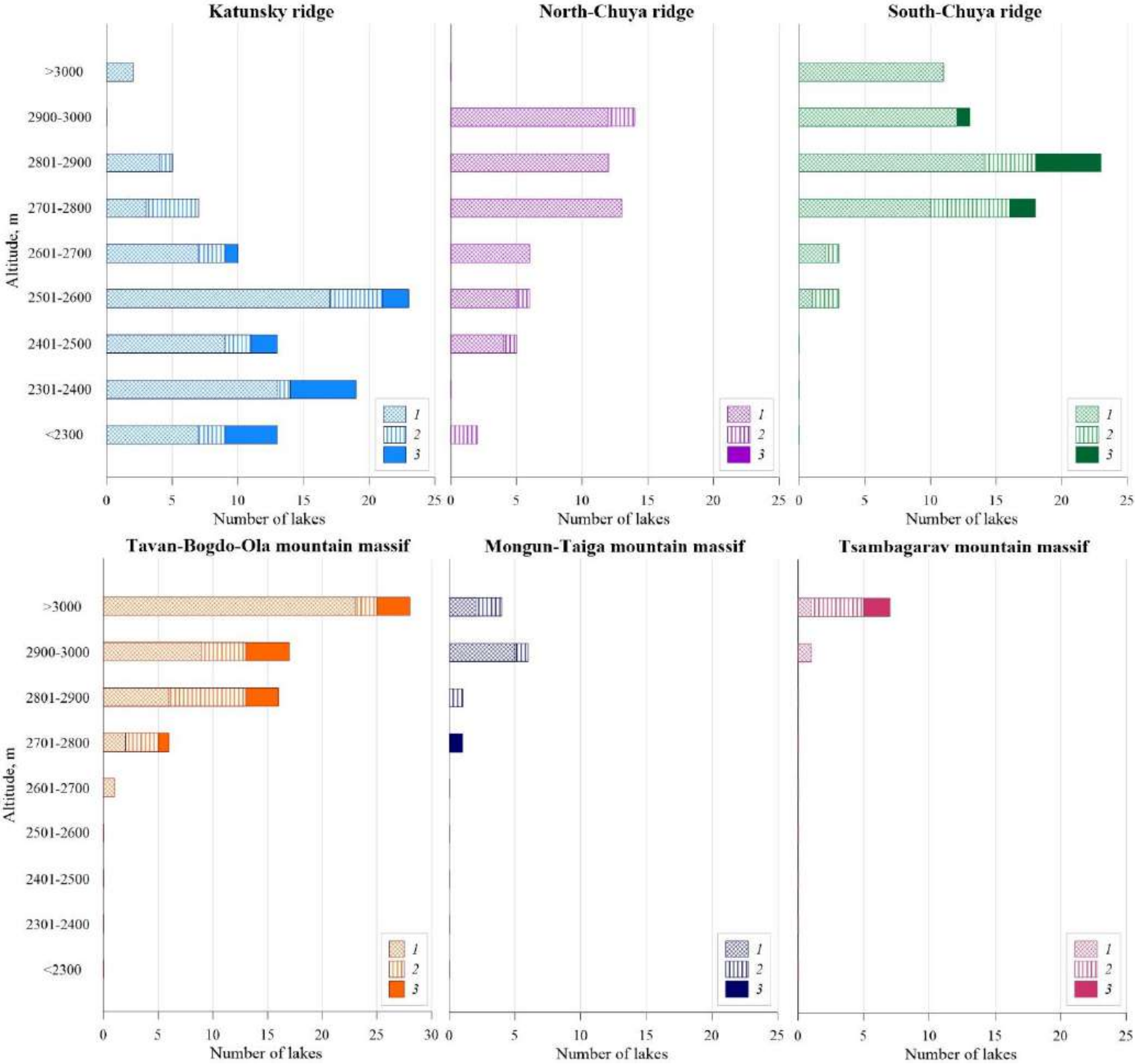


Fig. 4.16. Distribution of moraine-dammed and periglacial lakes by stages of development and by altitude in the territory of the Central Altai (Katunsky, North-Chuya and South-Chuya ridges) and the South-Eastern Altai (Tavan-Bogdo-Ola, Mongun-Taiga and Tsambagarav mountain massifs). Designations: 1 – transgressive, 2 – regressive, 3 – quasi-stable stages of development.

It has been established that most modern lakes are in a transgressive stage of development. There is a tendency for the percentage of lakes (out of the total number of lakes) in the transgressive stage to increase with altitude in the territory of the Central Altai and the Tavan-Bogdo-Ola mountain massif, since in higher altitude intervals there are modern glaciers margins, during the retreat of which they are formed new lakes. For the Mongun-Taiga and Tsambagarav mountain massifs, such a trend is not observed, due to the small glaciation area, the melting of which does not lead to the formation of new and growth of existing lakes. It is characteristic of the Central Altai and the Tavan-Bogdo-Ola mountain massif that lakes in the regressive and quasi-stable stages are located in lower altitude intervals, since the connection of these lakes with glaciers is reduced due to their retreat. However, for the Mongun-Taiga and Tsambagarav mountain massifs there is no such trend.

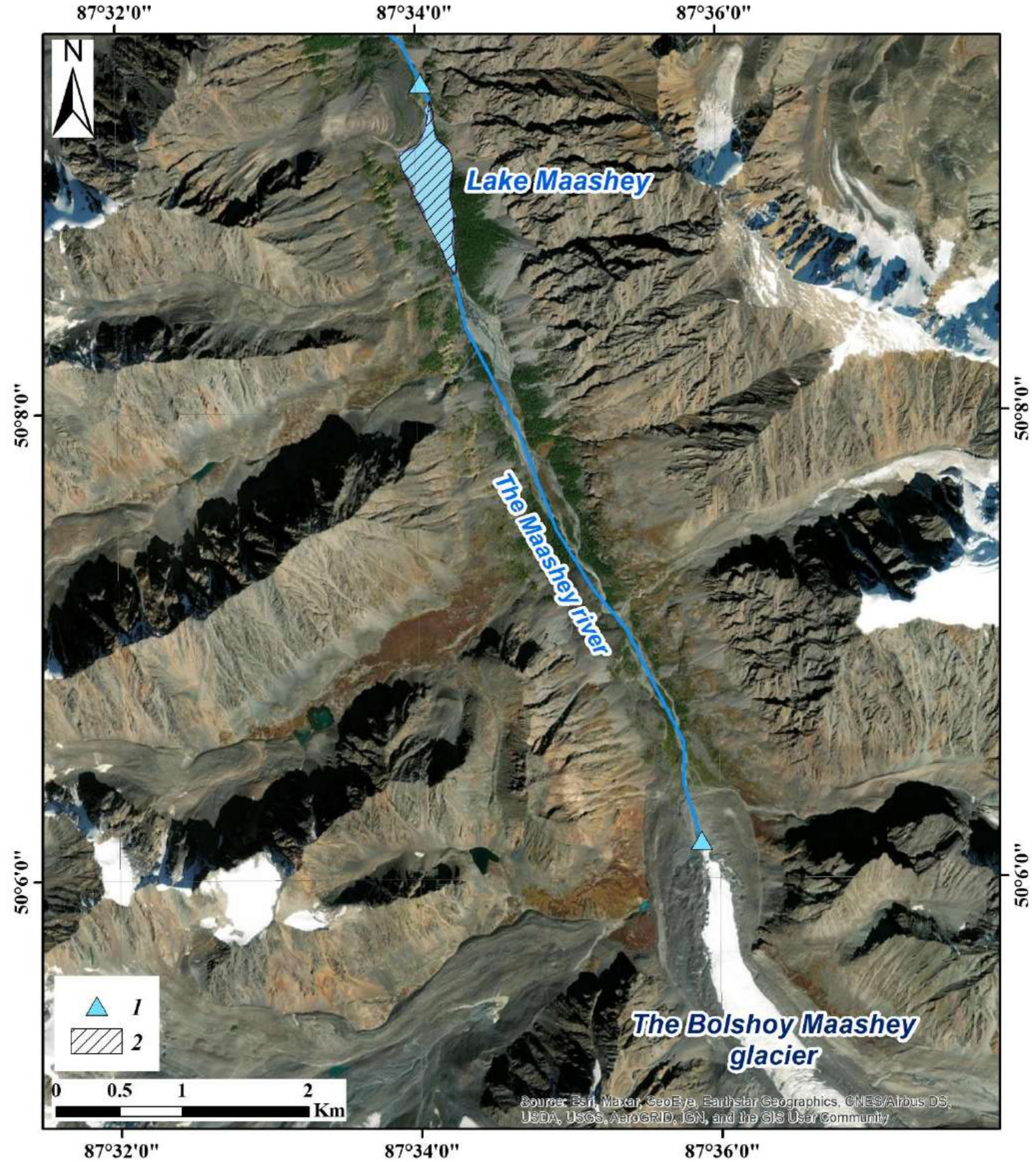
Due to the fact that the main part of the lakes is in a transgressive stage of development, that is, increase in size and have an unstable level regime, and, therefore, can outburst, it is necessary to conduct monitoring studies of these lakes and assess the characteristics of a possible outburst flood, mainly those lakes that are located in river basins flowing through populated areas and in the valleys of which infrastructure facilities are located.

Based on field research data and a supplemented classification of lake development stages (Table 4.3), it was established that outburst Lake Maashey and Lake Nurgan through in the period preceding the outburst were in a transgressive stage of development (increased in size). Therefore, these lakes were selected as objects for calculating the characteristics of outburst floods.

4.4. Study Objects for modelling in the Altai

Lake Maashey (North-Chuya Ridge, Altai Republic, Russia)

Lake Maashey was located in the upper reaches of the Mazhoy River (the left tributary of the Chuya River) on the territory of the North-Chuya Ridge at an altitude of 1984 m above sea level and was formed when the flow of the Mazhoy River was blocked by a rock glacier from the western part of the valley (Fig. 4.17) and a collapse of loose debris from its eastern part. The dam damming the lake had a complex heterogeneous structure and consisted of the terminal moraine of the Bolshoy Maashey glacier, an alluvial cone on the eastern side of the valley, and a rock glacier on the western side (Bykov, 2013).



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 4.17. Location of Lake Maashey.

