Earth-Science Reviews 229 (2022) 103999

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

# Moraine-dammed glacial lakes and threat of glacial debris flows in South-East Kazakhstan

Akhmetkal R. Medeu [a], Nikolay V. Popov [a], Viktor P. Blagovechshenskiy [a], Maulken A. Askarova [b], Alikhan A. Medeu [a], Sandguash U. Ranova [a], Aidana Kamalbekova [a], Tobias Bolch [c,*]

[a] Institute of Geography and Water Safety, Almaty, Kazakhstan
[b] Al-Farabi Kazakh National University, Almaty, Kazakhstan
[c] School of Geography and Sustainable Development, University of St Andrews, Scotland, UK

ARTICLE INFO

*Keywords:*
Debris flow
Glacial hazard
Glacial lake outburst flood
Hazard mitigation
Moraine-dammed glacial lakes
South-East Kazakhstan

ABSTRACT

Glacier retreat has caused the emergence of numerous moraine-dammed glacial lakes (MGL) over the last century which have become research foci in many mountain regions of the world. Outbursts of MGLs have caused destructive floods and debris flows, leading to numerous human casualties and significant material damage. The mountains of South-Eastern Kazakhstan have also become prone to lake outburst floods and related debris flows, specifically in the second half of the 20th century. This paper presents and reviews existing surveys and knowledge along with results of own investigations on the formation of MGLs and the characteristics of lake outburst floods and debris flows in the Kazakh part of Tien Shan. We suggest a workflow to identify the most dangerous types of lakes and provide information about their morphogenetic features and hazard criteria.

The number of MGLs increased since the 1970s with more than 160 existing in 2018. Forty were identified as being dangerous. Forty-eight lake outbursts occurred since 1950 with all the documented events happened between end of June and end of August. The most dangerous outbursts were caused by ruptures in ice-cored moraine dams. Outbursts of nine MGLs caused disastrous debris flows, with some occurring repeatedly. The number of outbursts decreased since the year 2000 compared to 1970–2000. However, due to ongoing glacier retreat new lakes are forming at higher altitudes. Their greater potential energy makes possible future outbursts more dangerous. *Re*-evaluation of existing methods to calculate the water volume and peak discharge based on bathymetric measurements and observed outbursts revealed that the applied equations provide suitable approximations and allow supporting mitigation and prevention measures. Finally, the presentation of implemented measures to lower the water level using siphons or artificial flow channels shows that they can reduce the lake outburst hazards. However, they are associated with risks and financial costs and it needs to be carefully considered whether protection measures of the endangered areas are more cost effective.

## 1. Introduction

Glacial lakes have become a widespread phenomenon in glacierised mountains on Earth due to glacier retreat since the Little Ice Age (Pörtner et al., 2019; Shugar et al., 2020). They are an integral element of the mountain landscape, characteristic of the Earth's mountain systems located in different latitudes and different continents (Liestol, 1956; Lliboutry et al., 1977; Ives et al., 2010; Dokukin and Khatkutov, 2016; Wangchuk and Bolch, 2020). These water bodies have attracted particular attention because in particular moraine-dammed glacial lakes (MGLs) are likely to discharge which can lead to catastrophic floods and glacial mudflows causing casualties and material damage (Ives et al., 2010; Carrivick and Tweed, 2016; Dokukin and Khatkutov, 2016; Kapitsa et al., 2018; Wilson et al., 2019).

MGLs typically develop and increase in size concomitant with the retreat of their parent glaciers. Glaciers in the central Asian Tien Shan shrank and lost mass significantly during recent decades (e.g. Sorg et al., 2012; Farinotti et al., 2015; Severskiy et al., 2016; Shean et al., 2020; Bhattacharya et al., 2021) in line with the reported global glacier retreat (Gardner et al., 2013; Zemp et al., 2019; Hugonnet et al., 2021). Hence,

* Corresponding author.
*E-mail address:* tobias.bolch@st-andrews.ac.uk (T. Bolch).

https://doi.org/10.1016/j.earscirev.2022.103999
Received 19 December 2020; Received in revised form 24 February 2022; Accepted 15 March 2022
Available online 30 March 2022

the number and surface area of glacial lakes has increased in the Tien Shan (Wang et al., 2013) as in most mountain ranges on Earth (Shugar et al., 2020; Clague and Evans, 2000; Buckel et al., 2018; Dokukin and Khatkutov, 2016; Gardelle et al., 2011; Nie et al., 2017; Bolch et al., 2019; Wang et al., 2020). Glacier retreat in the South-East Kazakhstan has caused the formation of numerous MGL (e.g. Narama et al., 2009; Bolch et al., 2011). Sudden discharge from these lakes caused frequent MGL outbursts and glacial debris-flow events in this region (Medeu et al., 2018).

The first signs of glacial lake formation processes in Ile Alatau began between the 1910s and the 1930s (Palgov, 1958 and references therein). Strong glacier recession, and the concomitant emergence and further development of MGLs occurred in the middle of the 20th century. In the late 1950 investigations of MGL started in the glacierised mountains of Kazakhstan, which includes the western and north-eastern ridges of Tien Shan, Zhetisu (Dzungarian) Alatau, Saur and Kazakhstan's Altai (Popov, 1991; Medeu et al., 2018). In recent decades, these processes have been most active and studied in the Karakoram-Hindu Kush-Himalaya mountains (Cenderelli and Wohl, 2001; Richardson and Reynolds, 2000; Wang and Zhang, 2013; Wang et al., 2015; Allen et al., 2019; Veh et al., 2019). Several models with various complexity have been suggested and applied to model the outburst flood from glacial lakes and its peak discharge (Westoby et al., 2014).

Different definitions of glacial lakes and moraine-dammed glacial lakes exist (e.g., Glaciological Dictionary, 1984; Kotlyakov and Komarova, 2012; Emmer, 2017). In our study we consider all types of lakes located within the extent of the moraines of the Little Ice Age (~1500–1859 CE) (Glaciological Dictionary, 1984). These zones, called "modern moraine-glacial complexes" in the Russian scientific literature, include the open parts of the glaciers and frontal or lateral moraines containing ice cores. In this study we focus on glacial lakes which form(ed) when the terminal moraine has prevented meltwater from leaving moraine-glacial complex. We thus use the general term moraine-dammed glacial lakes (MGL). The term "Glacial Lake Outburst Flood, (GLOF)" is commonly used to describe the sudden release of water held in glacial lakes dammed by glacial ice or moraines. In a broad sense, the term GLOF does not differentiate between types of lakes, genesis, and features of their hydrological regimes and mechanisms of drainage (Grabs and Hanish, 1993, Reynolds, 1995; Clague and O'Connor, 2015; Emmer, 2017).

The main aims of this study are to (a) review the existing knowledge about the occurrence of MGLs and GLOFs in South-East Kazakhstan, (b) evaluate the history of MGL research and preventative measures in Kazakhstan and put them into perspective of current knowledge and research, (c) present various mechanisms of MGL discharge, particularly determining the maximum (peak) discharge rates, which allows the assessment of their potential hazard, to (d) demonstrate preventive work to reduce glacial debris flow hazards, and to (e) suggest future direction of research.

## 2. Study Region

### 2.1. Location and general characteristics

Our study focuses on the mountains of South-East Kazakhstan (*Qazaqstan* according to the new Latin alphabet), located close to the border to Kyrgyzstan which includes the Ile (former name: *Zailiskiy*) Alatau ridge and the northern slope of the Kungei Alatau within 76–78°E and 42.8–43.3°N covering an area of about 4000 km$^2$ (Fig. 1). There are 11 glacierised river basins in our study area: Uzunkargaly, Chemolgan, Kaskelen, Aksai, Kargaly, Ulken (*Bolshaya, Big*) and Kishi (*Malaya, Small*) Almaty, Talgar, Esik, Turgen River basins on the northern slope of the Ile Alatau ridge, as well as the Shilek (*Chilik*) River basin (between the southern slope of Ile and the northern slope of Kungei Alatau).

The average elevation of the mountain ridges is 3800–4200 m above sea level (asl.). The ridges connect in their central part (Shilek-Keminsky mountain junction), where the highest point – Pik Talgar (4973 m asl.) – is located. The ancient sedimentary, igneous and metamorphic rocks of Lower Paleozoic dominate in the region (sandstones, porphyries, granites and gneisses). During the Alpine orogeneses this mountainous structure became folded. Piedmont and intermountain territories are formed of Neogene and Quaternary sediments complexes, which are of glacial, alluvial and proluvial-diluvial origin.

The climate of northern Tien Shan is semi-continental and influenced by circulation processes that extend to Kazakhstan and Western Siberia. The main features are strong solar radiation and the complex seasonal

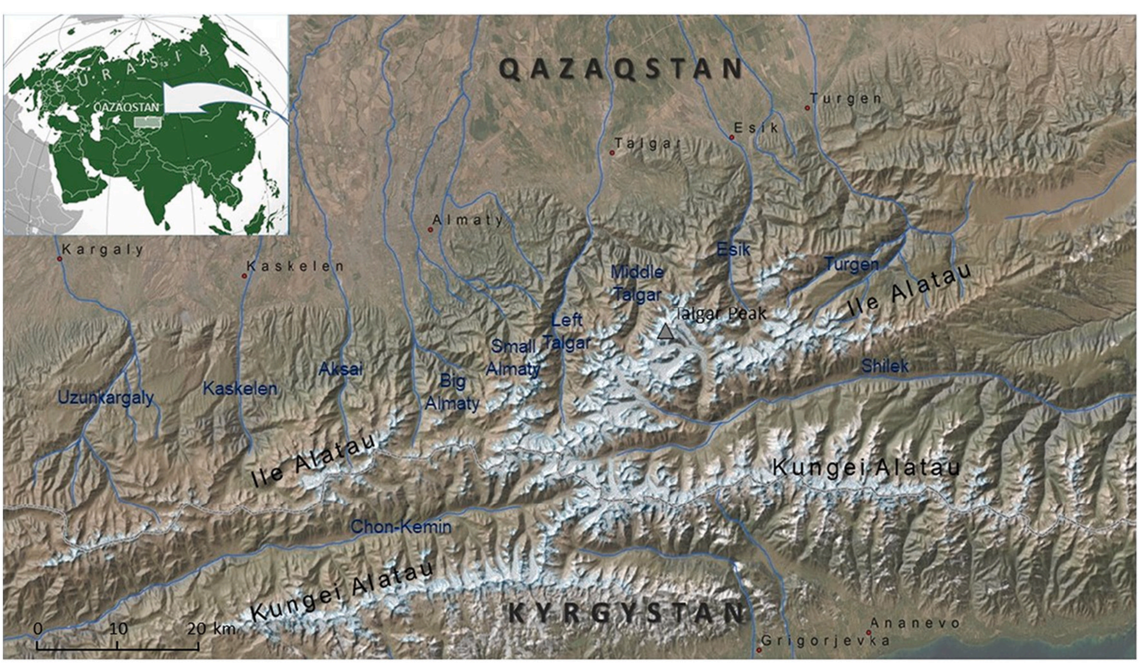


**Fig. 1.** Study region and its location on the map of Eurasia (inset); sources: satellite image: Landsat OLI, hillshade based on the SRTM DEM, glacier outlines: RGI consortium (2017), rivers and settlements: own digitisation.

nature of precipitation. In the foothills and mid-mountain zone, the climate is temperate-continental with the highest precipitation occurring in April and May due to cyclonic activities while in the high-mountain zone precipitation high precipitation occurs from April through August governed by convective precipitation and north-western cold air intrusions (Aizen et al., 1995). Mean annual air temperature at Tuyuksu Glacier station (3434 m asl.), located slightly lower than the glacier terminus, is about −3.3 °C with mean annual precipitation of about 1100 mm.

Permafrost is widespread over the whole study area and covers a significantly greater area than the regions glaciers (Bolch and Gorbunov, 2014). The lower boundary of the discontinuous permafrost is located between 2700 and 3000 m asl. While above 3600 m asl. Permafrost occurs in almost all conditions (Gorbunov et al., 1996; Bolch and Gorbunov, 2014). Hence, the modern moraines are located in elevations where permafrost occurrence is likely.

### 2.2. Past glacier and permafrost changes

In recent decades, the glaciers in the Ile and Kungei Alatau mountains have lost more than a third of their area. The observed glacier retreat was the most pronounced in the Kazakh part of Ile and Kungei Alatau (Bolch, 2007; Severskiy et al., 2016; Vilesov, 2018). Vilesov (2018) revealed, based on multitemporal glacier inventories derived from aerial images and satellite data, that glaciers in South-East Kazakhstan shrank more than 40% (from about 1775 km$^2$ to ~1030 km$^2$) between 1955 and 2015. The total number of glaciers decreased from 2793 to 2054; while larger glaciers disintegrated and small glaciers with an area of less than 1 km$^2$ disappeared (Vilesov, 2018). In general, during the period 1955 to 2008, glacier area decreased from 287.3 km$^2$ to 171.5 km$^2$, or by about 40% on the northern slope of the Ile Alatau. In Shilek River basin in the territory of Kazakhstan, the number of glaciers increased from 257 to 271 in the period from 1955 to 2005, while the glacier area decreased from about 287 km$^2$ to ~207 km$^2$, respectively (Vilesov, 2018). In-situ and geodetic mass balance measurements revealed that the tongue of Tuyuksu Glacier, located in Kishi Almaty basin, thinned by more than 70 m between 1958 and 2016. The mass loss rate of Tuyuksu Glacier was about 0.37 m water equivalent per annum (w.e. a$^{-1}$) over this time period (Kapitsa et al., 2020). Ground temperature measurements, established in the 1970s at Zhusalykezen Pass (altitude ~3300 m asl.) located close to Ulken Almaty basin showed a rise in permafrost temperatures between 0.3 and 0.6 °C and an increase in active-layer thickness of more than 20% (Marchenko et al., 2007; Bolch and Marchenko, 2009).