A detailed analysis of Landsat-3, 5, 7 satellite images made it possible to identify annual and interannual variability in the lake surface area, which indirectly indicated a change in the water inflow to the lake, and, consequently, its level regime. As an example of intra-annual variability, we present the reconstructed intra-annual cycle of changes in the lake area for 2011 over several time periods, which showed that in winter the lake completely emptied, and starting in June the lake basin was filled again: at the beginning of June (3.06.2011) the area lake area was 63000 m^2, in August (13.08.2011) it reached a maximum value of 255000 m^2, in September (14.09.2011) the lake began to empty, the area amounted to 238000 m^2, reaching at the end of September (30.09.2011) 191000 м^2. In October the lake completely emptied. This water level regime was confirmed by literature data (Bykov, 2013; Borodavko, Litvinov, 2013). The existence of the lake only in the warm period of the year indicated that the main source of feed for the lake was melted glacial waters, and the complete emptying of the lake in the autumn-winter period indicated the presence of filtration channels in the dam body, through which the outflow was carried out. The throughput capacity of the filtration channels was assessed for the period of reduction in the area and volume of the lake in the autumn period using the bathygraphic and volumetric curves of the lake obtained from the results of a tacheometric survey, and the value of the average discharge of the Maashey River measured during field work, which amounted to 1.3 m^3/s . The water outflow discharge through filtration channels varied from 1.4 to 1.6 m^3/s. Note that the contribution of glacial waters to the feeding of the Maashey River at the time of field research was 80% according to the isotope balance equation, which also confirms the predominantly glacial feeding of the lake.

Over the long-term period, the lake area increased towards the end of the ablation period of each year (transgressive stage of development, see Fig. 4.18), which is due to a large inflow of water as a result of increased glacier melting under non-stationary climatic conditions. Despite the fact that the lake emptied in the autumn-winter period, the next year during the warm period the lake basin was filled anew with melted glacial waters, and the lake volume became larger over time. The latter is confirmed by the identified statistically significant positive trends in the average annual (Fig. 4.19a) and average monthly air temperature during the ablation period (June, July, August) after 1980 (Rasputina et al., 2022) according to the Kara-Turek weather station, which is the closest to the study area.

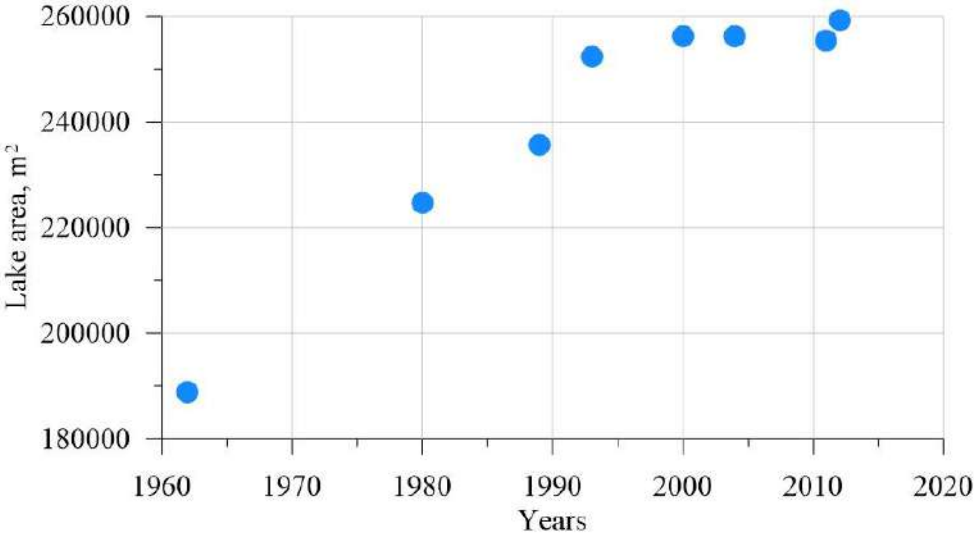


Fig. 4.18. Change in the area of Lake Maashey over time.

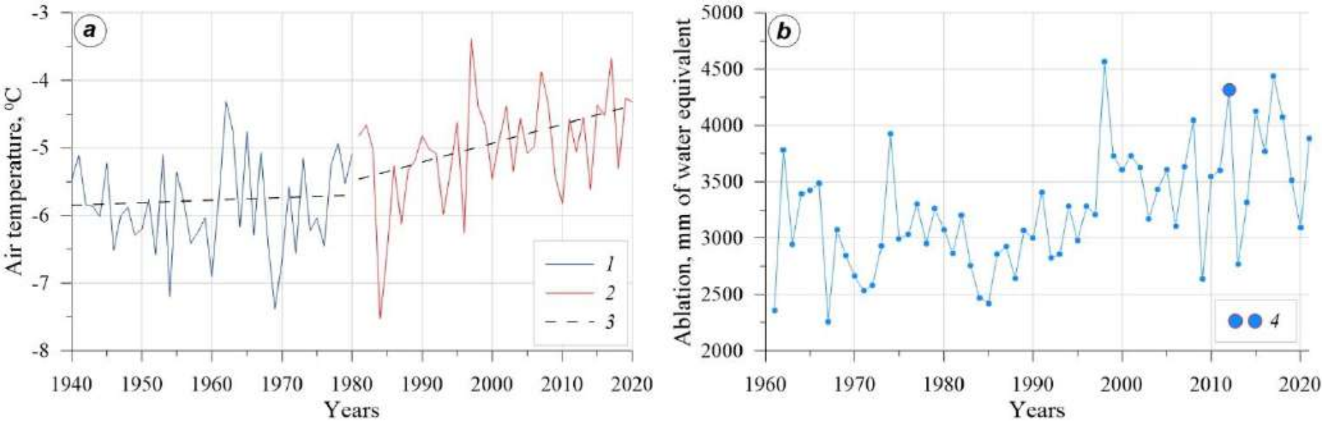


Fig. 4.19. The course of the average annual air temperature according to the Kara-Turek weather station (a); change in the average ablation value on the Bolshoy Maashey glacier during the summer season (b). Designations: 1 – course of average annual air temperature until 1980; 2 – course of air temperature after 1980; 3 – air temperature trends; 4 – ablation value on the Bolshoy Maashey glacier in 2012.

The most intensive increase in the lake size was observed from the late 1980s to the early 2000s and in the early 2010s. It was during this period (at the end of the 1980s) that the rate of the Bolshoy Maashey glacier retreat increased: from 3.2±1 m/year (from 1962 to 1989) to 7.1±2.0 m/year (from 1989 to 2010).), since 2010, the rate of retreat has doubled to 14.0±2.0 m/year (Ganyushkin et al, 2023). The acceleration of glacier retreat is a consequence, first of all, of the acceleration of its melting during ablation seasons. The latter is confirmed by our calculations (Fig. 4.19b), according to which, since the mid-1980s, there has been a clear trend towards an increase in the amount of melting. The year 2012, when the lake was outburst, is one of the top three years with the greatest melting in the entire period from the early 1960s to the present. According to our calculations, the amount of melting during the summer season in 2012 was 4317 mm in water equivalent.

The graph (Fig. 4.19b) reflects the acceleration of glacier melting, which in turn led to a more intensive growth of the lake area, and, accordingly, an increase in water mass.

As the water volume in the lake increased, the water pressure on the dam increased, which could weaken it. Lake Maashey existed until July 2012. The impact of an external trigger in the form of prolonged intense precipitation on July 15, 2012 led to the watering of the dam, its erosion, and the formation of an outburst flood and associated mudflow. As a result of the mudflow, two bridges were destroyed (on the Mazhoy and Chuya rivers). According to the Kara-Turek weather station, which is located 82 km west of the lake basin, the daily amount of precipitation during the lake outburst period was as follows: July 13 – 19.8 mm, July 14 – 13.6 mm, July 15 – 34 mm (Bulygina et al., 2014). Moreover, on the last day (July 15, 2012), 34 mm of precipitation fell within 12 hours, which falls into the category of dangerous meteorological phenomena for mudflow-prone mountainous areas according to the list of hazardous phenomena of the West Siberian UGMS (http://www.meteo-nso.ru/pages/115/). Due to the mountainous relief and the distance of the weather station from the Lake Maashey basin, it is not possible to determine exactly how much precipitation fell in the river valley in question. However, it is assumed that the amount of precipitation that fell was close in magnitude to the category of dangerous meteorological phenomena.

Field research in the Lake Maashey basin was carried out in September 2022. To restore the hydromorphometric characteristics of the lake that preceded the outburst (water level, lake volume and lake depth), a tacheometric survey of the Lake Maashey basin was carried out. Tacheometric survey of the relief was carried out to the boundary of the high water level, which preceded the outburst (Fig. 4.20).

Fig. 4.20. Photo of the high water levels of the lake: lack of vegetation (a) and color of the boulders (b).

Based on the completed tacheometric survey, the bathymetric scheme of Lake Maashey before the outburst was restored (Fig. 4.21), the curve of the dependence of the lake volume on its depth (Fig. 4.22) and its morphometric characteristics were obtained.

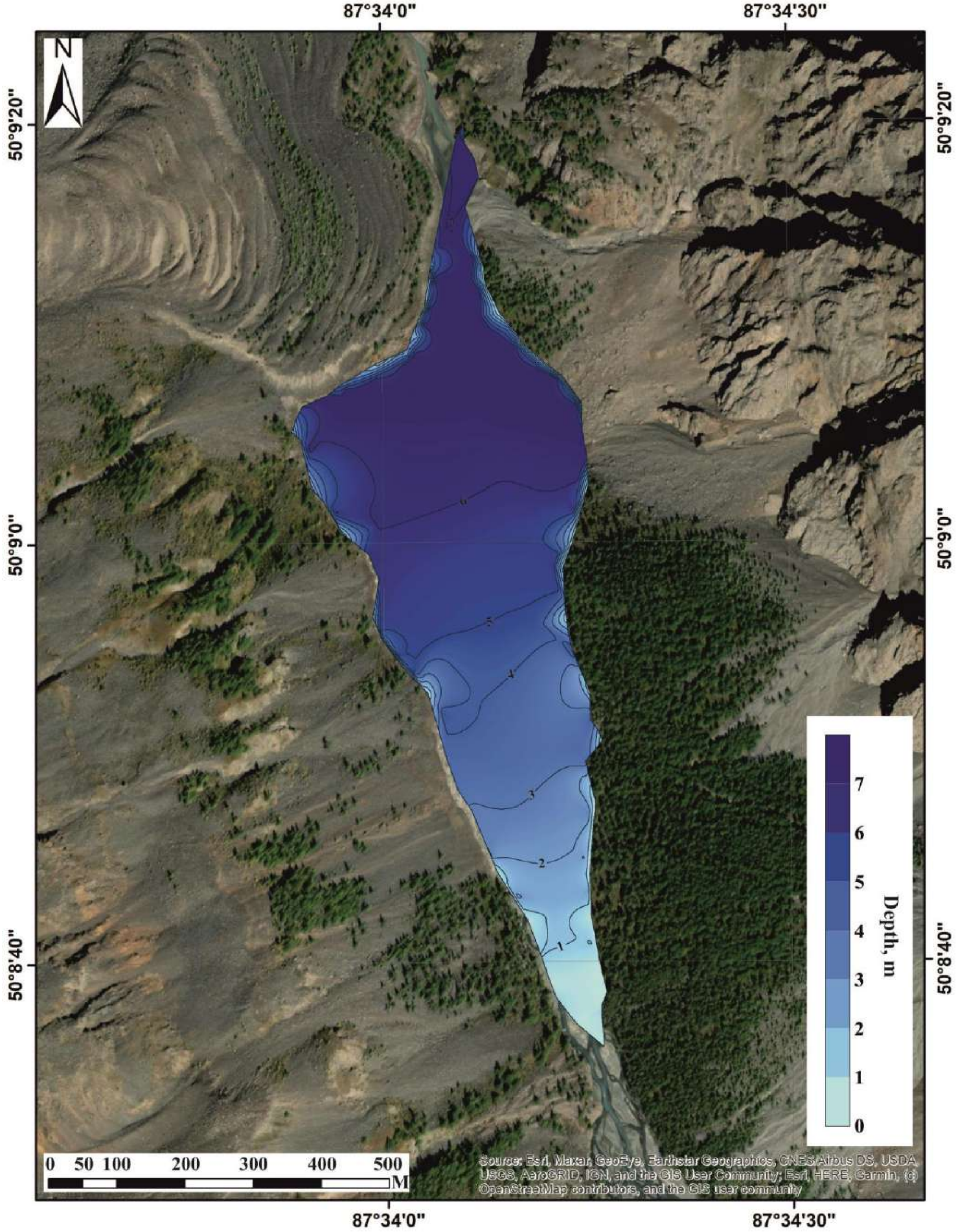


Fig. 4.21. Bathymetric scheme of Lake Maashey before its outburst. Isobaths are drawn every 1 m.