## 3. Past and present-day data and methods to study moraine-dammed lakes and their outbursts in South-East Kazakhstan

The following sections provide more details about the history of past and more recent work. An overview of the work conducted and the general workflow of the investigations of the MGLs to identify hazardous and dangerous glacial lakes is presented in Fig. 2.

### 3.1. Remote sensing-based investigations

The first important step is to identify the location of the glacial lakes and then to investigate their characteristics and changes over time. This can be best achieved with remote sensing data.

#### 3.1.1. Identification and evolution of moraine-dammed glacial lakes

The MGLs in our study were visually identified and manually mapped by various organizations (especially the Hydro-Meteorological Service of the Kazakh SSR/Kazakhstan [Kazhydromet], the Kazakhstan Debris Flow Protection Organization [Kazselezashchita] and the Institute of Geography, Almaty) at different periods of time. The earliest complete inventory exists for 1968/69 and the lakes were mapped from aerial images (Tokmagambetov et al., 1980). The inventory was displayed on simple maps and the information about the lake position and area handwritten in tables. Further inventories based on aerial images exist for some periods in the 1980s. At a later stage satellite images were used. Scientists from the Institute of Geography manually delineated the lake boundaries and generated the inventories based on satellite imagery and GIS software. The satellite images used includes Landsat TM/ETM+ (spatial resolution 30 m) for ~1990 and 2000 and Sentinel-2 (10 m) for 2018. The lake outlines were compared to conducted field measurements of the margins of selected lakes (see Section 3.2). The mapped outlines showed a good fit to the measured ones.

#### 3.1.2. Dam characteristics and past outburst events

Remote sensing data and in particular high-resolution aerial images

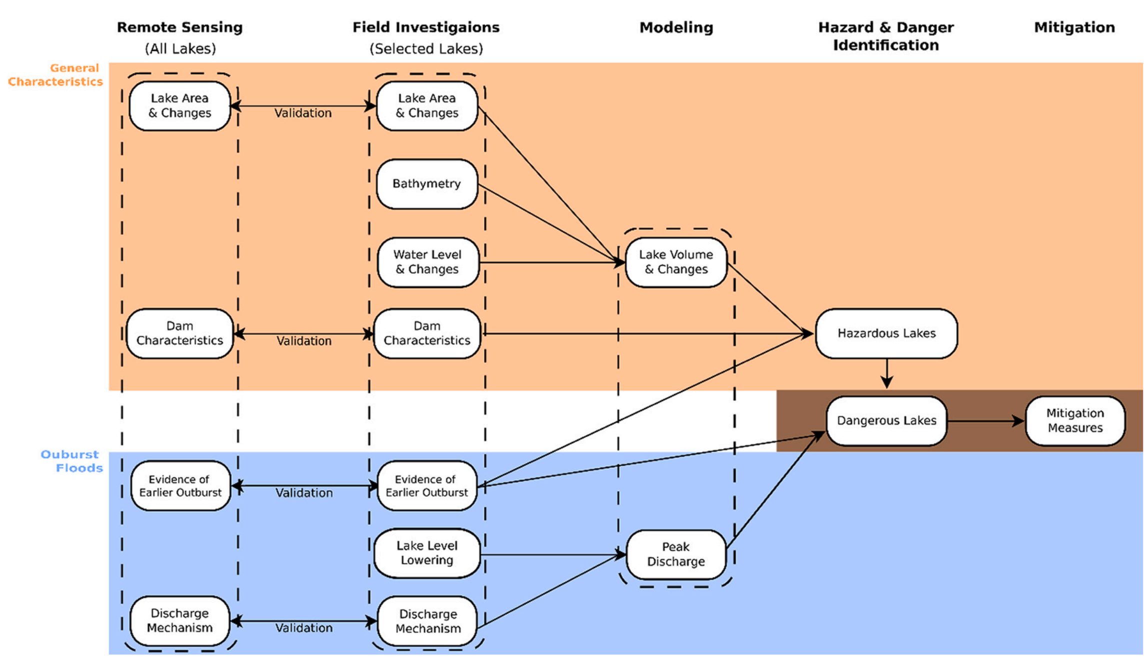


**Fig. 2.** General workflow for investigation of moraine-dam glacial lakes and identification of hazardous and dangerous glacial lakes.

have been used to obtain relevant further information to estimate the potential hazard of a glacial lake and to support the calculation of peak discharge. The obtained information includes the width of the moraine dam and the frontal moraine slope (the latter was obtained in earlier time with the support of small-scale topographic maps and later using digital elevation models) and identification of evidence of the type of drainage (via surface channels or tunnels). The conducted field investigations supported the remote-sensing-based investigations in particular for better identification of the drainage types.

### 3.2. Field investigations

Field investigations can provide detailed information about the characteristics of MGLs, their surroundings and their evolution. However, these investigations are laborious and not all glacial lakes can be reached. In the earlier days the lakes investigated were selected based on past outburst events, later the investigations were further guided by the interpretation of aerial photos or satellite images.

#### 3.2.1. Characteristics of the glacial lakes and moraine dams

The earliest field measurements were conducted on lakes No. 2 and 6 in Kishi Almaty (for the location see Figs. 3 and 4) by Institute of Geography (E. Vilesov, P. Cherkasov) during the international geophysical year (1956/57). The general characteristics of the lakes and their damming moraines were inspected. It was known from previous lake outburst and debris flow events (e.g. 20.08.1951 and 7.8.1956, Kavetsky and Smirnov, 1957; Kolotilin, 1959) that these lakes are a direct threat to the city of Almaty and moreover they could be relatively easily accessed. The first total station and bathymetric surveys of glacial lakes and water-retaining dams were conducted in 1968–1969 by Kazhydromet. Total station surveys were performed according to the established requirements for building plans and maps at scales 1:1000, 1:500 and larger, in conventional coordinates using theodolites of the type TT-2, TT-3 (Ural Optical and Mechanical Plant, 1954–1967). During the 1970s -1990s total station surveys were performed by employees of Kazselezashchita, Kazhydromet and the Institute of Geography (with the participation of N. Popov, A. Medeu and V. Blagovechshensky) employing T-30 and T-15 instruments (Ural Optical and Mechanical Plant, 1973–1979) with the use of range finders, levelling and total tachometer staff. Hydrological posts were established by Kazselezashchita on several lakes to monitor the water level and the temperature regime. A level survey of the installed heads of piles or water gauges was

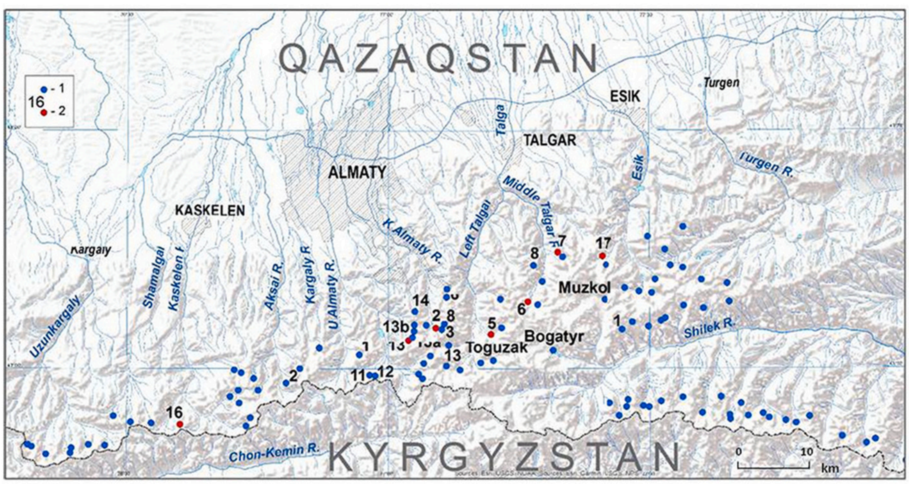


**Fig. 3.** Distribution of the moraine-dammed glacial lakes (MGL) in the mountains of the South-East Kazakhstan based on the own 1990 inventory: 1 - MGLs, 2 - MGLs which caused glacial debris flows during in the 1970–2000 period. The numbering of the lakes are based on the MGL inventory of the Kazakhstan debris flow protection organization. Background: hillshade based on the SRTM DEM, rivers and settlements: own digitisation.

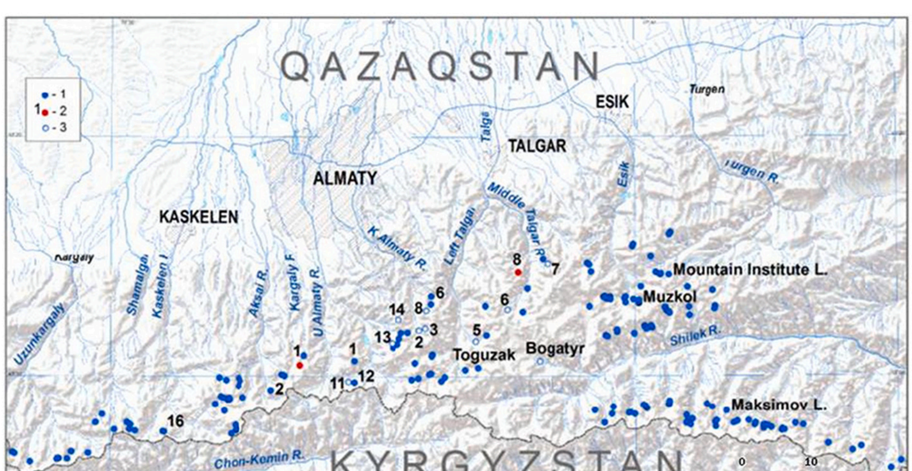


**Fig. 4.** Distribution of the moraine-dammed glacial lakes (MGLs) in the mountains of the South-East Kazakhstan in the period based on our 2018 inventory: 1 - MGLs, 2 - MGLs which caused glacial debris flows during 2000 and 2018, 3 – MGLs emptying before 2000. The numbering of the lakes are based on the MGL inventory of the Kazakhstan debris flow protection organization. Background: hillshade based on the SRTM DEM, rivers and settlements: own digitisation.

performed with NV-1 levels, or devices similar in accuracy. Bathymetric surveys of selected MGLs were performed simultaneously with total stations and levellers by employees of Kazselezashchita and the Institute of Geography. The depth at the pivot points was measured using lots. Most of the measurements were made from inflatable boats, approximately at equal fixed intervals in time and distance. The average total measurement error was in the range of 10–20%. This relatively small error was achieved by a high accuracy of depth measurement, usually less than 0.1 m, as well as by increasing the number of measurements.

Lakes No. 2 and 6 in Kishi Almaty and selected further MGLs have been consistently investigated since 2000 by employees of Kazselezashchita and the Institute of Geography (with the participation of A. Medeu, V. Blagovechshensky, N. Kasatkin and V. Kapitsa). The accuracy of measurements of both the geodetic work and bathymetric surveys has increased in accordance with new measurement devices. For tachometric surveys, modern devices 2 T-30, 2 T-30P and other nomogram tachometers TN, DALTA-010; DALTA-020 were used between 2005 and 2017. For the depth measurement the Lowrance LMS 480 m echo sounder, with an operating frequency of 200 kHz and equipped with a 12-channel GPS receiver, was applied (with a depth measurement error of up to 10 cm). In 2017, a portable 24-channel Garmin GPSMAP 64 receiver was used for more accurate positioning.

#### 3.2.2. Observations and characteristics of past outburst events

All past MGL outburst events which could be clearly determined (e.g. due to flood and debris flows observed at the edge of the mountains) were recorded by since about 1950 by Kazhydromet, Kazselezashchita and the Institute of Geography. Few earlier events which had a large impact on the infrastructure or caused fatalities were also recoded. In particular for catastrophic events, field investigations were conducted to explore the reasons for the flash floods and debris flows. In case of MGL outbursts the dam characteristics were investigated. Within this study all available literature and the related information therein were considered. Several of these references were published by authors of this study (see also Section 4.3).

In a few cases the lowering of the lake water level during its emptying could be observed. Observations were made in particular for the glacial lake close to Tuyuksu Glacier (Lake no. 2) on July 15, 1973, Lake no. 17 close to Zharsai Glacier on July 3, 1977, Lake no. 13 close to Soviets Glacier on August 3, 1977, and Bogatyr Lake on July 23, 1985 (Golubev, 1974; Plekhanov et al., 1975; Keremkulov and Tsukerman, 1984; Keremkulov, 1985; Popov, 1986b). These measurements, along with field investigations of the outburst mechanism, the drainage channels or tunnels and discharge measurements at hydrological posts downstream, were instrumental to be able to calculate, calibrate and validate the empirical formulas of the peak discharge (see 3.3.2).

### 3.3. Empirical formulations and modelling

#### 3.3.1. Estimation of lake volumes

The estimation of the volumes of glacial lakes based on the empirical relationship between the lake area and its volume is well established (e.g. Huggel et al., 2002; Cook and Quincey, 2015). However, it needs to be noted that the applied formulas can provide large erroneous values for individual lakes and should be adjusted to the specific conditions of the study regions. The conducted bathymetric measurements of several lakes in the study region allowed Popov (1986b, 1988) to establish the following formula between the volumes and areas of lakes for South-East Kazakhstan:

$$V = 0.059\ S^{1.44} \tag{1}$$

where V is the volume of the lake in $m^3$ and S the lake area in $m^2$.

This formula was used to estimate the volume of lakes in the presented studies of the study region and previous work in case no bathymetric measurements were available for the particular lake.

For the lakes where measurements of the depth available, the following more detailed formula was used (Keremkulov, 1985):

$$V = 0,09\ S_{max}^{0,10}\ h^{2,48} \tag{2}$$

$$S = 0,21 S_{max}^{0,13} h^{1,51} \tag{3}$$

where $S_{max}$ - is the maximum area of the lake, $10^3$ $m^2$;
h - is the depth of the lake, m;
S - is the estimated area of the lake, $10^3$ $m^2$.

#### 3.3.2. Estimation of peak discharges

An important element in assessing the lake outburst hazard is the condition for maximum (peak) discharge. A large lake outburst flood serves as a trigger for glacial debris flows which can cause even stronger destructions that the flood waves. The peak discharge depends besides the lake volume in particular also on the characteristics of the discharge mechanisms. The main discharge mechanisms in our study area are (a) discharge via open channels formed in the moraine dam, (b) discharge via underground tunnels through the moraines ("piping"), and (c) discharge via ruptures in thawed permafrost bodies.

Various methods exist to estimate the peak water discharge during lake drainage based on water volume and the time of water out-flow from the lake, most widely applied are empirical-statistical models (e.g. Clague and Mathews, 1973; Costa and Schuster, 1988; Westoby et al., 2014 and references therein). Further models include more specific information such as cross sectional area or the slope angle for the frontal moraine or were developed the different drainage types and triggers (e.g. Haeberli, 1983; Costa and Schuster, 1988). These models require direct measurements or observations which are mostly unavailable since lake outburst events are rare phenomena. However, few observations are available also for our study region (see Section 3.1.2). These observations allowed the determination of the time taken for water drainage, to obtain peak flow values as well as to calculate hydrographs of the MGL drainage in SE-Kazakhstan. Important parameters which can be considered without direct measurements but obtained from high-resolution remote sensing data are cross-sectional area and hydrostatic pressure in the channel, which depends on the height difference between MGL water horizon and tunnel outlet (Popov, 1984; Keremkulov and Tsukerman, 1985; Bizhanov et al., 1998; Medeu et al., 2015). The following two formulars for discharge via open channels and tunnels were applied by the authors for the study region (Table 1).

Eq. (5) is suitable for discharge via open channels and was calibrated using field measurements in the study region (Popov, 1986b). The

**Table 1**
Empirical formulas for calculating the MGL peak discharge via tunnels applied in this study.

| Drainage type/ Trigger | Equation | | Reference |
|---|---|---|---|
| Ice dam, open channel | $Q_{max} = \lambda\ S_{max}$ | (5) | Popov (1986b) |
| Tunnel | $Q_{max} = 75\ (V/10^6)^{0.67}$ | (6) | Clague and Mathews (1973) |
| | $Q_{max} = \alpha W^{1,25} H^{0.5}$ | (7) | Vinogradov (1977), Medeu et al. (2018) |
| | $Q_{max} = (tg\phi/nA^*)^{0.5}$ | (8) | Keremkulov and Tsukerman (1984) |

where $Q_{max}$ is a maximum flow rate of water ($m^3/s$), λ corresponds to the channel thawing intensity (m/s), and $S_{max}$ is the maximum water surface area ($m^2$), V is the total lake volume ($m^3$), α is an empirical coefficient and depends on the length of the tunnel, W is the cross-sectional area of the tunnel ($m^2$), H is the excess of lake water level above the tunnel entrance (m), t stands for time and has a value in the interval 1000–2000 s, ϕ is the tilt angle of the frontal moraine slope, n is a dimensionless coefficient (typical values range from 1.25–1.35), A* is the resistivity ($cm^2/m^6$) which can be according to Keremkulov and Tsukerman (1984) " resolved as accumulation of information on outburst floods and the morphometric characteristics of the flow channels".

**Table 2**
Indicators characterizing the possible hazard and outburst susceptibility and possible debris-flow danger of the MGLs in SE-Kazakhstan.

| № | Parameter | Susceptibility and Possible consequences* | Reference |
|---|---|---|---|
| 1 | Intensive growth of water in the lake | Increased lake outburst threat | Vinogradov (1977), Markov and Popov (1980), Popov (1988), Medeu et al. (2018) |
| 2 | High temperature background for at least 7–10 days | Increased melt runoff | Kavetsky and Gulina (1964), Vinogradov (1977) |
| 3 | Funnel-shaped structure of the lake bed | Enhanced bottom filtration from the lake | Kobrushko and Stavissky (1978), Dokukin et al. (2012), |
| 4 | Presence of active thermo-karst processes in the body of a water-retaining frozen dam | Increased probability of an outburst | Golubev (1974) |
| 5 | Irregular fluctuations of water level in the lake (in a river flowing out of a lake) | Blockages of intra-morainic drainage channels in the lake bottom | Plekhanov et al. (1977), Tokmagambetov et al. (1978) |
| 6 | Occasional filling of the lake basin | Blockages of intra-morainic drainage channels in the lake bottom | Keremkulov and Kirenskaya (1985), Popov (1981) |
| 7 | Strength of water-retaining dam | Increased outburst and debris-flow probability with decreasing dam strength | Popov (1991) |
| 8 | Location of the lake near the crest of frontal moraine | Increased outburst and debris-flow probability | Kolotilin (1959), Kobrushko and Stavissky (1978), Lliboutry et al. (1977), Popov (1986b) |
| 9 | Debris flow channel with slopes between 10 and 25°, folded with friable material | Condition for debris flow processes | Vinogradov et al. (1976), Tokmagambetov et al. (1980) |
| 10 | The volume of the lake is 5–30,000 $m^3$ (area 3–5000 $m^2$) | Possibility of lake outburst with formation of debris flows of 1–2 categories | Medeu et al. (2018) |
| | The volume of the lake is 30–100,000 $m^3$ (area 5–20,000 $m^2$) | Possibility of a lake outbursts with formation of debris flows of 2–3 categories | |
| | The volume of the lake is more than 100,000 $m^3$ (area of more than 20,000 $m^2$) | Possibility of a lake outbursts with formation of a catastrophic debris flow of 3 categories | |

proposed model by Clague and Mathews (1973) (6) of lake discharge via tunnels in the ice-cored moraines include the maximum volume of the lake, and thus model its emptying as quasi-instantaneous (flash flood). Eq. (7) is a modification of the widely used hydraulic correlations between water pressure and the cross-sectional area of the pressure pipe.

### 3.4. Identification and classification of potentially hazardous and dangerous moraine-dammed glacial lakes

The information obtained from field investigations, remote sensing and from the empirical estimations allowed the identification of hazardous (lakes with a high outburst susceptibility) and dangerous lakes (as defined in our study by being hazardous and have high probability of debris-flow as determined by the water volume and the peak discharge) (Fig. 2).

The main hazard criteria in the framework of older studies included only the volume of water and the “strength of water-retaining bulkhead”, which was determined visually based on the interpretation of aerial images and selected field investigations (Popov, 1991). A further simple classification was proposed by Baimoldayev and Vinokhodov (2007) who distinguished “dangerous”, “potentially dangerous” and “non-dangerous” lakes among the non-stationary and stationary reservoirs. Their criteria for this qualitative classification of MGLs were only the water volume, features of the hydrological regime and the past outburst activity.

A more sophisticated classification was developed by Popov (1997) and Bizhanov et al. (1998) and was further refined by Kapitsa et al. (2018) and Medeu et al. (2018) based on the results of field studies carried out in the 1990s and 2000s, as well as the examination of aerial photographs and satellite images.

The hazard criteria used included the following:

- Presence of precedents for earlier discharges while maintaining the possibility of filling the lake depression.
- Intense lake development expressed as an increase in area and volume of the water.
- A sharp modification in the water regime of the lake (expressed in a sharp drop / rise of the water level, the occurrence of subsidence on the underground runoff paths, and rapid filling of previously empty lake hollows).
- Significant changes in the moraine-glacial lake system, causing damage to the integrity of the water-retaining dam, changes in filtration paths and underground flow.

Taking the past investigations, existing literature and the knowledge of past outburst events into account, we used the following indicators to characterize the outburst susceptibility (the hazard level) of the MGLs (Table 2).

These indicators include indicators for occurrence of debris flows which are usually more dangerous due to the large volume of material they are transporting. Important factors are the availability of large amount of debris either from the dam (indicator 8) or in the channel below the lake (9). Furthermore, the water volume of the lake and possible peak discharge is important as a certain strength is needed to be able to transport the debris. The debris flows of categories 1, 2, 3 (indicator 10) are natural events that (1) occurred within the moraine-glacial complexes only, (2) which reached the mid-mountain zone and (3) the foothills. We consider lakes as potentially dangerous if they are hazardous and they have the potential to generate a large debris flow which could reach the foothills of the mountains. They are identified by the water volume, the peak discharge and the strength of water-retaining dam. The potentially dangerous MGLs were investigated and if a potential outburst could have a large impact infrastructure or cause fatalities mitigation measures were conducted. The lakes where mitigation measures have been conducted were selected by expert judgment and costs.

## 4. Results

### 4.1. Inventories of moraine-dammed glacial lakes

Within the first inventory carried out by the KazHydromet, 128 glacial lakes were identified on the northern slopes of the Ile Alatau (cf. Fig. 3) between 1968 and 1969 (Popov, 1991). Our own inventory for 1990 based on Landsat TM data revealed 148 MGLs (total area 2.13 $km^2$). In 2018, using Sentinel-2 data, more than 160 MGLs (2.38 $km^2$)

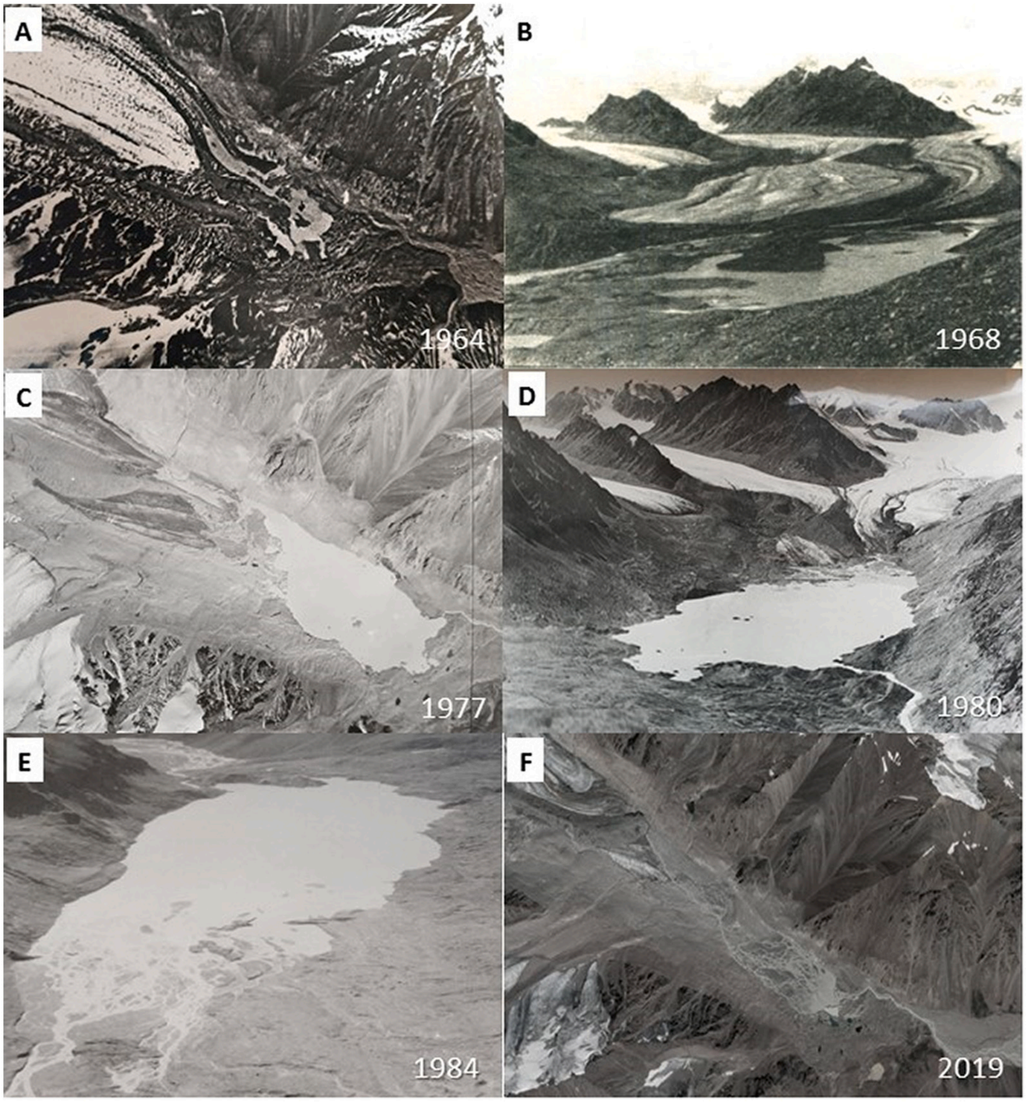


**Fig. 5.** Evolution of the Bogatyr Lake in the Shilek River basin: A – aerial survey in 1964, B - perspective shot of the lake until 1968, C – aerial survey in the summer of 1977, D - perspective shot of 1980, E - perspective shot of 1984, F – current state (2019) of the lake hollow after emptying (see Section 5).

were found in our whole study area despite the fact the several MGLs drained (Figs. 3 and 4).