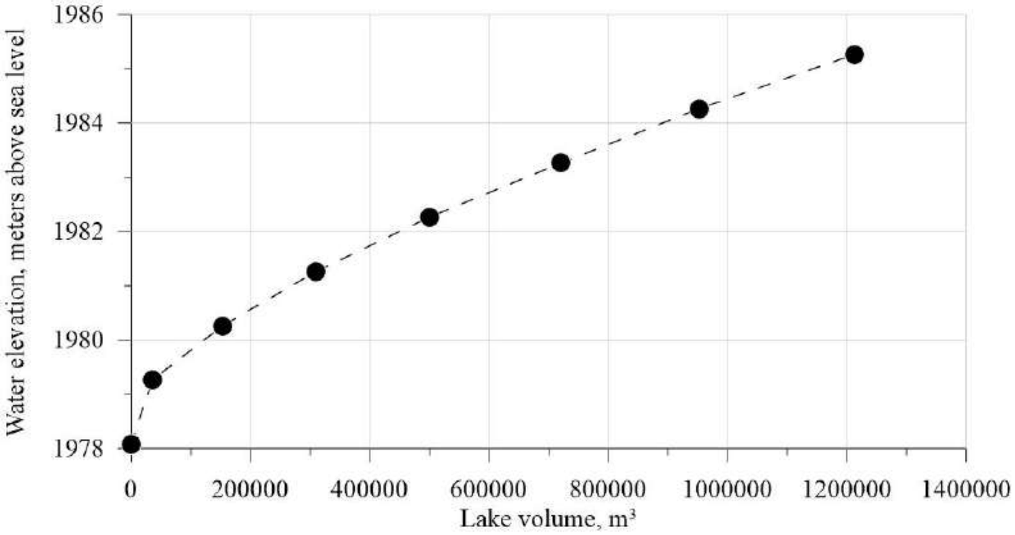


Fig. 4.22. The curve of the dependence of the lake volume on the water surface elevation.

The length and width of the lake were 1480 m and 423 m, respectively. The maximum depth according to the survey results turned out to be equal to 7.5 m, and the average – 4.7 m. According to published data, the lake average depth was 3-3.5 m (History of lakes..., 1995; Borodavko, 1998), which is 1.2 meters less than that obtained from field research results in 2022. The Lake Maashey area before its catastrophic emptying was 259000 m^2 with a corresponding lake volume of 1.21 million m^3. Since the lake completely emptied during the outburst, the entire water volume was used to form the outburst flood and the associated mudflow.

The completed tacheometric survey also made it possible to establish the shape and obtain the morphometric characteristics of the breach formed in the dam body as a result of the outburst (Fig. 4.23): height – 10 m, width along the bottom and crest - 7 and 69 m, respectively. The breach area turned out to be 415 m^2.

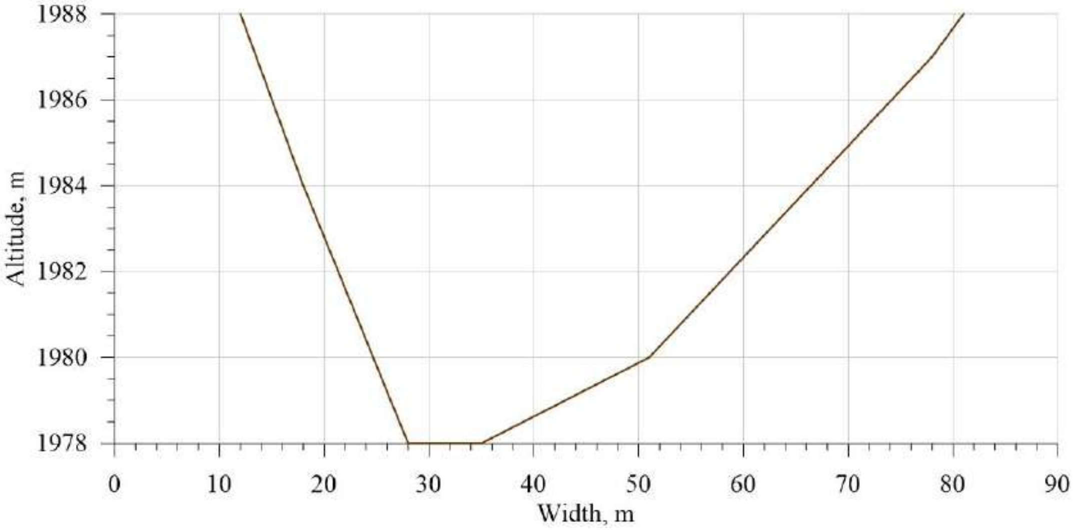
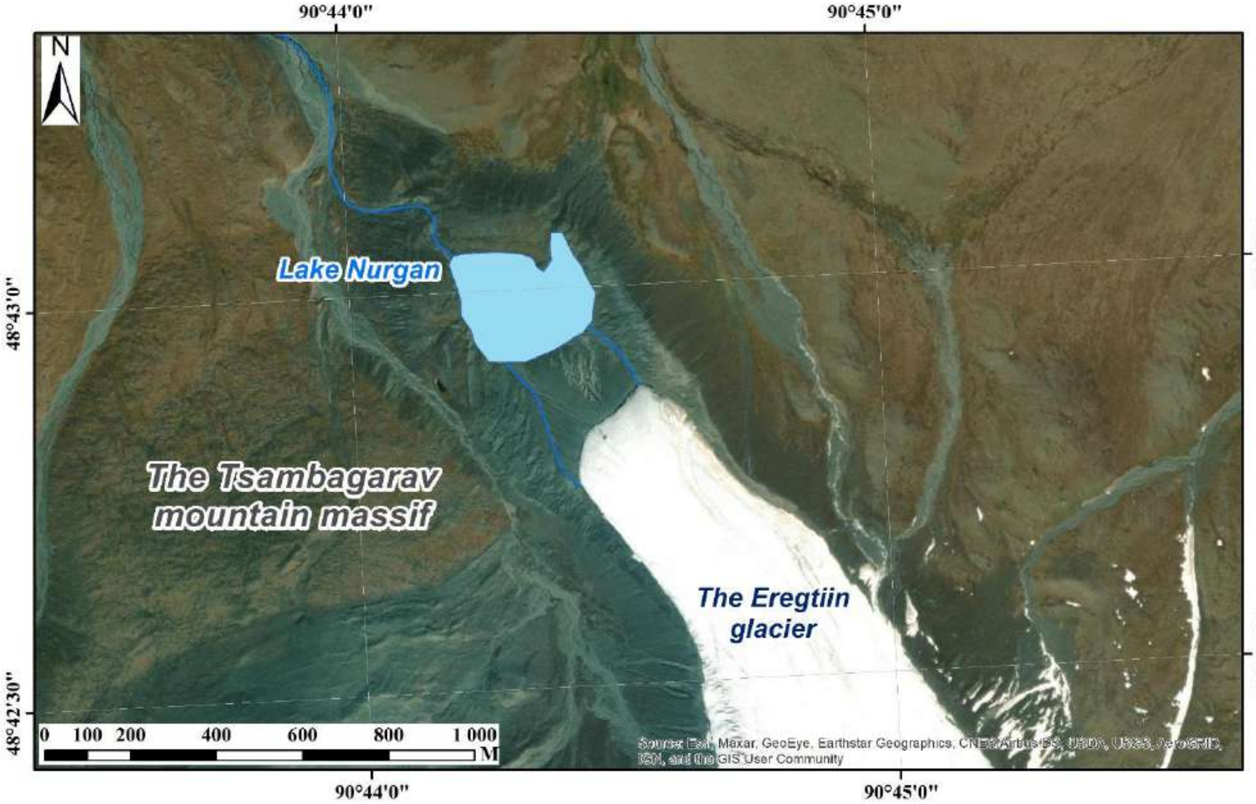


Fig. 4.23. A breach formed in the dam body.

Based on detailed field studies, it was hypothesized that the Lake Maashey outburst began at a water level below the elevation of the dam crest. Prolonged intense precipitation likely led to severe watering of the dam and increased water filtration through it. The outburst was initiated by an intense water outflow through the filtration channel, followed by the collapse of the soil above the channel, overflow through the open channel and complete dam destruction. The formation of a filtration channel in the body of a dam damming a lake is a common trigger mechanism for the moraine dams outburst (Chang, Zhang, 2010; Liu et al, 2013; Westoby et al, 2014; Chen et al, 2019; Neupane et al, 2019) and is described in section 2.1. of this thesis.

Lake Nurgan (Tsambagarav mountain massif, North-Western Mongolia)

Lake Nurgan is a moraine-damme lake and is located in the northern part of the Tsambagarav mountain massif at an altitude of 2980 m above sea level. At the present time, the lake is located 230 m north of the Eregtiin glacier and is connected to it through streams flowing from the glacier and flowing into the lake (Fig. 4.24). The dam damming Lake Nurgan consists of loose moraine material.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 4.24. Scheme of Lake Nurgan location.

The main source of feed for the lake is melted glacial water, which was confirmed by the analysis of multi-temporal Sentinel satellite images for 2022-2023 (Appendix 3), which showed significant intra-annual variability in the size of Lake Nurgan.