In general, available data on MGLs shows that the 1970–1980s saw intense lake development. This period further coincided with a strong increase of their outburst activity (see Section 4.4). The lake number and area has been further growing until today. At the present time a number of lakes have expanded substantially: for example, the lake near the Mining Institute Glacier in the Turgen River basin and the lake at Maksimova Glacier in Shilik River basin (cf. Fig. 5), where measurements of Kazselezashchita and the Institute of Geography, Almaty revealed a volume of water of about 1.5 million $m^3$.

In order to get information about lake abundance as well as their evolution, we calculated the ratio of lakes with an area of more than 5000 $m^2$ and the area of glacier cover (Table 3). Glacier area is based on the years of the closest available glacier inventory for the whole region (1990 and 2008). The lake ratios show that the lake formation in the study region is progressing intensively, especially in the intra-mountainous basin of the Shilek River. This basin lagged behind in the previous period in the development of lakes in comparison to the northern slope of Ile Alatau (Table 3).

**Table 3**
Lake coefficients of the Ile and Kungei Alatau glacial zone.

| Territory | Year | Glacier Area (F), $km^2$ | Number of Lakes (N) | Lake Ratio (N/F)* |
|---|---|---|---|---|
| North slope of Ile Alatau | 1990 | 204.7 | 67 (1970–1995) | 0.33 |
| | 2008 | 172.0 | 95 (2000–2018) | 0.62 |
| Shilek River basin | 1990 | 226.6 | 22 (1970–1995) | 0.10 |
| | 2008 | 204.5 | 65 (2000–2018) | 0.30 |

* N\F coefficient – dimensionless quantity.

### 4.2. *Characteristics of the evolution of moraine-dammed glacial lakes*

The detailed measurements of area and depth, along with further field investigations, allowed for insights into the specific characteristics of the evolution of MGLs. At the first stage, increase in lake extents mainly results from the retreat of surrounding glaciers; lake depths, however, remained relatively stable. At the next stage the lake volume increased with a depth increase due to activation of thermokarst processes and melting of ice beneath the lake. In this case, the depths of the studied lakes were 10–15 m on average, but can reach up to 30 m

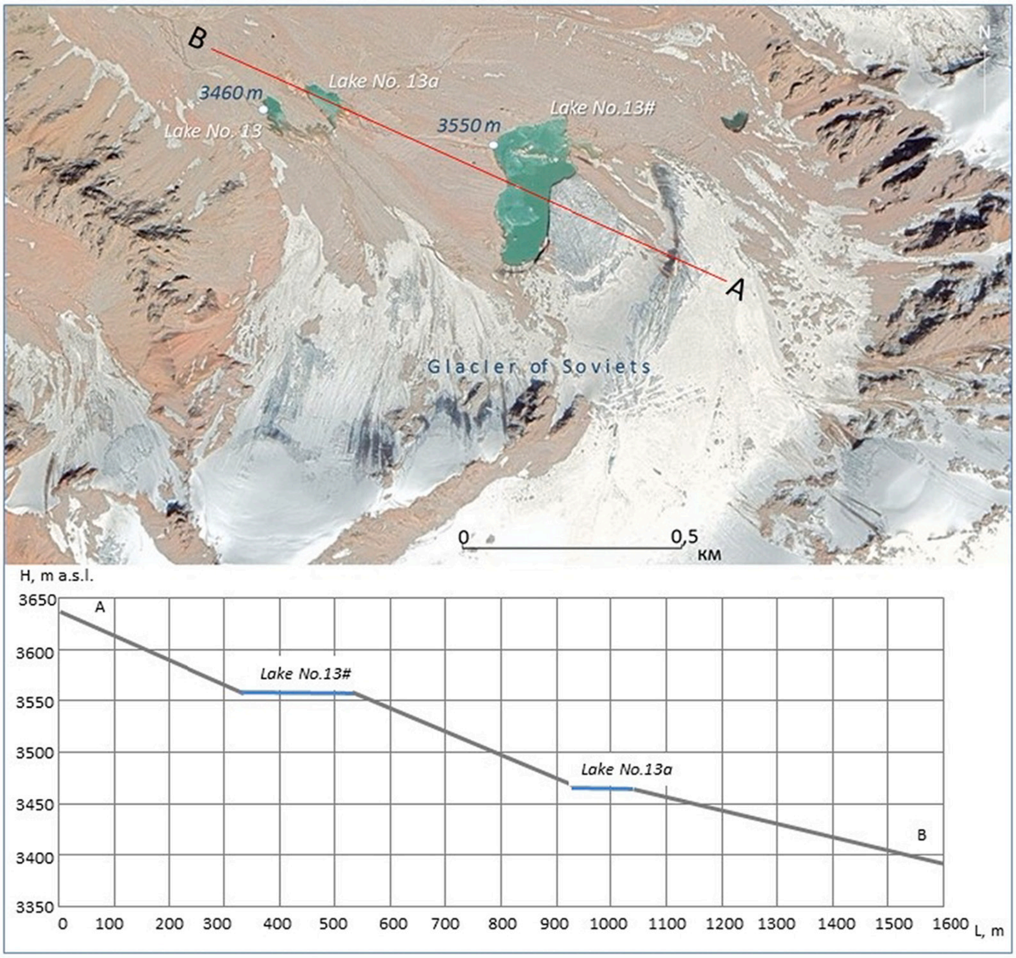


**Fig. 6.** A group of lakes near Soviets Glacier in the upper Kumbelsu River basin (above) and elevation profile along the line AB (below).

(Palgov, 1958). Alternatively, MGL development is initiated by the appearance of supraglacial lakes favoured by debris-cover which expand and then merge. Eventually these lakes can evolve into MGL with further development of the MGL according to a similar scenario as for lakes that form at glacier termini. This process, which is common in the Himalaya (cf. Benn et al., 2012), is, however, an exception in the Kazakh Tien Shan according to our observations.

Some lakes drained or outburst once they reached a critical area and depth. After one or a series of outbursts the lakes disappeared. The bed of some of these drained lakes were filled with glacial alluvial sediment (e.g., lakes No. 2, No. 3 in Kishi Almaty basin, No. 13, No. 14 in Ulken Almaty basin, and Bogatyr Lake in the Shilek basin, cf. Fig. 5).

From this, we can identify a dichotomy in MGL behaviour:

There are (a) stationary lakes with consistent water levels for a long time and (b) non-stationary lakes which form and drain regularly.

The former are usually lying at lower hypsometric levels, on the upper Quaternary grass-covered moraine surfaces. They typically produce no outbursts during their development and have retained a substantial part of the water volume since their emergence. Runoff from the lake occurs mainly through developed surface channels through the crest of modern moraines. A typical example of a stationary moraine-dammed glacial lake is Bogatyr Lake, located at the glacier of the same name in the upper reaches of the Shilek River at an altitude of 3450 m asl. (Fig. 4). Since the emergence of shallow depressions filled with water on the surface of the modern moraine in the 1940s, the volume of water of the lake has grown from 3.4 million $m^3$ in 1972 to 9.3 million $m^3$ in 1985 (Fig. 5).

In contrast, non-stationary lakes are temporary. The depression formed behind the modern moraine may not dam the glacier melt waters, as it can drain using the underground drainage system (tunnels) inherited from the glacier. In such a situation, the formed basin remains empty for many years and fills occasionally, usually for a short time at the beginning of ablation period. Such temporarily occurring MGLs can be classified as non-stationary lakes. Typical examples are Lake No. 16 (Kaskelen), Lake No. 17 (Esik), Lake No. 5 (Left Talgar), Lake No. 7 and Lake No. 8 (Middle Talgar), Lake No. 8 (K. Almaty) and Lake No. 1 (Kargaly).

Ongoing glacier retreat typically leads to the emergence of overdeepenings. These became, in our study region, the core of future lake formation at the next high-level hypsometric stage. A typical example is the upper Kumbelsu River. The single glacier disintegrated into several small glaciers. One former tributary now terminates about 90 m higher where Lake №13b (cf. Fig. 3) developed intensively (Fig. 6).

### 4.3. *Past moraine-dammed glacial lake outburst events*

#### 4.3.1. *General characteristics of past outburst events*

Overall, 48 GLOF events in the Ile Alatau (northern and southern slopes) were documented which occurred between 1951 and 2019 (Fig. 7), an average of 0.7 GLOF events per year.

If we assume that approximately 100 to 120 potentially hazardous MGLs were present in the northern slope of Ile Alatau during this period, it is likely that the probability of a random GLOF event in the study region does not exceed 0.5–0.6% per year (Kavetsky and Smirnov, 1957; Gerasimov, 1978; Vinogradov, 1977; Popov, 1986a; Medeu et al., 2018).

The temporal distribution of GLOF events (Fig. 7) revealed a high

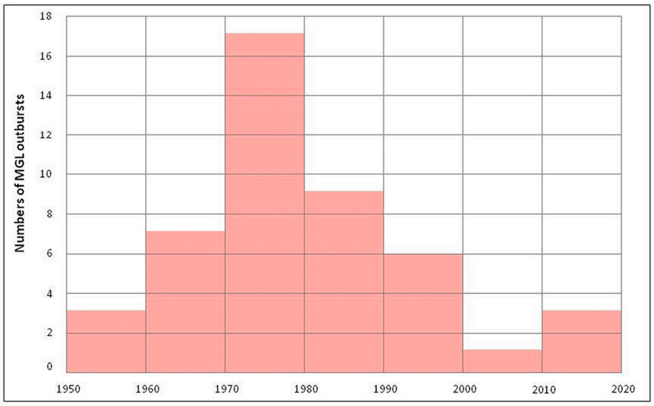


**Fig. 7.** Numbers of recorded GLOF events between 1951 and 2019 (Data sources: Bizhanov et al., 1998, Duysenov, 1971, Esenov and Degovets, 1979, Gorbunov and Severskyi, 2001, Kapitsa et al., 2018, Karamanov and Degovets, 1992, Kavetsky and Smirnov, 1957, Kirenskaya et al., 1977, Kolotilin, 1959, Medeu et al., 2015, Popov 1986, 1987, 1997, Vinogradov et al., 1976, Kazselezashita, pers. comm.)

**Table 4**
Intra-annual distribution of the well documented GLOF events in the Ile Alatau in 1951–2019.

| Month | June | July | | | August | |
|---|---|---|---|---|---|---|
| 10-day period | III | I | II | III | I | II |
| Number of MGL outbursts | 3 | 5 | 4 | 4 | 3 | 6 |

outburst activity between 1970 and 2000 with most GLOFs occurring between 1970 and 1985. The GLOF frequency has been lower from 2000 to the present with the lowest number between 2000 and 2010.

A further important finding of the analysis of well documented past outburst events in the Ile Alatau is that they occurred in the warm period of the year, starting from the end of June to August (Table 4).

From these 25 documented GLOF events, nine had a volume up to 30,000 $m^3$, seven a volume between 30,000 and 100,000 $m^3$ and nine had a volume greater than 100,000 $m^3$.

Overall, outbursts of 9 MGLs led to the formation of glacial debris flows (Table 5, Figs. 3 and 4). Some of which are attributed to the largest debris flows, accompanied by numerous casualties (1963, 1973, 1977; Plekhanov et al., 1975, 1977, Popov, 1978, Bizhanov et al., 1998). It should be noted that despite the comparatively small number of the indicated lakes, many MGLs classified as dangerous drained repeatedly (Table 5).

While some precursory stages exist (typically the so called "stage of readiness"), they are rarely identified prior to the outburst. Below, we present information on the prerequisites and conditions observed during the documented outbursts of some MGLs. In addition, we clarify the date and time of outbursts, as well as quantitative characteristics of floods and the consequences of these outbursts (Table 5).

Since 2010 only three large debris flow events which reached the forelands of the mountains occurred after GLOFs:

- In 2014 based on a GLOF of Lake №8 in Middle Talgar River. A previous outburst of this lake took place in 1993 (Baimoldayev and Vinokhodov, 2007).
- In 2015 based on a GLOF of Lake №1 in Kargaly River basin (Medeu et al., 2018).

**Table 5**
Information on documented GLOF events in the Ile Alatau ridge and their consequences.

| River Basin, Glacier, №MGL | Date of outburst | MGL outburst background | Drainage mechanism (emptying) | Effects * | Reference |
|---|---|---|---|---|---|
| Kishi Almaty, Central Tuyuksu gl., lake №2 | 20.08.1951 | Presence of a surface reservoir with an unstable hydrological regime (volume up to 20,000 $m^3$) | Collapse of part of the moistened slope of the frontal moraine (length 600–700, width 50–60, depth 15–20 m), emptying the lake of 20,000 $m^3$ | Debris flows of second category (up to 50 $m^3$/s), small damage in the mid-mountain zone | Kolotilin (1959) |
| Kishi Almaty, Central Tuyuksu gl., lake №2 | 07. 08.1956 | Presence of a surface reservoir with an unsteady hydrological regime (volume up to 35,000 $m^3$) | Water discharge from the ice tunnel, emergence of landslide funnels, the maximum breakthrough flow rate of 25–32 $m^3$/s | Debris flows of third category (500–1000 $m^3$/s) in the riverbed, mudflow volume 1.1 million $m^3$/s, damages in the mid-mountain zone | Kavetsky and Smirnov (1957), Kavetsky and Gulina (1964), Vinogradov (1977) |
| Esik, Right Zharsay gl., lake №17 | 06.07.1958 | Temporary filling of the lake basin (approximately 200,000 $m^3$) | Underground discharge of the lake through the ice tunnel (length up to 200–300 m), breakthrough emptying of the lake with a flow rate of about 20 $m^3$/s | Debris flows of third category (several thousand $m^3$/s) in the river channel, volume up to 4 million $m^3$, damages in the mid-mountain zone | Popov (1981) |
| Issyk, Ave. Zharsai gl., lake №17 | 07.07.1963 | Temporary filling of the lake basin (approximately 460,000 $m^3$) | Underground discharge of the lake via the ice tunnel (length 200–300 m), breakthrough emptying of the lake with a flow rate of about 20–50 $m^3$/s | Debris flows of third category (7–12,000 $m^3$/s) in the river channel, debris flow 5.8 million $m^3$, significant damage in the river valley and in the foothills, human casualties | Popov (1981), Vinogradov (1977) |
| Kishi Almaty, Central Tuyyksu gl. lake №2 | 15.07.1973 | Partial lapse of the lake dam integrity (drop of 2 m in August 1972, filtration flooding) (volume 216,000 $m^3$) | Thawed parts (wetted part) of the lake dam with formation of a surface channel, peak (maximum) breakthrough flow rate 250–350 $m^3$/s | Category 3 debris flow (5–10,000 $m^3$/s) in the riverbed, significant damage in the river valley, human casualties | Vinogradov et al. (1976); Vinogradov (1977), Keremkulov and Tsukerman (1985) |
| Middle Talgar, TEU-Severny gl., lake №6 | 15.07.1973, secondary sat down: 16, 18, 19.08.1973 | Formation of the hollow in the body of the lake dam, discharge of the lake with a volume of 24,000 $m^3$ | Emptying through the hollow with formation of debris flow on the moraine (length - 850, depth - 30 m) | Debris flow of second category in the middle part of the river (up to 25 $m^3$/s) | Shusharin and Markov (1976) |
| Middle Talgar, TEU-Severny gl., lake №6 | 15., 21.07 and 02.08.1974 | Breakdown of the lake dam integrity | Discharge of the lake with a volume of 26,000 $m^3$ from the mudflow cut formed in 1973 | Floods of category 2: 100, 250 and 300 $m^3$/s in the zone of modern moraines, the upper part of the river valley | Shusharin and Markov (1976) |

(continued on next page)

Table 5 (*continued*)

| River Basin, Glacier, №MGL | Date of outburst | MGL outburst background | Drainage mechanism (emptying) | Effects * | Reference |
|---|---|---|---|---|---|
| Ulken Almaty, Kumbel gl. lake №14 | 19.08.1975 | Defrosting moraines along the drainage paths | Surface channel formation, moraine collapse (length –70–80, width 5–6, depth 3–4 m), partial emptying of lake №14 (volume up to 5000 $m^3$) | Debris flow of medium power (up to 300 $m^3$/s), minor damage | Kirenskaya et al. (1977), Plekhanov (1977) |
| Esik, Zharsai gl., lake №17 | 25–28.06.1977 | Temporary filling of the lake basin (approximately 460,000 $m^3$) | Surface overflow and discharge via an open channel (length - 150, depth – 20 m, width-3-5 m) | High water up to 5–7 $m^3$/s, in the bed of the river landslides up to 500 $m^3$/s | Plekhanov et al. (1977) |
| Esik, Zharsai gl., lake №17 | 03.07.1977 | Temporary filling of the lake basin (residual volume of water 40,000 $m^3$) | Underground discharge of the lake along the old ice tunnel (length up to 150 m) | High water up to 35–40 m3/s, lower in the channel of the Landslides category 2 river with a flow rate of up to 630 $m^3$/s | Plekhanov et al. (1977) Popov (1981) |
| Ulken Almaty, Soviets gl., lake №13 | 03.08.1977 | Melting of ice-cored m oraines with formation underground drainage paths, the presence of a lake with a volume of 96,400 $m^3$ | Discharge along the surface channel, removal of the thawed areas, collapse of the moraine (length - 200 width - 35, depth - 25 m), maximum breakthrough flow rate 210 $m^3$/s | Debris flows of third category in the river valley at the outlet of the mountains the maximum discharge is about 10,000 $m^3$/s), significant material damage, human casualties | Bizhanov et al. (1998), Esenov and Degovets (1979), Gorbunov and Severskyi (2001), Popov et al. (1980), Popov (1978) |
| Middle Talgar, Sportivny gl. lake №7 | 21.06.1979 | Temporary filling of the lake basin (water volume 82,000 $m^3$) | Discharge of the lake through the ice tunnel | Flooding up to 15 $m^3$/s, then mudflow of category 2–340 $m^3$/s, significant damage in the river valley | Shusharin and Popov (1981) |
| Kaskelen, Glac. №. 25, lake №16 | 23.07.1980, 05.07.1986, 24.06.1988 | Temporary filling of the lake basin (1980 - water volume 240,000 $m^3$, 1986 - water volume 90,000 $m^3$, 1988 - water volume 70,000 m3) | Discharge of the lake along the left tunnel (channel length 200 m), 1980 - flash flood up to 23 $m^3$/s, 1986 - flash flood 16 $m^3$/s | 1980 debris flows of third category up to 500 $m^3$/s in the river valley damage, 1986 debris flows of second category, 100 $m^3$/s in the river valley, 1988 - flood floods of 20–25 $m^3$/s in the river valley. | Popov (1984), Baimoldayev and Vinokhodov (2007), Bizhanov et al. (1998) |
| Shilik,. Bogatyr gl., Bogatyr Lake | 23–24.07.1985 | Intensive development of the lake (max. Water volume 9.3 million $m^3$) | Artificial emptying of the lake via open channel with a flow rate of about 100 $m^3$/s | Debris flow of third category, no damage | Baimoldayev and Vinokhodov (2007), Bizhanov et al. (1998), Popov (1997) |
| Middle Talgar, N/N gl. lake №8 | 06.07.1993 | Temporary filling of the lake basin (water volume 100,000 $m^3$) | Discharge of the lake via the ice tunnel (length 200 m), flood on the moraine with a flow rate of up to 10–15 $m^3$/s | Debris flow of second category (up to 1340 $m^3$/s), damage in the river valley | Baimoldayev and Vinokhodov (2007), Bizhanov et al. (1998) |
| Middle Talgar, N/N gl. lake №8 | 17.07.2014 | Temporary filling of the lake basin (water volume 35,000 $m^3$) | Discharge of the lake via the ice tunnel (length 200 m), flood - up to 20 $m^3$/s | Debris flow of second category, up to 80 $m^3$/s in the riverbed | Baimoldayev and Vinokhodov (2007) |
| Kargaly, Kargalinsky gl., lake №1 | 23.07.2015 | Temporary filling of the lake basin (volume 325,000 $m^3$) | Discharge of the lake via the ice tunnel (length 100–150 m) | High water up to 5 $m^3$/s, then debris flow of second category, up to 25–30 $m^3$/s, damage at the river exit from the mountains | Medeu et al. (2018) |
| Kargaly, Kargalinsky gl., lake №1 | 14.08.2019 | Temporary filling of the lake basin (volume up to 200,000 $m^3$) | Discharge of the lake via an ice tunnel with a flow rate of up to 5 $m^3$/s | Mudflow, in the riverbed - up to 25–30 $m^3$/s | Kazselezashita information |

* Note: The debris flows of 1, 2, 3 categories are natural events that occurred within the moraine-glacial complexes (1), which reached the mid-mountain and foothill zones (2,3).

- In 2019 again based on a GLOF of Lake №1 in Kargaly River basin in 2019 (this study, Kazselezashita pers. comm.).

These recent events show that glacial debris flow hazards emanating from MGLs in the region remains high. This is likely due to ongoing glacier recession leading to intensive growth of the lake volumes, and the refilling of empty lake basins.

#### 4.3.2. *Detailed examples of selected outburst events*

Several MGL drained due to overflow of an ice-cored moraine since the late 1970s. Earlier, similar phenomena were not observed in the study area. Such drainages were most likely not detected due to their relatively low magnitude and low level of resulting damage. The maximum discharge events are formed by about half time of the complete lake drainage.

MGL draining via open channels were observed in four cases (for the location see Fig. 4):

- Lake №17 at Zharsay Glacier in Esik River basin (1977),
- Lake №8 at Igly Tuyuksu Glacier (Fig. 8B) in Kishi Almaty River basin (1981),
- Lake №5 at Kalesnik Glacier (Fig. 8A) in the Left Talgar River basin (1984),
- Bogatyr Lake in Shilik River basin (1985).

In the latter case, emptying of the lake via an open channel was caused artificially (Section 5). Fig. 8 provides insights into the characteristics of these outlet channels.

MGL drainage via ice tunnels is more dangerous and the most common mechanism for the discharge in our study area. The lakes are drained underground, using previously existing (inherited) drainage channels to discharge water. For non-stationary MGLs the drainage system is often composed of ice tunnels through which meltwater drained for many years. Short-term filling of the basins occurs in case of blockages of such underground drainage channels, leading to the formation of a lake. According to observations, outbursts are accompanied by noise, the release of water and boulders on the outer slopes of the dam, indicating a pressurized water outflow during lake drainage. A

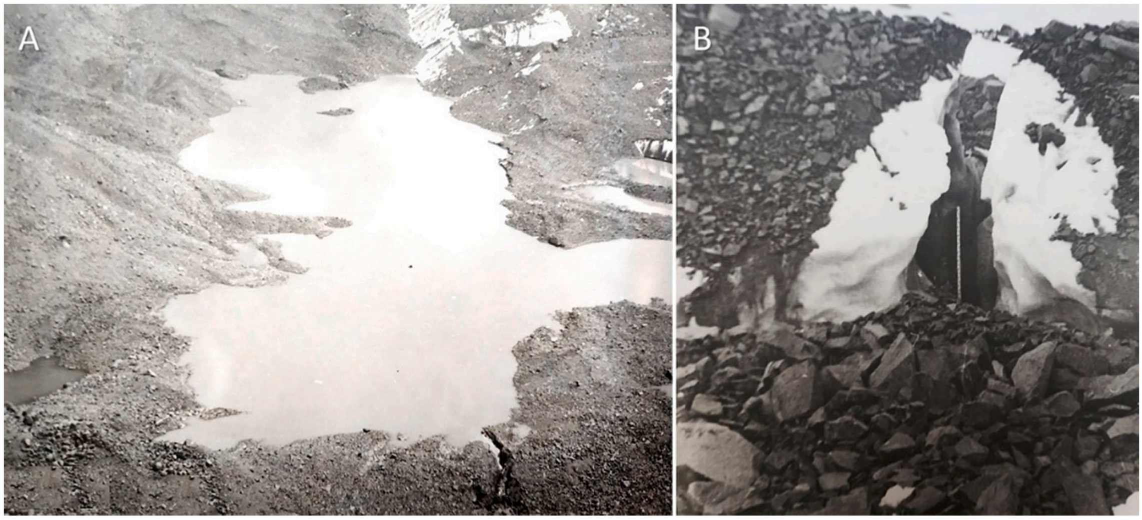


**Fig. 8.** Open ice channels during the MGL discharge: A - Discharge of the lake N°5 at Kalesnik Glacier, June 16, 1984 with a forming open ice channel in the crest of the modern frontal moraine, B - open ice channel after the outburst of lake N°8 at Igli Tuyuksu Glacier in 1981.

peak in water discharge in the initial phase is characteristic for such outburst events. The time needed to drain the water rarely exceeds several hours. Examples of GLOFs through ice tunnels are: 1993, Lake N° 7 in Middle Talgar basin; 2014, Lake N° 8 in Kargaly basin; 2015 and 2019, Lake N° 1 in Kargaly basin (Medeu et al., 2015).