In the spring-summer period, when the greatest ablation is observed, the moraine-dammed lake begins to increase in size, reaching the largest volume of water mass in July-August (the area of the lake on May 10, 2022 was 31500 m^2, on June 17, 2022 - 42100 m^2, July 4, 2022 – 61900 m^2). In the autumn-winter period, there is a significant reduction in the lake size, which indicates the presence of filtration channels in the dam body of the lake (22.09.2022 the lake area was 50400 m^2, 14.11.022 – 26200 m^2, 10.01.2023 – 23000 m^2, 24.03.2023 – 22700 m^2, 10.04.2023 – 23500 m^2). At the time of field research (August 2019), the lake area was 62100 m^2 with a corresponding water volume of 513600 m^3.

Field hydrological studies on the Lake Nurgan were carried out in July-August 2019. Detailed results of the work are presented in the article (Pryakhina et al., 2021). In the relief of the Lake Nurgan basin, traces of changes in the volume and flow direction from the lake have been preserved. Field studies in 2019 showed that on the northern slope of the lake basin, lake terraces are preserved, recording the early lake levels at heights of 2988 and 2991.5 m (Fig. 4.25a).

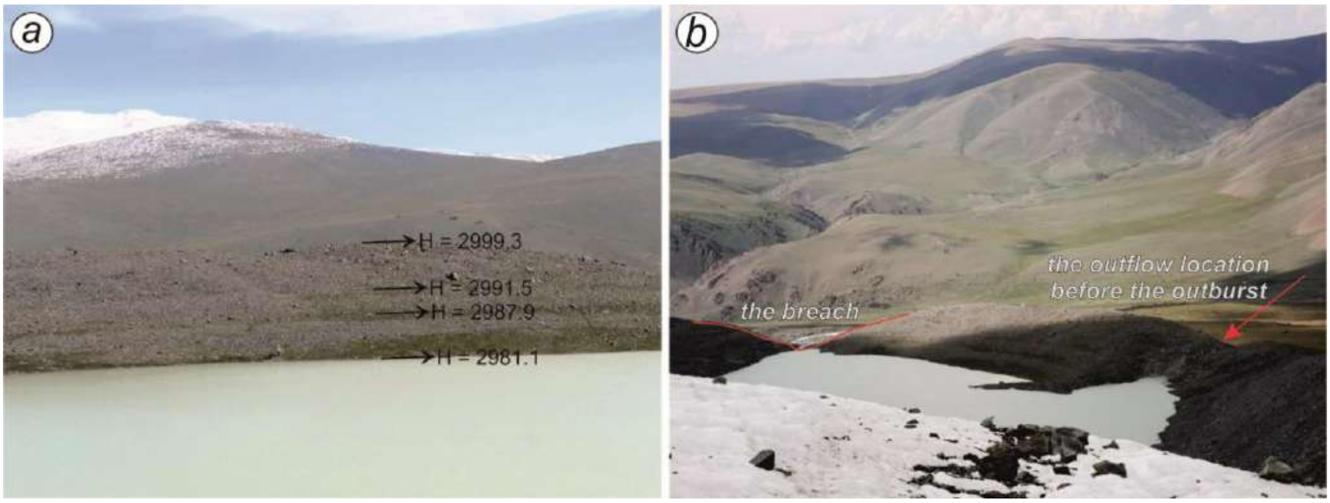


Fig. 4.25. Terraces on the northern slope of the Lake Nurgan basin (a), the northern slope of Lake Nurgan (b). Photos by *Boronina A.S.* and *Popova S.V.*

A short V-shaped valley originates from the level of the upper terrace, cutting through the lateral moraine ridge in the northeastern part of the lake basin (Fig. 4.25b). The height of the incision reaches 2994 m, which is approximately 11 m higher than the water level in the lake in 2019. Currently, this valley is dry. Analysis of a topographic map at a scale of 1:100000 for the study area (M 46-110) (Fig. 4.26a) showed that back in 1969, the flow from the lake passed through this part of the moraine, which means its maximum level was approximately 11 m higher modern. At the same time, an analysis of the Corona satellite image from August 11, 1968 (Fig. 4.26b) shows that at that time the lake area was 54570 m^2, that is, 13% less, and the water level was approximately 1.5–2.0 m lower. This means that, most likely, the hydrographic network in this section of the topographic map reflects the situation in 1948–1949. Accordingly, it can be assumed that high lake levels occurred between the end of the Little Ice Age and the middle of the 20th century. Between 1948 and 1968, the destruction of the moraine line in the northwestern part of the basin and the lake outburst occurred (that is, the lake outburst occurred at maximum water levels, when the lake was in a transgressive stage of development). Currently, in this place there is a V-shaped valley cutting through the moraine line to the lake's water line (Fig. 4.25b), and surface water outflow from the lake was also recorded there (Pryakhina et al., 2021).

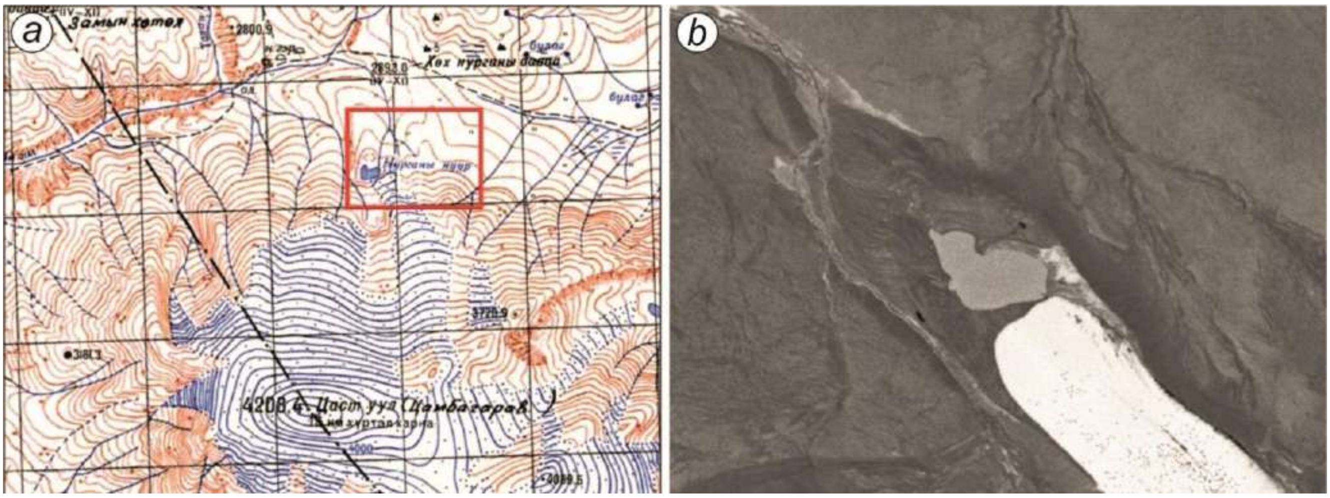


Fig. 4.26. Fragment of a topographic map of the Tsambagarav ridge (a), fragment of the Corona image (b) (Pryakhina et al., 2021).

Based on the results of the bathymetric survey, a scheme of the Lake Nurgan depths (Fig. 4.27) and a curve of the dependence of the lake volume on its depth (Fig. 4.28) were constructed.

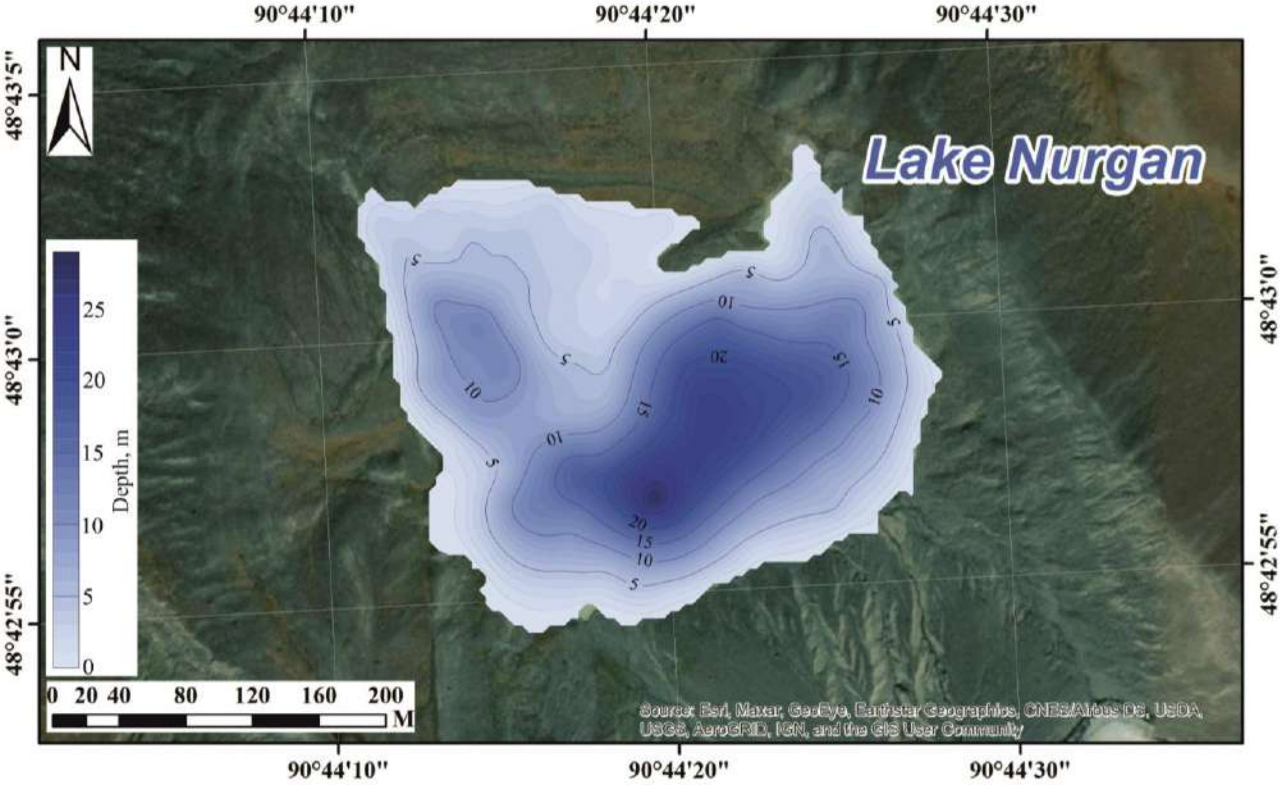


Fig. 4.27. Bathymetric scheme of Lake Nurgan. Isobaths are drawn every 5 m.