MGL discharge via ruptures in thawing permafrost bodies of modern moraines is the most dangerous of the three discharge mechanisms, as they likely lead to the formation of a powerful outburst flood wave. Catastrophic discharge of glacial lakes above ground level due to destruction of lake dams are known in various mountainous regions of the Earth (Haeberli, 1983; Clague and Evans, 2000; Richardson and Reynolds, 2000; Emmer and Vilímek, 2013). It should be noted that cases of ice or debris mass movements into lakes, which are quite characteristic for the Cordillera (South American Andes), Karakoram-Hindukush-Himalayas, are not widespread for the Ile and Kungei Alatau study region.

The debris flow catastrophe in Kishi Almaty River on 15th July 1973, which caused significant material damage and human casualties, was caused by the outburst via dam rupture of Lake N°2 at Central Tuyuksu Glacier. A powerful flood wave with a peak flow rate of about 250–350 $m^3/s$ occurred via a rupture in the lake dam and the flow rate was more than two orders of magnitude higher than the average surface runoff from the glacier (Plekhanov et al., 1977; Vinogradov, 1977). Accordingly, rapid destruction of lake dam took place with formation of a 30-m-wide rupture in the upper part.

However, these studies did not consider the fact that a few years


**Fig. 9.** MGL discharge by rupture in thawed moraine dams: A – situation after the discharge of lake N°2 at Tuyuksu glacier (1973) (Vinogradov, 1977). In the inset, the site of the lake bulkhead's breakthrough as of 1970 (view from the downstream, from Duysenov, 1971), B – lake N°13 at Soviets glacier after the outburst with rupture of the crest of the frontal moraine (1977), the maximum level of filling the lake basin was noted.

before the outburst, there was a deep, well-defined channel in the dam of the lake at the site of rupture which developed by surface and filtration runoff in the direction of a underlying small lake (Lake №3). This can be clearly identified in a photograph taken in 1970 (Fig. 9A, from Duysenov Duysenov, 1971). Consequently, the water of MGL №2 discharged via a rupture, which formed in the weakest part of the dam, on the site of a previously existing drainage channel and thawed core, which was affected by surface water for several years before the outburst.

A similar process caused the catastrophic discharge of MGL №13 at Soviets Glacier in the upper Ulken Almaty River. After the outburst, it became apparent that the 15–20 m deep rupture exposed thawed material, covered with a 1.5 m layer of frozen rocks. The ice core in the lake dam was also absent (Fig. 9B).

The data shows that understanding the processes of formation and further development of MGLs is more than urgent at present. This is consistent with the ongoing context of documented general glacier shrinkage. It should be noted that, despite an increase in the number of MGLs, their total outburst activity has on average decreased during the last two decades.

### *4.4. Evaluation of equations applied in South-East Kazakhstan to calculate peak discharges*

Existing data from past outburst events in Kazakhstan enabled us to apply and evaluate the different equations used to calculate peak discharge (Table 1). In this study we used the characteristic hydrographs for lake discharge via open channels which are based on direct observations of water level decreases of Lake №17 at Zharsay Glacier in 1977 and Lake №5 at the Kalesnik Glacier in 1984 (Fig. 10).

These direct observations showed that for conditions of the Ile

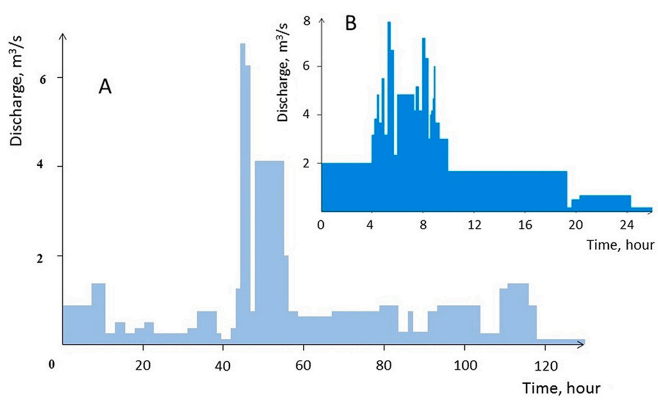


**Fig. 10.** Hydrographs of the MGL discharge via open channels generated based on observations: A – Lake №17 (at the right Zharsay Glacier, 1977), B – Lake №5 (at Kalesnik Glacier, 1984). Data source: Kazselezashchita.

Alatau, the maximum values of λ (which correspond to the channel thawing intensity) of Eq. (5) for MGL discharge via open channels (Table 1) are very close to 0.00017 m/s (0.612 m/h, Popov, 1986b).

Other available field data allowed further calculations of peak discharge from specific lakes in the Ile Alatau using different equations for outflow via tunnels (Table 1) and to compare their results (Table 6). Due to the lack of data on the cross-sectional area of the draining tunnels, the peak discharge during the outbursts of Lake № 16 in the upper Kaskelen River (1980 and 1986) was determined from the hydrographs.

The result for Lake no. 7 show that Eq. (6) (Clague and Mathews, 1973) which was widely applied in SE Kazakhstan matches the observations relatively well but might result in some overestimates. Eq. (7) (Medeu et al., 2018) matches the observations equally well but more detailed measurements are needed.

Due to the lack of data on the cross-sectional area of the draining tunnels, the peak discharge during the outbursts of lake № 16 in the upper Kaskelen River (1980 and 1986) was determined from the hydrographs and only Eq. (6) could be applied. Results show that the calculated values are in the right order of magnitude, but for the one outburst event the peak discharge is overestimated by about 20% while the other event the peak is underestimated by about 14%.

Eq. (8) (Table 1) includes a dimensionless coefficient n, and A* (the resistivity of the main drainage channel). This contains a number of uncertainties such as hydraulic resistance in the area in which the pressure loss is equal to velocity head in the outlet section, depending on the cross-sectional area of the main drainage channel. The resistivity of the drainage system, as assumed to be an ice tunnel, also includes a certain level of uncertainty. Nevertheless, according to the proposed method, calculations of the maximum flow rates and reconstruction of hydrographs of the lake outburst were carried out by Keremkulov and Tsukerman (1985). This allowed the authors to conclude that the shape of constructed hydrographs corresponds to their qualitative description and, in general terms, to the real object and can therefore be used to support the identification of dangerous lakes and preventative mitigation measures.

However, a comparison of calculated and observed hydrographs of discharge for Lake №16 shows a clear difference both in form, discharged water volume, and time of discharge (Fig. 11).

Even though the initial data for constructing the different hydrographs were the same, the discrepancies in the observed and modelled hydrographs (Fig. 11) clearly shows the influence of the uncertainties and the shortcomings of the models. In practice, using this equation to model lake discharge does not seem appropriate. To consider this option, a more in-depth knowledge on the cross-sectional area of ice tunnels and hydraulic resistance is required. Such data is, however, rarely available for MGLs.

Nevertheless, the peculiarities of lake discharge via ice tunnels and the shape the hydrograph (Fig. 11) show that a peak at an initial stage can be explained by pressure discharge from the basin. According to the

**Table 6**
Results of calculation for peak discharge during the GLOF events via tunnels.

| Observed / estimated discharge characteristics | Volume of flash flood, thousand $m^3$ | Maximum depth above the entrance to the tunnel, m | Flow section of the tunnel, m | Peak discharge, $m^3/s$ |
|---|---|---|---|---|
| Lake №7 (g. Sportivniy, Talgar River, 1979) | | | | |
| Maximum outburst discharge calculated based on the observed cross section of water flow and the slope of the channel below the lake | 82.0 | 13.3 | 2.7 × 1.9 × 3.69 | ≤ 15.0 |
| $Q_{max} = 75\ (V/10^6)^{0,67}$ (6) | | | | 14.04 |
| $Q_{max} = \alpha W^{1,25} H^{0,5}$ (7) | | | | 16.36 |
| Lake №16 (g. №25, Kaskelen River, 1980, 1986) | | | | |
| Observed Hydrograph, 1980 | 220.0 | 13.8 | 6.31 | 22.7 |
| $Q_{max} = 75\ (V/10^6)^{0,67}$ (6) | | | | 27.2 |
| Observed Hydrograph, 1986 | 80.0 | ? | ? | 16.0 |
| $Q_{max} = 75\ (V/10^6)^{0,67}$ (6) | | | | 13.8 |

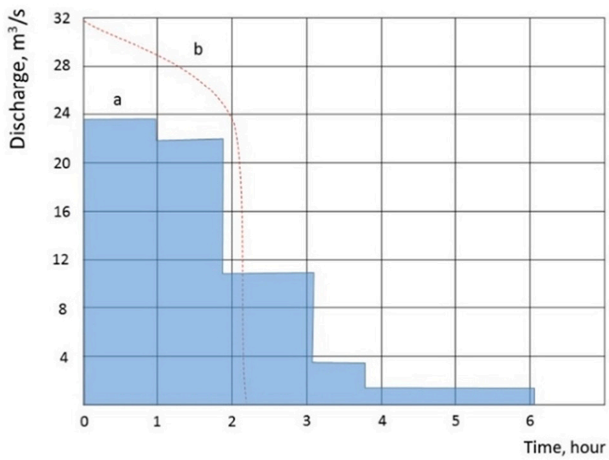


**Fig. 11.** Hydrographs of the lake №16 discharge in the Kaskelen river basin (1980): a – histogram of observed values, b - calculated according to Eq. (4) (Keremkulov and Tsukerman, 1985).

observer, the first stage of emptying of Lake №16 was accompanied by appearance of a funnel above the inlet tunnel, approximately 6–8 m in diameter (Popov, 1984). A shallow part of a hydrograph indicates loss of pressure at the tunnel's outflow. Observational data confirms the hypothesis of the formation of a snow and ice plug at the entrance of the drainage tunnels.

Such a mechanism requires the formation of a drainage tunnel through a pre-existing dead ice cave and the destruction of the outer wall downstream. Both Lake №6 at Glacier TEU-North in the Talgar River basin in 1974, as well as large MGL at Tushinsky Glacier in Zhetisu Alatau in 1982 outburst according to this scheme. In these cases, the roof of the ice tunnel collapsed soon after the outbursts, forming a large open gap of outcropping ice-permafrost slopes (Popov, 1986b; Bizhanov et al., 1998).

### 4.5. Hazardous and dangerous glacial lakes

As part of the repeated inventories and lake investigations carried out by Kazselezashchita in Ile Alatau during the 1980s, 18 out of the identified 128 MGLs were assigned to the category of "potentially debris flow hazardous" (hence dangerous, cf. 3.4, Popov, 1991). All these lakes have also a volume close to or larger than 100,000 m$^3$. Among the largest are Lake №13 (located in Ulken Almaty River basin, with a volume of 138,000 m$^3$, Lake №8 Toguzak (Talgar River) with a volume of 349,000 m$^3$, and Lake Muzkol (Esik River) with a volume of 97,600 m$^3$. In the Uzunkargaly-Shilek river basins, 35 dangerous lakes were identified in the 1970s and 1980s, among which were Lake №16 (Kaskelen River) with a volume of 248,000 m$^3$, Lake №2 (Aksai River) with a volume of 400,000 m$^3$, Lake №13 with a volume of 232,000 m$^3$, lakes №5 and №8 Toguzak (Talgar River) with volumes of 247,000 and 466,000 m$^3$, respectively, Lake №17 (Esik River) and the aforementioned Bogatyr Lake (Shilek River) with a volume of 9.1 million m$^3$. We refer to Fig. 5 for the location of the lakes.

In 2018 about 40 lakes out of more than 160 mapped based on the Sentinel-2 satellite scene were identified as dangerous by own investigations using the criteria presented in Table 1. It should be noted that various researchers assessed the outburst hazard and danger of lakes using different criteria. In earlier times the lake volume was the main factor while subsequent studies used more detailed criteria (see 3.4). In Figs. 3 and 4, only lakes classified as potentially dangerous throughout the different periods are marked. The different approaches highlight the need for a reassessment of the MGLs.

## 5. Mitigation of moraine-dammed glacial lake outburst hazards: A summary of prevention measures

The disastrous lake outburst and debris flow events from the 1950s and 1960s raised the awareness of the government of the Kazakh SSR and early preventive measures regarding MGLs were set up in the 1960s and 1970s by the government. However, such measures were not systematically undertaken and were mainly limited to the use of siphons to reduce water volume in lakes, as well as construction of evacuation trenches in natural outflow channels. The level of Lake №2 at Central Tuyuksu Glacier was lowered by two meters in the early 1960s using three siphon pipelines. This was the maximum possible lowering as the achieved height of water rise through the siphons (4 m) was close to practically achievable under the local conditions. The maximum height of water increase due to atmospheric pressure at sea level is assumed to be around 10 m, and at an altitude of 3350 m with an atmospheric pressure of about 590 hPa, the theoretical height cannot exceed 6 m. Considering the inevitable losses in siphon pipelines on valves and joints, this height in meters of water column is further reduced by 30%. The achieved lake level decrease did not prevent further lake development and its catastrophic outburst in 1973. Since the depths of large MGLs can reach up to 30 m, the use of siphons cannot serve as a guaranteed method for eliminating outburst hazard in Kazakhstan.