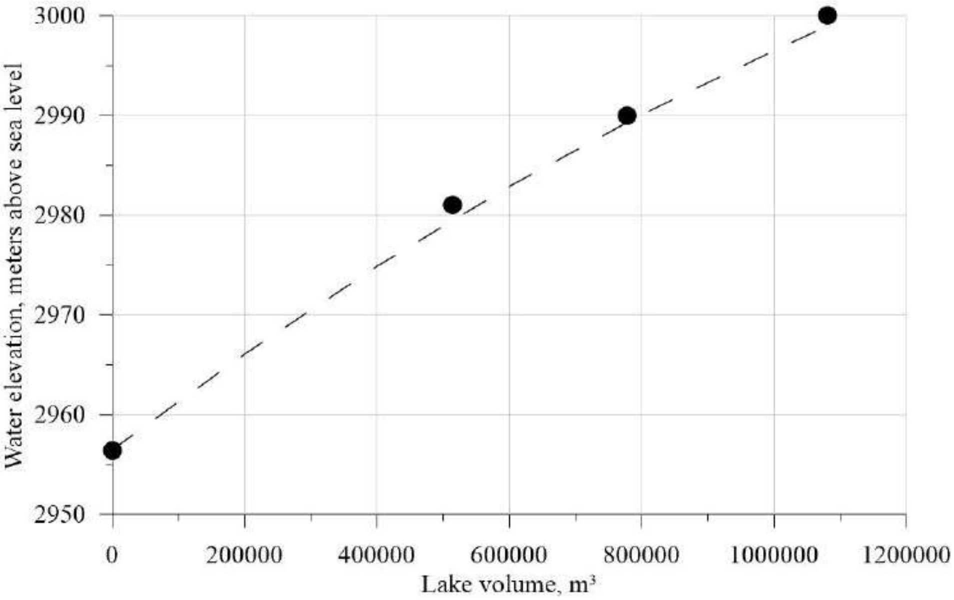


Fig. 4.28. Curve of the dependence of Lake Nurgan volume on the water level in it at maximum filling.

As a result of the tacheometric survey, the maximum value of the lake volume that preceded the lake outburst was obtained, and the dimensions of the resulting breach were established: the maximum width along the moraine dam crest was 165 m, and along the bottom - 30 m, depth - 17 m. The breach area and its the average width was estimated at 1640 m^2 and 96 m respectively.

Based on field research, a hypothesis was put forward that the lake outburst as a result of water overflow over the dam crest.

4.5. Chapter Conclusions

It was found that the reduction in the glaciation area in the study territory is due to a statistically significant increase in air temperature, while no clear trends in changes in precipitation are observed. Deglaciation of the Altai territory led to changes in lake complexes. Over the past 22 years, several trends have been observed:

1. on the territory of the Central Altai (Katunsky, North-Chuya and South-Chuya ridges) there is an increase in both the number of periglacial and moraine-dammed lakes and their total area.
2. The Mongun-Taiga and Tsambagarav mountain massifs (the South-Eastern Altai), due to their small glaciated area, are characterized by a small number of moraine lakes, which change little over time. The total area of lakes also remains virtually unchanged.
3. On the Tavan-Bogdo-Ola mountain massif territory (the South-Eastern Altai), a different trend is observed: in higher altitude intervals there is both an increase in the number of lakes and an increase in their total area, but in lower altitude intervals there is a decrease in the number and total area of reservoirs.
4. The upper limit of the altitudinal interval of the maximum distribution of periglacial and moraine-dammed lakes at the present time (2022) is located higher in comparison with

2000 by an average of 100-200 m, which is associated with the ongoing retreat of the glaciers margins, with the exception of the Mongun-Taiga and Tsambagarav mountain massifs. In the latter case, the glaciated area of the massifs is much smaller compared to other study mountain massifs, that is, the volume of melted glacial waters is not enough to form new periglacial and moraine-dammed lakes.

The identified differences in the trends in changes in the spatial and temporal distribution of lakes indicate that in the South-Eastern Altai territory, which is characterized by a more arid climate, the existence of lakes is completely determined by the volume of melted glacial waters entering the lakes. The ongoing retreat of glaciers leads to a reduction in the connection of moraine-dammed lakes located in lower altitude intervals with glaciers, resulting in the degradation of lakes up to their complete disappearance. In the Central Altai, due to the larger area of glaciation and more humid climatic conditions, the lakes degradation does not occur against the background of the retreat of glaciers, since, firstly, there is a sufficient volume of runoff from glaciers, and secondly, the existence of lakes that have lost connection with glaciers and located in a quasi-stable stage, is provided by rain and melted snow waters. The existing close connection between the reduction in the glaciation area and the changes occurring in moraine-dammed and periglacial lakes indicates that lakes are indicators of the process of mountain glaciation degradation.

Taking into account data from field observations and the results of analysis of satellite images, the existing classification of stages of lake development was supplemented (Zimnitsky, 2005):

1. the concept of a quasi-stable stage of development was introduced;
2. morphological and hydrological-morphometric characteristics of each stage of development are proposed, mainly the features of the level regime of each stage are described.

The supplemented classification of the stages of development of moraine-dammed and periglacial lakes makes it possible to determine at what stage a particular lake is located, to assess its further development, including identifying potentially outburst-hazardous lakes in conditions of poor hydrological knowledge, which will reduce the degree of information uncertainty in a particular area. Thus, it was established that the outburst lakes Maashey, Nurgan and «Barsovo» were in a transgressive stage of development in the period preceding the outburst. Thus, the transgressive stage of development, characterized by an active increase in the volume and area of the lake and an unstable level regime, is the most potentially dangerous. Lakes at this stage of development should be objects of close monitoring in areas where mountainous areas are developed.

Field studies, which were carried out in the basins of Lake Maashey and Lake Nurgan, made it possible to put forward hypotheses about the trigger mechanisms of lake outbursts, as well as to obtain detailed characteristics of lakes before the outburst for subsequent mathematical modelling of the outburst flood characteristics, including the size of the resulting breaches, with the help of which it was estimated quality of the performed modelling.

Chapter 5. Analysis of the results of modelling the characteristics of outburst floods

Based on the methodology proposed in this thesis for calculating the characteristics of an outburst flood, real lake outbursts were simulated: an outburst of the moraine Lake Nurgan (Tsambagarav mountain range) and an outburst of the landslide Lake Maashey (North-Chuya ridge).

The initial conditions for modelling were set: the lake volume preceding the outburst (data on lake volumes were obtained as a result of field studies in 2019-2022), the dimensions of the initial filtration channel (for the case of a lake outburst as a result of filtration channel erosion (piping)) or the initial the breach size (for the case of an outburst as a result of water overflowing over the crest), characteristics of the moraine material from which the dam is constructed (specific gravity of the material, percentage of clay content, plasticity index). Modelling was carried out for the heterogeneous structure of moraine dams damming lakes. Since sampling for the granulometric composition was not carried out for lakes, numerical experiments were carried out (various ratios of loam, sandy loam and gravel were used). For modelling, two fractions were taken (loam and sandy loam or loam and gravel), which are most often found when describing the composition of moraines, therefore in Table. 5.1, column No. 5 shows two values for the specific gravity of the material, and the table also shows the initial conditions for modelling outburst floods for selected lakes. During modelling, the time step was set to 1 s.

Table 5.1.

Initial conditions for mathematical modelling

Characteristic	Outburst mechanism	Initial volume, m^3	Initial channel diameter/breach depth, m	Specific gravity of the dam material, kg/m^3	Clay percentage, %	Plasticity index
Lake						
Nurgan	overflow	1080728	0.1	2590/2750	10/16	3/15
Maashey	piping	1212208	0.01	2700/2750	13/16	5/15

Based on the results of the modelling, the main characteristics of outburst floods were obtained (hydrograph and volume of the outburst, time of passage of the outburst flood, flow velocity through the breach) and dimensions of the breach.

5.1. Results of Lake Maashei outburst modelling

After conducting field research in September 2022, it was hypothesized that Lake Maashey outburst began at a water level below the level of the dam damming the lake. Prolonged intense precipitation likely led to severe watering of the dam and increased filtration of water through it. The outburst was initiated by an intense outflow of water through the filtration channel, followed by the collapse of the soil above the channel, the overflow of lake water through the open channel and the complete the dam destruction. Based on this assumption, a mathematical modelling of the outburst was carried out based on the described calculation methodology (the formation of a filtration channel in the dam body was specified as the outburst mechanism) (Fig. 5.1).

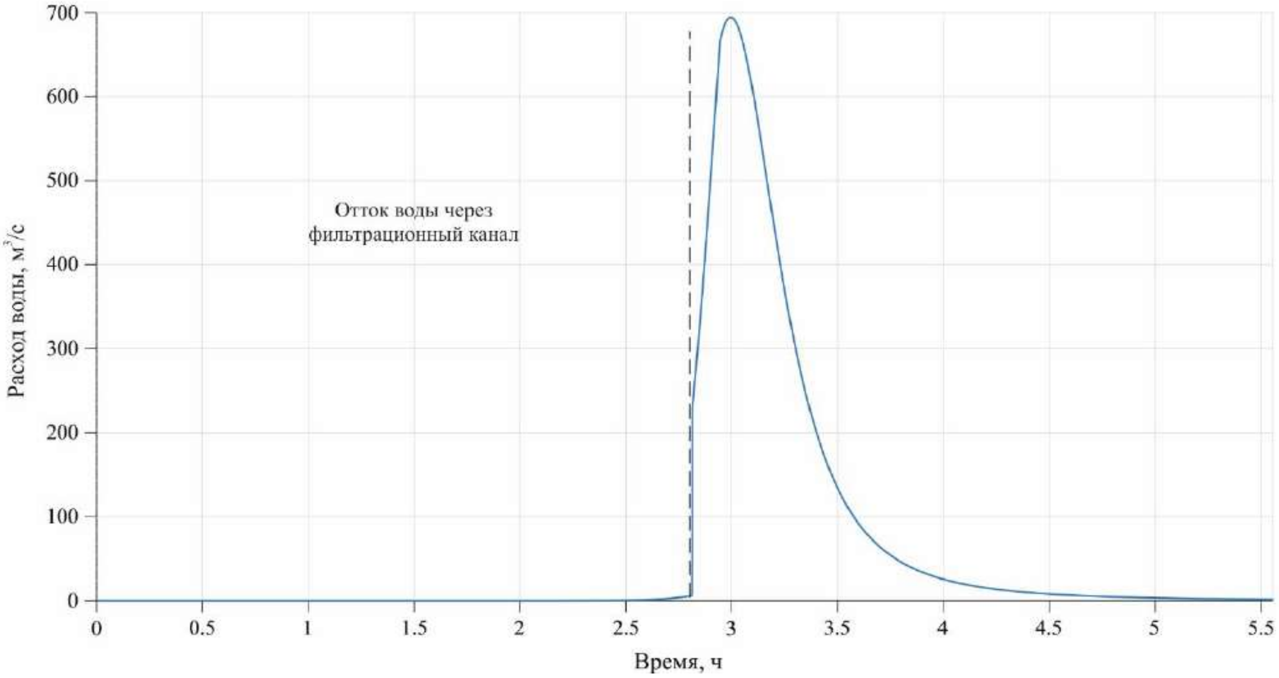


Fig. 5.1. Calculated hydrograph of the outburst flood formed as a result of Lake Maashey outburst during the formation of a filtration channel in dam the body.

According to the results obtained, the emptying of water through the filtration channel took about 3 hours, and an outburst flood wave was formed during the subsequent water overflow. The maximum discharge according to the calculation results was 694 m^3/s. Average flow velocities during an outburst varied from 0.2 m/s at the beginning of the outburst and reached 5-6 m/s at the peak of the outburst flood. The outburst flood duration, according to the calculation results, was about 5.5 hours. During the outburst, Lake Maashey completely emptied (Fig. 5.2).

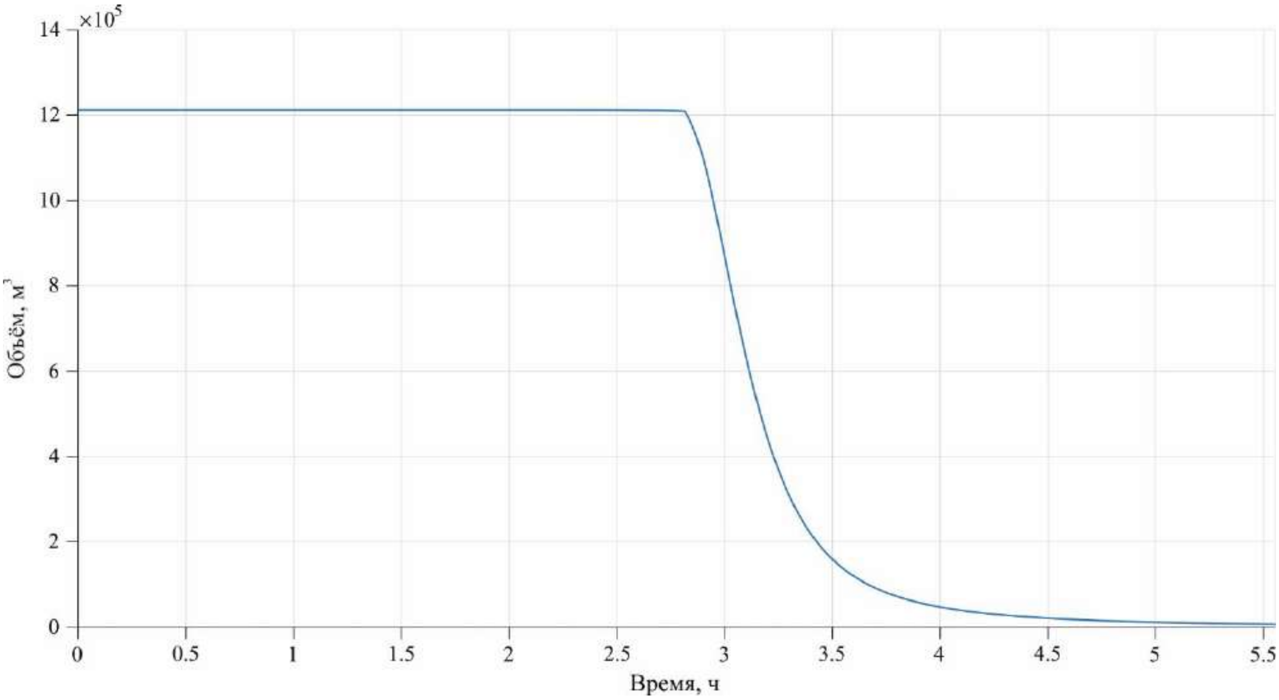


Fig. 5.2. Change in the volume of Lake Maashey during an outburst.

During the time interval (about 3 hours) when lake water is emptied through the filtration channel, the change in water volume occurs very slowly. As soon as the soil collapses above the channel, the water volume immediately begins to rapidly decrease until the lake is completely empty.

As a result of the outburst, a breach was formed along the entire height of the dam (10 m) with an area of 476 m^2 (observed 415 m^2) (Fig. 5.3).

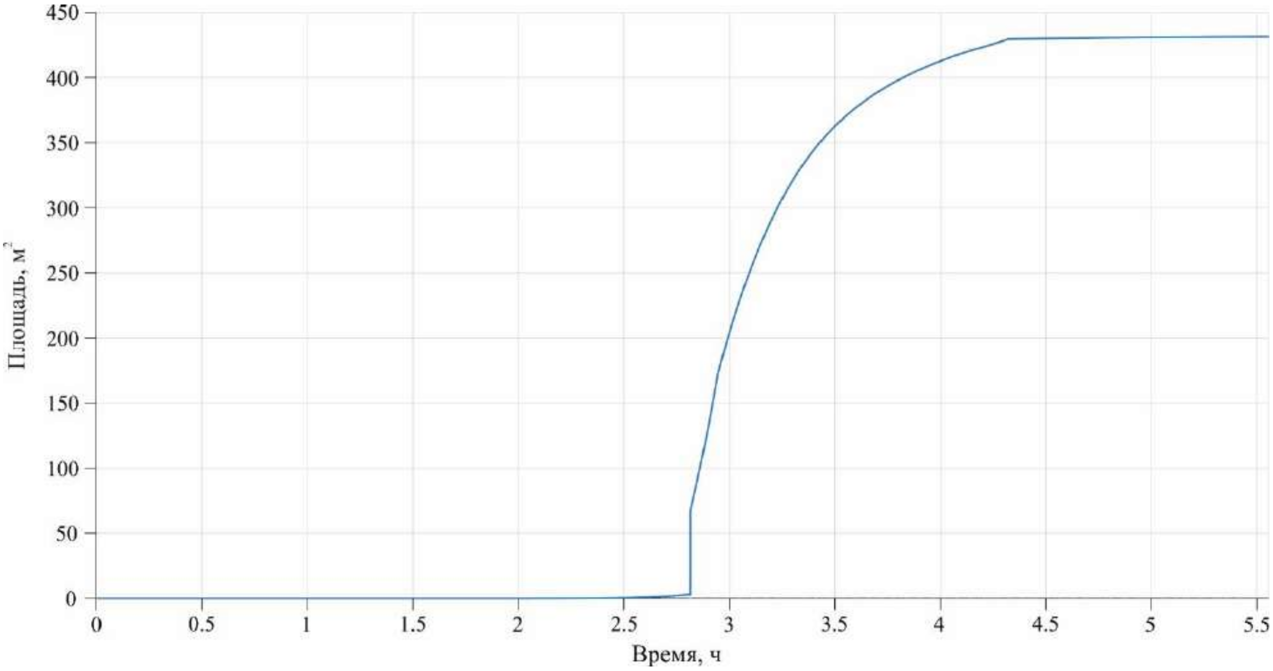


Fig. 5.3. Development of the breach in time during the outburst of Lake Maashey as a result of the formation of a filtration channel in the dam body.

The average breach width was 47.5 m (the average width calculated from observed data was 41.5 m). The error in the obtained width and cross-sectional area of the breach was about 15%.

As part of the discussion, we note that according to published works (Borodavko et al, 2013), after the outburst of Lake Maashey, mathematical modelling of the outburst flood wave movement along the Maashey River valley was performed using the HEC-RAS software package. The initial outburst hydrograph in this case was calculated using empirical formulas (Cenderelli, 2000; Costa, 1988), according to which the maximum discharge of the outburst flood at the dam site was 800 m^3/s. In the case of this approach, the schematization of the hydrograph is not entirely correct, since the morphometric characteristics of the lake and the characteristics of the soil from which the dam was constructed, on which the magnitude of the maximum discharge of the outburst flood and its duration depend, are not taken into account. Also, when using empirical formulas, the development of the breach was not calculated. Although the resulting breach size is often the only verification information for assessing the quality of the modelling, since there is no possibility of comparing the simulated maximum discharges with the observed values.

The quality of modelling the characteristics of an outburst flood using the methodology proposed in this thesis was assessed by comparing the dimensions of the breach calculated using the methodology and measured due to the fact that these data are the only verification information. The comparison showed that the discrepancy between the calculated and measured sizes does not exceed 15%. Since the morphometric characteristics of the breach were obtained 10 years after the lake outburst, then, given the fact that the breach sides are composed of loose clastic material, the breach dimensions could have changed over the past period of time, which may explain the discrepancy between the observed and calculated breach width. Therefore taking into account possible changes in the dimensions of the breach, the modelling result can be considered satisfactory. The calculated flow velocities also seem plausible.

5.2. Results of Lake Nurgan outburst modelling

Mathematical modelling of a real outburst of Lake Nurgan was carried out for the lake volume preceding the outburst, which was reconstructed using an elevation map constructed from field data. Based on field research carried out in August 2019 and analysis of satellite images for different years, it was hypothesized that the mechanism of the outburst of the moraine-dammed lake was the water overflow through the dam crest, therefore the calculation according to the methodology was carried out for this case (Fig. 5.4).

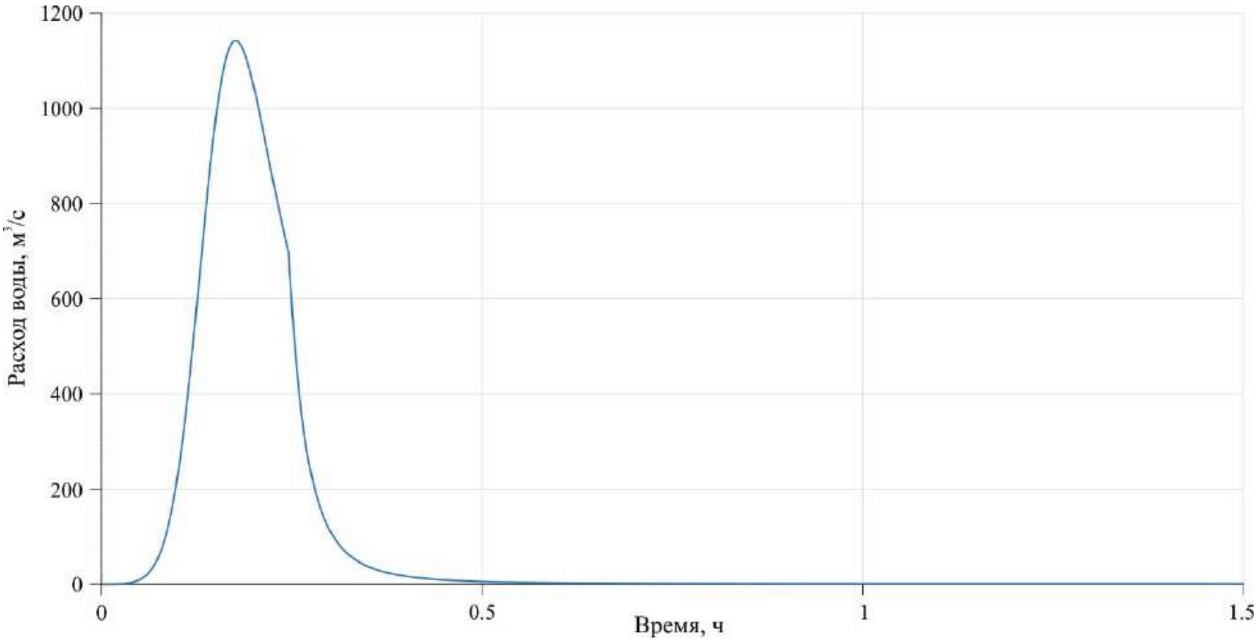


Fig. 5.4. Calculated hydrograph of the outburst flood formed during the outburst of Lake Nurgan as a result of water overflowing through the dam crest.