The use of siphons and pumps to lower the water level of MGLs can however be an effective solution when it is combined to other engineering activities. Kazselezashchita has constructed evacuation lines in discharge channels of MGLs via explosions and subsequent "washout" due to small releases and manual refinement. In this way, the volumes of some stationary MGLs on the northern slope of the Ile Alatau could be partly reduced in the 1970s. Examples are lakes No. 2 and No. 6 in Kishi Almaty River basin, lakes No. 13, No. 1, No. 11, and No. 12 in Ulken Almaty River basin and No. 13 in Kaskelen River basin. It should be noted that these works were carried out without a detailed study of the MGLs hydrological regime and structure of the water-retaining moraine dam.

However, large-scale construction work of deep trenches and tunnelling in moraines is impossible for most lakes due to their location in the remote mountain environment. Moreover, financial costs of such measures exceed the cost of construction of reliable protective structures aimed at intercepting mudflows in mountain valleys. Nevertheless, timely detection of potentially dangerous glacial lakes and precursory signs for potential debris flow danger, allows for emergency work using the energy of lake water to form an outflow channel.

Given specifics of the indicated types of MGLs, one effective way to reduce a threat is to replace the mechanism of emptying the lake from the hazardous "emptying through ice tunnel" to the much less dangerous - "emptying via an open channel". For this purpose, it is necessary to clear as much of the dead ice as possible at the surface of the lake dam, lower the level of the moraine crest and cause surface overflow when the water level reaches maximum values.

In 1985, before a real threat of an impending surge of Bogatyr Glacier (cf. Mukherjee et al., 2017), a large-scale effort was carried out to empty Bogatyr lake in Shilek River basin (see also Fig. 5). For the first time in Kazakhstan, an MGL was artificially drained using open channels along the outcropping ice core (Fig. 12). Within two days of removing the moraine ridge using explosives, about 7 million m$^3$ of water discharged via an open channel in the ice core and the lake level was lowered by about 10 m. The maximum discharge flow rate was 105 m$^3$/s which did not have negative impacts in the lower Shilek River valley.

Preventive work on emptying MGLs in the study area has persisted until the present day. Siphons and pumps are used to lower the water level in the lakes. Deepening and expansion of evacuation channels is carried out using mechanized tools. One example is Lake No. 6 in Kishi Almaty River basin which formed at an altitude of 3600 m above sea level near Manshuk Mametova Glacier (Fig. 13). During the 1990s the

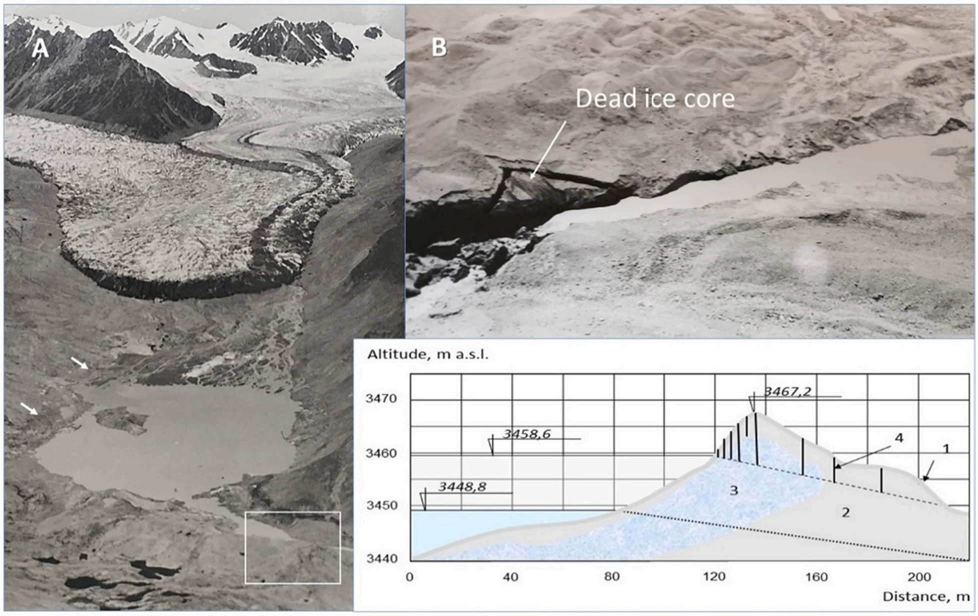


**Fig. 12.** The Bogatyr Lake in front of surging glacier after emptying (1985): A - the level of maxi-mum filling is noted, a lake dam and evacuation canal are highlighted, B - lake dam with an open channel. Inset, schematic diagram 1 - an active layer of modern moraine, 2 - permafrost, 3 - ice core, 4 - holes with explosive.


**Fig. 13.** Preventive work on the MGL in the Ile Alatau: A - the MGL №13-bis (U. Almaty River basin) water pumping by and siphons, B – deepening of the evacuation channel for emptying the MGL №6 (the K. Almaty River basin); source: Medeu et al. (2018).

lake became the most dangerous in the Ile Alatau and its volume exceeded 190,000 m$^3$ with a maximum depth of 18.5 m. Water volume in the lake increased due to thawing of buried ice strata and retreat of the glacier tongue. At present, the volume of the lake exceeds 200,000 m$^3$, despite the ongoing preventive work, and substantial water level decrease is prevented by the frozen moraine core, which has been exposed by the channel.

## 6. Discussion

### *6.1. Inventory and evolution of moraine-dammed glacial lakes*

Several glacial lake inventories exist for South-East Kazakhstan both generated by local scientists with the focus on the study region and by international scientists as part of mapping larger regions. For the earlier inventories, especially for those based on aerial images (e.g. Tokmagambetov et al., 1980; Popov, 1991), no digital outlines are available making direct comparisons impossible. A further complication is that the definition of “glacial lake” varied, and different lakes were included in the inventories. However, there are a few recent glacial lake inventories with outlines available which allow more detailed analyses. Most studies used Landsat images and automated methods to delineate glacial lakes for larger regions where SE Kazakhstan is included. Wang et al. (2020) and Chen et al. (2021) generated inventories for whole High Mountain Asia while Shugar et al. (2020) investigated lakes globally. Wangchuk and Bolch (2020) developed a fully automated method to map glacial lakes using both optical (Sentinel-2) and microwave (Sentinel-1) imagery. For comparison we both investigated the lakes visually and the information provided in the data bases and only considered the glacier-fed proglacial lakes. Both the number and area of the identified glacial lakes vary significantly between the inventories. The global study by Shugar et al. (2020) identified only few larger lakes while Wang et al. (2020) is the most detailed study. However, even this study failed to identify several glacial lakes in comparison to our detailed manually derived inventory (Table 7).

All available studies agree that there was a strong increase of both number and area of glacial lakes between about 1990 and the most recent time despite the fact that several lakes drained. Hence, the genesis, evolution and distribution of the MGLs in the study area and their close relationship to the general trend of glacier retreat and to comparable moraine-glacial complexes in various mountain systems of the Earth (Narama et al., 2009; Emmer, 2017, Shugar et al., 2020).

**Table 7**
Comparison of different glacial lake inventories for South-East Kazakhstan covering the whole region of this study.

| Study | No. Lakes ~1990 | Area Lakes [km$^2$] ~1990 | No. Lakes ~2018 | Area lakes [km$^2$] ~2018 | Change No. | Change Area [km$^2$] | Change Area [%] | Change Area [%/a] |
|---|---|---|---|---|---|---|---|---|
| This study | 148 | 2.13 | 160 | 2.38 | +12 | +0.25 | 12% | ~0.3% |
| Shugar et al. (2020) | 9 | 0.96 | 14 | 1.48 | +5 | +0.52 | 54% | ~1.9% |
| Wang et al. (2020) | 83 | 2.15 ± 0.50 | 106 | 3.18 ± 0.70 | +23 | +1.03 | 48% | ~1.7% |
| Chen et al. (2021) | n.d. | n.d. | 70 | 2.43 | n.d. | | | |
| Wangchuk and Bolch (2020) | n.d. | n.d. | 60 | 2.52 | n.d. | | | |

However, there is a clear variation among the different studies between the magnitude of increase. Those studies covering our whole study region report an increase of about 1.7 and 1.9% per year. Wang et al. (2013) report a 26% increase between 1990 and 2012 (~1.2%/a on average) for the whole northern Tien Shan (Ile and Kungöy Alatau, including the Kyrgyz part) and Bolch et al. (2011) report an increase of 74% between 1972 and 2007 (2.1%/a on average) for the central part of Northern Tien Shan, including the Kyrgyz part where most of the lakes are located. Our study also reveals an increase of both the number and area of glacial lakes but the increase is significantly lower in comparison to the other studies. We also identified a higher number glacial lakes. We believe that our results offer a precise record as we manually delineated the glacial lakes using higher resolution data and we have also detailed local knowledge. Small lakes are often not identified in automated approaches or omitted due to a size threshold. Moreover, misclassifications are common due to the heterogeneous nature of the lakes. The studies using automated methods, e.g. identified the large Bolshaya Almatinka Lake as glacial lake which is actually a lake which was blocked by a landslide and has now an artificial dam. This lake was therefore excluded for the comparison shown in Table 7. It needs, however, also to be noted that both the methodological differences, different definitions as well as slightly contrasting study periods are possible reasons for the variations among the studies.

This comparison shows the clear need for a reassessment of both the former inventories and the recent ones using consistent methodology and definitions to obtain both the most accurate inventory and information of the growth of the lakes. We also want to highlight the importance of open access of the data availability to enable direct comparisons.

### 6.2. *Identification, assessment and frequency of past outburst event*

The documented number of glacial debris flows and floods in South-East Kazakhstan was highest in the second half of the 20th century and a limited number have been reported after 2000. This tendency is in line with the globally reported occurrence of glacial lake outbursts which showed decline on average after the 1970s despite ongoing atmospheric warming and a general increase in number and area of glacial lakes (Harrison et al., 2018). A remote sensing-based study found an unchanged GLOF frequency in the Himalayas since the availability of suitable imagery at the end of the 1980s (Veh et al., 2019). However, it needs to be noted that the past outburst events were not identified in a consistent way and automated remote sensing-based analysis is only possible with the availability of Landsat TM data since the mid 1980s. These facts might cause some biases. This is true for all studies and in particular also for South-East Kazakhstan where the outbursts were mainly identified based on reported floods at the foothills. It is therefore recommended to reassess the occurrence in a systematic way. This could be done in a first instance using an automated method based on lower resolution satellite imagery such as multi-temporal Landsat and Sentinel- 2 data (cf. Veh et al., 2019). A detailed assessment should then be visually conducted in a systematic way based on available high resolution aerial images or satellite images (such as Corona KH4, e.g. Bolch et al., 2011) from an earlier time period and very high-resolution satellite images (spatial resolution 1 m or better) such as Pléiades or Worldview for the contemporary time.

### 6.3. *Empirical formulations and modelling: Lake volume and peak discharge events*

#### 6.3.1. *Lake volume*

Several empirical formulations were developed to estimate the lake volume from the surface area (Table 8). These formulas were established based on measurements in a specific region (e.g. Evans, 1986a; Inland Waters Directorate, 1977; O'Connor et al., 2001) or based on a compilation of existing bathymetric measurement compiled from the literature either for larger regions or even based on measurements in different regions on Earth (e.g. Huggel et al., 2002; Wang et al., 2013; Cook and Quincey, 2015). Widely applied formula includes the formula presented by Huggel et al. (2002) which is based on selected measurements of different types of glacial lakes worldwide but also Inland Waters Directorate (1977) which was developed for several ice-dammed lakes in the Canadian Rockies. Recently, Kapitsa et al. (2018) developed a new formula for SE Kazakhstan based on 45 measurements in the Ile Alatau and Zhsetu (Dzungarian Alatau).