According to the calculation results, the maximum discharge was reached 15 minutes after the start of the outburst and amounted to 1142 m^3/s. The period of passage of the outburst flood was about 25-30 minutes. Average flow velocities varied from 0.7 m/s at the beginning and end of the outburst flood to 5 m/s at the peak of the outburst. The outburst flood volume was estimated at 510000 m^3. This shows that Lake Nurgan has not completely emptied (Fig. 5.5).

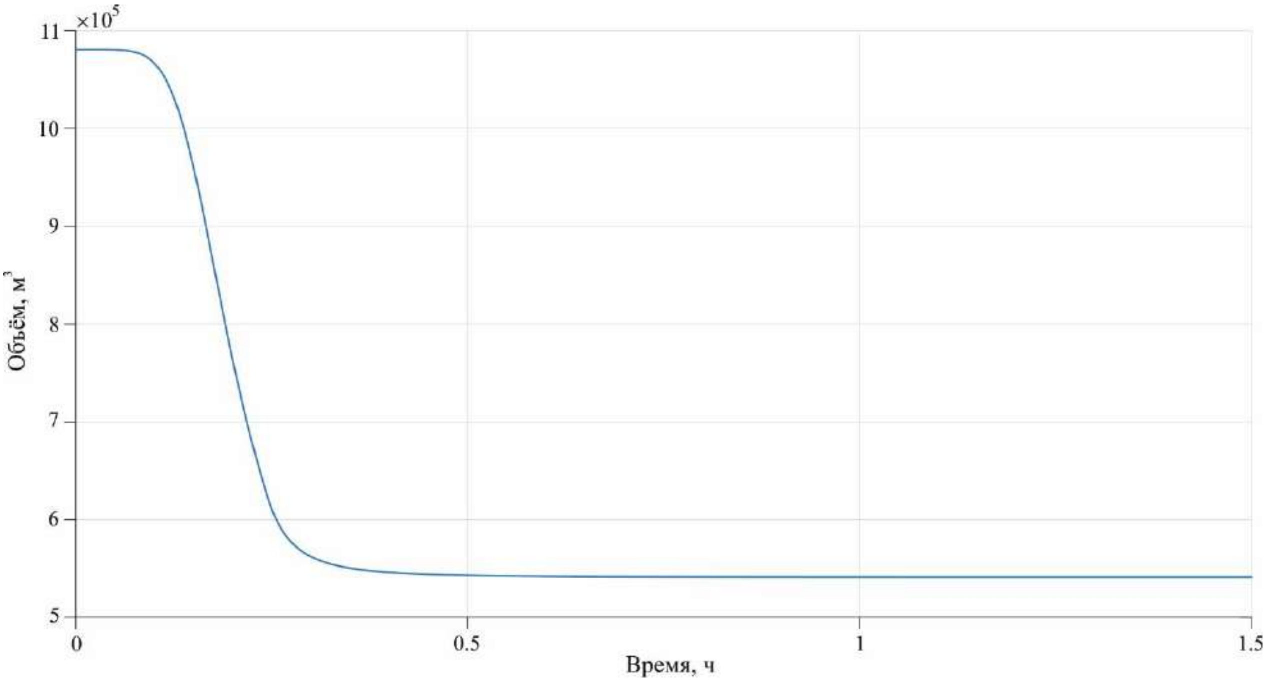


Fig. 5.5. Change in the volume of Lake Nurgan during its outburst.

The depth of the resulting breach was 18.2 m, and the breach area was 1596 m^2 (Fig. 5.6).

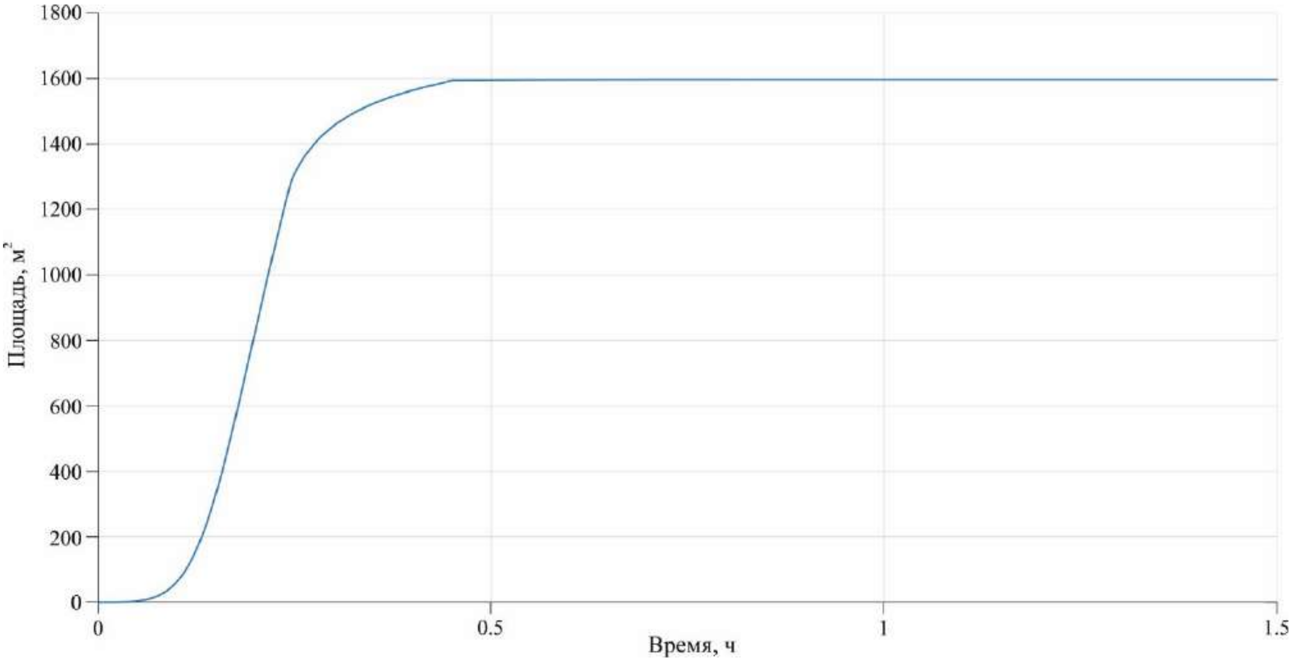


Fig. 5.6. Development of the breach in time during the outburst of Lake Nurgan as a result of water overflowing through the dam crest.

The dimensions of the breach obtained using the proposed methodology were compared with data obtained from tacheometric surveys. The breach depth is overestimated by 7%. The average breach width according to the calculation results was 87.2 m, which is 9.2% less than the actual one, and the calculated area of the breach was 2.7% less than the observed one. The dimensions of the resulting breach are the only verification information by which the calculation algorithm can be checked. The obtained simulation results differ slightly from the real data, which allows us to conclude that the simulation result is satisfactory.

5.3. Chapter Conclusions

Mathematical modelling of outburst floods was carried out for real cases of outbursts of lakes located in the Altai (Lake Maashey and Lake Nurgan). According to the hypothesis put forward that the outburst of Lake Maashey could have occurred as a result of the erosion of the filtration channel in the dam body and the subsequent collapse of the soil above the channel, the calculation of the outburst flood using the proposed methodology was carried out for this scenario. Modelling of the outburst of Lake Nurgan was carried out for the case of water overflowing through the dam crest (an analysis of topographic maps and aerial photographs indicated a lake outburst as a result of its overtopping and subsequent overflow). Calculations of outburst floods were carried out taking into account the heterogeneous composition of the moraine dam. The quality of the modelling was assessed based on the results of comparing the breach values calculated by the methodology with its measured values, since the breach dimensions are the only verification information. The discrepancy when comparing the calculated breach areas with the measured values did not exceed 15%. When assessing the accuracy of the calculations performed, it should be borne in mind that the survey of the resulting breaches was carried out after a long period of time. During this period, the breach dimensions could have changed slightly due to the possible shedding of moraine material from the sides of the breach. Thus, the results of the conducted mathematical modelling are satisfactory.

Conclusion

In the process of carrying out the thesis, the aim of the thesis was achieved – assessment the characteristics of outburst floods formed during of high-mountain moraine-dammed lakes outbursts, based on mathematical modelling, field investigations and Earth remote sensing data.

Main results of the thesis:

1. An analysis of more than 100 Russian and foreign published scientific works showed the need to develop a methodology for calculating the hydrograph of an outburst flood formed during the destruction of a moraine dam of heterogeneous composition for the two most common triggers of destruction: water overflow through the dam crest and the formation of a filtration channel in the dam body.
2. The main advantage of the proposed methodology, in contrast to similar existing models, is the ability to calculate outburst characteristics both for the case of water overflow through the dam crest and/or for the case of erosion of the filtration channel in the moraine dam body with a heterogeneous composition of the moraine. The heterogeneity of the moraine material was taken into account by introducing the characteristics of several fractions of the soil composing the moraine dam. To more correctly display the process of development of the breach, the model introduced the calculation of flow velocities in depth. The approximation of the cross-sectional shape of the breach proposed by the author is more correct than those traditionally used (triangular and trapezoidal), describes the development of the breach over time and better takes into account the change in shape by taking into account the unevenness of the erosion rate.
3. As a result of numerical experiments, quantitative criteria for choosing the size of the initial breach and the filtration channel diameter during modelling were proposed: the initial breach length is no more than 1% of the dam length, the breach depth is no more than 20 cm, the channel diameter is no more than 10 cm.
4. It has been shown that the erosion rate and, accordingly, the maximum discharge significantly depend on the granulometric composition of the soil composing the moraine dam. The selection of parameters such as the specific gravity of the dam material and the clay content in it for modelling must be carried out on the basis of the experience gained, the developed methodology and the results of special field studies.
5. Approbation of the mathematical model on the results of physical experiments showed the adequacy of the model, which is confirmed by a good correlation of model hydrographs of outburst floods and hydrographs obtained from the results of experiments.
6. Approbation of the developed calculation methodology on published data on real outbursts of moraine lakes showed a satisfactory result: the discrepancy between the

calculated and observed characteristics was no more than 12.5%. Thus, the proposed methodology can be used to assess the characteristics of possible outbursts, and the resulting calculated outburst flood hydrograph can be used as input information for mathematical modelling of mudflows.

7. It was revealed that the reduction in the glaciation area in the Altai, due to a statistically significant increase in air temperature, is showed up in changes in lake complexes in different regions in different ways. In the more arid the South-Eastern Altai, when the connection between moraine lakes and glaciers is reduced, lakes degrade until they disappear completely. While in the more humid the Central Altai, lake degradation does not occur due to the significant contribution of rain and melted snow waters to the feeding of lakes.
8. For the period from 2000 to 2022 there is a shift in the upper limit of the interval of maximum distribution of lakes by 100-200 m higher only for mountain ranges with a large area of glaciation. The close connection between the retreat of glaciers and the changes occurring in moraine and periglacial lakes suggests that the lakes are indicators of the process of mountain glaciation degradation.
9. The existing classification of stages of lakes development (Zimnitsky, 2005) has been supplemented: the concept of a quasi-stable stage of development has been introduced; morphological and hydrological-morphometric characteristics of each stage are proposed, the features of the level regime of lakes at different stages of development are described. Determining the stages of development of lakes makes it possible to assess their further development, including identifying potentially outburst-dangerous reservoirs in conditions of poor hydrological knowledge.
10. Potentially outburst-hazardous lakes are in a transgressive stage of development (they have an unstable level regime and are actively increasing in size). This was confirmed by the results of a study of Lake Maashey and Lake Nurgan that actually outburst in the Altai. Therefore, lakes that are actively increasing in size and have an unstable level regime should be objects of close monitoring in areas of development of mountainous territories.
11. Based on the data obtained during detailed field studies and Earth remote sensing data on the configuration of moraine dams of lakes, the positions of high water levels, changes in the direction of flow, the mechanisms of outburst of lakes Maashey (erosion of the filtration channel in the moraine dam body) and Nurgan (water overflow through the dam crest) were determined. The satisfactory results of the mathematical modelling of the outbursts of Lake Maashey and Lake Nurgan are confirmed by the good convergence of

the calculated by the methodology and the observed sizes of the breaches. To date, the dimensions of the breach are the only verification information. Discrepancies (up to 15%) when comparing the calculated areas of breaches with measured values are explained by the period of time that passed between the calculations performed and the outbursts that occurred

The completed research, in the opinion of the author, can serve as a contribution to the solution of fundamental and applied problems related to the process of outburst floods formation and the development of moraine-dammed and periglacial lakes. The results of the thesis are especially relevant against the backdrop of poor hydrological knowledge of lakes located in areas of modern mountain glaciation, and the proposed calculation methodology and classification of stages of lake development will make it possible to assess the risks of dangerous hydrological phenomena and reduce the degree of information uncertainty.

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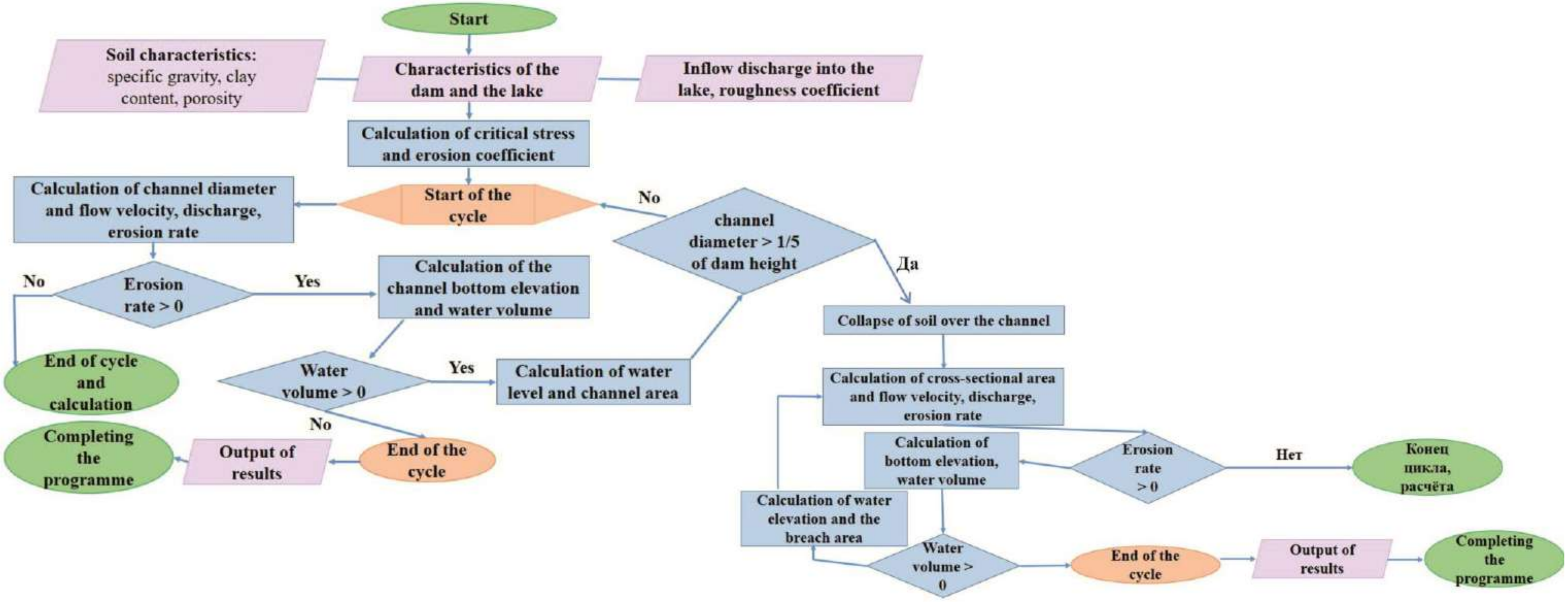
Appendixes

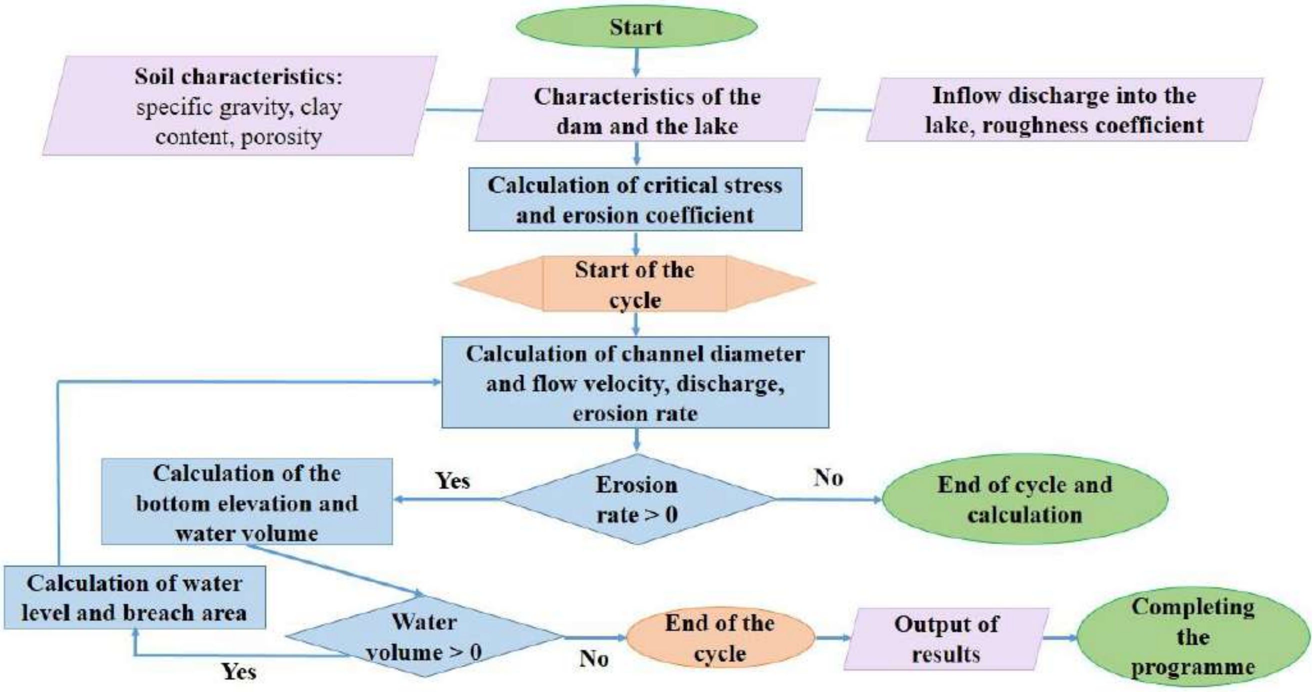
Appendix 1

Block scheme for calculating the characteristics of a lake outburst during erosion of a filtration channel.



Appendix 2

Block scheme for calculating the characteristics of a lake outburst during water overflows through the moraine dam crest.



Appendix 3

Satellite imagery used to analyze the variability of moraine-dammed lakes

Date	Satellite	Spatial resolution, m	Satellite imagery ID
22.07.2000	Landsat 7 Sensor ETM+	15	EPP144R025_7F20000722
7.08.2000	Landsat 7 Sensor ETM+	15	EPP144R026_7F20000807
27.06.2000	Landsat 7 Sensor ETM+	15	EPP145R025_7F20000627
27.08.2000	Landsat Sensor ETM	15	MEN-46-45_UL_2000
28.06.1962	Corona	1.8	DS009038052DF039
8.08.1980	Landsat 3	30	LM03_L1TP_155025_19800808_20200905_02_T2
17.08.1989	Landsat 5	30	LM05_L1TP_144025_19890817_20200829_02_T2
12.08.1993	Landsat 5	30	LT05_L2SP_144025_19930812_20200913_02_T1
22.07.2000	Landsat 7	15	EPP144R025_7F20000722
18.08.2004	Landsat 7	15	LE07_L1TP_144025_20040818_20170119_01_T1
13.08.2011	Landsat 7	15	LE07_L1TP_145025_20110813_20200909_02_T1
15.08.2022	Landsat 9	15	LC09_L1TP_141026_20220815_20230402_02_T1
10.04.2023	Sentinel-2	10	S2A_MSIL2A_20230410T045701_N0509_R119_T45UYQ_20230410T091259
24.03.2023	Sentinel-2	10	S2A_MSIL1C_20230324T050651_N0509_R019_T45UYQ_20230324T065644
10.01.2023	Sentinel-2	10	S2A_MSIL2A_20230110T050201_N0509_R119_T45UYQ_20230110T081003
14.11.2022	Sentinel-2	10	S2A_MSIL1C_20221114T051051_N0400_R019_T45UYQ_20221114T054313
22.09.2022	Sentinel-2	10	S2A_MSIL2A_20220922T045701_N0400_R119_T46UCV_20220922T085450
4.07.2022	Sentinel-2	10	S2A_MSIL1C_20220704T045711_N0400_R119_T46UCV_20220704T065335
17.06.2022	Sentinel-2	10	S2A_MSIL1C_20220617T050701_N0400_R019_T45UYQ_20220617T070314
17.07.2020	Sentinel-2	10	L1C_T45UWQ_A026471_20200717T051132