In order to evaluate the results of these formulas, we compared these to measured volumes of selected glacial lakes in with various characteristics and sizes (Table 9). The results show that five out of ten suggested formulas match on average the measurements with a deviation of $+-20\%$ and two even within $+-10\%$. Interestingly this includes the

**Table 8**
Selected suggested empirical formulations to estimate the volume of glacial lakes.

| Formula volume (m$^3$) vs. area (m$^2$) | Number of lakes (regional distribution) | Lake characteristics | Reference(s) |
|---|---|---|---|
| $V = 0.059\ A^{1.44}$ | > 40 (SE Kazakhstan) | Moraine-dammed lakes | Popov (1986b, 1988) |
| $V = 0.035\ A^{1.5}$ | n.a. (Canadian Rockies) | Ice-dammed lakes | Evans (1986a); Inland Waters Directorate (1977) |
| $V = 3.114\ A + 0.0001685\ A^2$ | 8 (Rocky Mountains in Oregon, US) | Moraine-dammed lakes | O'Connor et al. (2001) |
| $V = 0.104\ A^{1.42}$ | 15 (globally) | Moraine and ice-dammed lakes | Huggel et al. (2002) |
| $V = 0.096\ A^{1.426}$ | 39 (globally) | Supraglacial, moraine and ice-dammed lakes | Wang et al. (2013) |
| $V = 55\ A^{1.25}$ | 16 (Himalaya) | Moraine-dammed lakes | Fujita et al. (2013) |
| $V = 0.0578\ A^{1.4683}$ | 33 (Greater Himalaya) | Moraine-dammed lakes | Khanal et al. (2015) |
| $V = 0.1746\ A^{1.3725}$ | 30 (globally) | Moraine and ice-dammed lakes | Cook and Quincey (2015)[1] |
| $V = 0.1697\ A^{1.3778}$ | 45 (globally) | Moraine and ice-dammed lakes | Cook and Quincey (2015)[2] |
| $V = 0.044\ A^{1.479}$ | 45 (SE Kazakhstan) | Moraine-dammed lakes | Kapitsa et al. (2018) |

[1] Based on 30 glacial lakes from literature.
[2] Based on 30 glacial lakes from literature plus the lakes reported in Huggel et al., 2002

**Table 9**
Comparison of measured and modelled volumes of selected glacial lakes in different valleys Ile Alatau.

| Lake, Reference | Area ($m^2$) | Measured max. depth (m) | Measured Volume ($m^3$ x $10^6$) | Modelled Volume ($m^3$ x $10^6$) based on different suggested empirical formulas (see Table 8) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Popov (1986) | Evans (1986a) | O'Connor et al. (2001) | Huggel et al. (2002) | Wang et al. (2013) | Khanal et al. (2015) | Cook and Quincey (2015)[1] | Cook and Quincey (2015)[2] | Kapitsa et al. (2018) |
| Kishi Almaty Molodezhnyj No. 1 (1) | 7492 | 9.8 | 0.0276 | 0.0224 | 0.0227 | 0.0328 | 0.0330 | 0.0322 | 0.0283 | 0.0363 | 0.0370 | 0.0237 |
| Kishi Almaty No. 1 (2) | 20,100 | 17.5 | 0.1436 | 0.0928 | 0.0997 | 0.1307 | 0.1341 | 0.1314 | 0.1203 | 0.1407 | 0.1441 | 0.1018 |
| Kishi Almaty No. 6 (1) | 5500 | 11.0 | 0.0170 | 0.0144 | 0.0143 | 0.0222 | 0.0213 | 0.0207 | 0.0179 | 0.0238 | 0.0242 | 0.0150 |
| Ulken Almaty No. 15 (2) | 37,200 | 12.8 | 0.1823 | 0.2251 | 0.2511 | 0.3490 | 0.3215 | 0.3161 | 0.2971 | 0.3274 | 0.3365 | 0.2531 |
| Turgen No. 13 (2) | 96,500 | 29.8 | 1.1029 | 0.8883 | 1.0492 | 1.8696 | 1.2447 | 1.2309 | 1.2042 | 1.2115 | 1.2513 | 1.0365 |
| Akkol Lake (2) | 159,500 | 23.7 | 2.5060 | 1.8316 | 2.2295 | 4.7834 | 2.5407 | 2.5200 | 2.5185 | 2.4145 | 2.5006 | 2.1794 |
| Average deviation (%) from measurements | – | – | | −15.5 | −7.1 | 48.7 | 21.5 | 19.2 | 10.7 | 25.8 | 29.0 | −5.9 |

(1) Kasatkin and Kapitsa (2009), (2)Kapitsa et al. (2018)

formula by Inland Waters Directorate (1977) and applied by Evans (1986a) for landslide-dammed lakes which was developed based a few ice-dammed lakes only. The best fit shows unsurprisingly the newly developed formula by Kapitsa et al. (2018) which was calibrated for glacial lakes in the study region. The formula by Popov (1986b, 1988), often applied in the study area, underestimates the volume of most glacial lakes by on average about 15% while the formula by Huggel et al. (2002) overestimates the volume by more than 20%. This is in tendency in line with Kapitsa et al. (2018) who also found a higher overestimation by the formula suggested by Huggel et al. (2002). When estimating the potential impact of an outburst, a slight overestimation rather than an underestimation of the volume is advantageous as otherwise modelling results of potential outbursts and peak discharges could underestimate the impact. This could have more severe impacts in case of an outburst if mitigation measures such as protection construction are planned based on the underestimated results.

Individual lakes can have higher deviations from the measurements. The highest deviation has Lake No. 13 in Turgen Valley which has an untypically long flatter part towards the moraine dam (Kapitsa et al., 2018). All formulas clearly overestimate the volume of this lake with the lowest overestimation by the two formulas calibrated in the study region. Without considering this lake the formula by Popov underestimates the average volume by clearly more than 20% and also the formula by Inland Waters Directorate (1977)/Evans (1986a) has a

**Table 10**
Results of calculation for peak discharge during the GLOF events via tunnels.

| Observed / estimated discharge characteristics | Reference | Peak discharge, $m^3/s$ |
|---|---|---|
| Lake №7 (g. Sportivniy, Talgar River, 1979, flash flood volume: 82.0 × $10^3$ $m^3$, max. Depth at entrance to tunnel: 13.3 m, flow section of the tunnel, 2.7 × 1. 9 × 3.69 m) | | |
| Maximum discharge calculated using a hydraulic model based on the observed cross section of the water flow and the slope of the channel below the lake | | ≤ 15.0 |
| $Q_{max} = 75 (V/10^6)^{0.67}$ (6)[a] | Clague and Mathews (1973) | 14.04 |
| $Q_{max} = \alpha W^{1.25} H^{0.5}$ (7) [a] | Vinogradov (1977), Medeu et al. (2018) | 16.36 |
| $Q_{max} = 0{,}0000055 (P_E)^{0.59}$ (9) [a] | Costa and Schuster (1988) | 4.54 |
| $Q_{max} = 46 (V/10^6)^{0.66}$ (10) [a] | Walder and Costa (1996) | 8.83 |
| $Q_{max} = 0.72 V^{0.53}$ (11) [b] | Evans (1986b) | 28.95 |
| $Q_{max} = 0.0048 V^{0.896}$ (12) [b] | Popov (1991) | 12.13 |
| Lake №16 (g. №25, Kaskelen River, 1980, flash flood volume: 220.0 × $10^3$ $m^3$, max. Depth at entrance to tunnel: 13.8 m, flow section of the tunnel, 6.31 m) | | |
| Observed Hydrograph, 1980 | | 22.7 |
| $Q_{max} = 75 (V/10^6)^{0.67}$ (6) [a] | Clague and Mathews (1973) | 27.2 |
| $Q_{max} = 0{,}0000055 (P_E)^{0.59}$ (9) [a] | Costa and Schuster (1988) | 8.31 |
| $Q_{max} = 46 (V/10^6)^{0.66}$ (10) [a] | Walder and Costa (1996) | 16.93 |
| $Qmax = 0.72 V^{0.53}$ (11) [b] | Evans (1986b) | 48.84 |
| $Q_{max} = 0.0048 V^{0.896}$ (12) [b] | Popov (1991) | 29.38 |
| Lake №16 (g. №25, Kaskelen River, 1986, flash flood volume: 80.0 × $10^3$ $m^3$, max. Depth at entrance to tunnel and flow section of the tunnel not known) | | |
| Observed Hydrograph, 1986 | | 16.0 |
| $Q_{max} = 75 (V/10^6)^{0.67}$ (6) [a] | Clague and Mathews (1973) | 13.8 |
| $Q_{max} = 46 (V/10^6)^{0.66}$ (10) [a] | Walder and Costa (1996) | 8.69 |
| $Qmax = 0.72 V^{0.53}$ (11) [b] | Evans (1986b) | 28.57 |
| $Q_{max} = 0.0048 V^{0.896}$ (12) [b] | Popov (1991) | 11.87 |

where $Q_{max}$ is a maximum flow rate of water ($m^3/s$), λ corresponds to the channel thawing intensity (m/s), and $S_{max}$ is the maximum water surface area ($m^2$), V is the total lake volume ($m^3$), tw stands for time and has a value in the interval 1000–2000 s, α is an empirical coefficient and depends on the length of the tunnel, ϕ is the tilt angle of the frontal moraine slope, n is a dimensionless coefficient (typical values range from 1.25–1.35), A* is the resistivity ($cm^2/m^6$) which can be according to Keremkulov and Tsukerman (1984) " resolved as accumulation of information on outburst floods and the morphometric characteristics of the flow channels". W is the cross-sectional area of the tunnel ($m^2$), H is the excess of lake water level above the tunnel entrance (m).), $P_E$ is the potential energy of the reservoir (J), determined as a result of dam's height (m), volume ($m^3$) and specific gravity of water (9800 N/$M^3$).

Notes
[#]Maximum (peak) discharge in initial period of the outflow into the tunnel, for glacier dammed lakes.
[a]Formulas suggested for dam failures initiated by piping.
[b]Formulas suggested for dam failures initiated by overtopping/surface flow.

clearly higher volume underestimation. Almost all formulas match best Akkol Lake and Lake No. 1 in Kishi Almaty. These lakes have a relatively homogeneous shape (slightly longer than wide and a relatively parabolic shape in depth. While Lake No. 1 is in contact with the glacier Akkol Lake, which is also moraine dammed, is since long time not in contact with the glacier anymore.

The comparison shows that the considered formulas apart from O'Connor et al. (2001) provide a suitable estimation of the overall volume (up to about 25% error), but those developed based on measurements of selected glacial lakes in the study area have the lowest error. However, the deviation can be large for individual lakes in particular for those with irregular shape. It is, hence, recommended apart from conducting more in-situ measurements and to calibrate the formulas for the study region to further develop existing formulas including a shape factor or to further develop and apply more physics-based models similar to those who estimate the glacier-bed topography and allow to identify overdeependings (e.g. Linsbauer et al., 2016) but applying them to former glacier conditions.

### 6.3.2. Peak discharge

Empirical relationships between lake volume and peak water discharge during the outburst events are of great practical significance in assessing MGL outburst hazard in Kazakhstan. In this discussion section we compare the results presented in Section 4.4 to further widely applied empirical formulas to estimate the peak discharge using the similar data from the observed outbursts in the study region.

The maximum values of λ (Eq. (5)) for MGL discharge via open channels (Table 1) of 0.0612 m/h, match well the similar λ values (0.6 m/h) which were observed in the Caucasus, when water overflowed an ice dam (Dokukin et al., 2012; Dokukin and Khatkutov, 2016). The identified relationship also provides suitable results for glacial lakes in other mountain regions of the Earth (Popov, 1986b, 1988).

The results for Lake No. 7 shows that the Eqs. (6) and (7) previously applied in the study region match the modelling based on a hydraulic model relatively well (Table 10). Eqs. (9) and (10) provide clearly too low values. Eq. (11) shows clearly overestimated values while Formula (12) produces results closer to the measurements. Eq. (12) was also developed based on examples from the study region but not for piping as an initial trigger, rather for overtopping of the terminal moraine. Similar results are found for the peak discharge of the outbursts of Lake No. 16 (Table 10). This comparison shows that the applied formulas for the study region provide reasonable results for the estimation of the peak discharge and were well chosen. The well-known Eq. (6) (Clague-Mathews equation, Clague and Mathews, 1973) for determining maximum discharge during the outburst through an ice tunnel, obtained for large glacier dammed lakes with water volume in a wide range from 2.6 × 106 $m^3$ (Strupvatnet Lake, Norway, 1969) to 2 × 1012 $m^3$ (lake Missoula, Montana, Pleistocene), proved also to be suitable for evaluating the characteristics of relatively small-volume MGLs in south-eastern Kazakhstan. In general, this connection between flood volume and peak discharge is also observed for outburst cases with different triggers; both when ice masses or rock (debris) collapse into lakes, as well as the moraine dam's loss of stability (Evans, 1986b; Huggel et al., 2002).

These empirical-based formulas provide a simple method to estimate the peak discharge and, hence, a robust first order approximation which can be used for a basic hazard assessment. The major advantage is their simplicity as only one or few input values are needed. The results of this comparison show that the trigger mechanism is of less importance to consider but the formulas should be calibrated and validated based on past observations of the respective study regions under consideration. For more detailed information about the timing, duration and magnitude of outburst events hydraulic models are recommended. These need, however, more robust measurements which can and should only be conducted at few lakes with a high danger and risk level as these are laborious and can also be dangerous in remote high mountain environments.

## 6.4. Identification of hazardous and dangerous glacial lakes

As mentioned in Section 4.5 various researchers assessed the outburst hazard of lakes in the study region using different criteria. We used criteria such as the lake volume, lake growth, fluctuations of the water level, characteristics and location of the moraine dam, presence of thermocarst features, or a period of high temperatures. These criteria established in this study region are based on the experience of the researchers and the specifics of the study region. One of the most important causes of outbursts is the failure of the moraine-dams (Emmer and Vilímek, 2013; Rounce et al., 2016). Typical causes for dam failure are (1) overtopping (e.g. due to a flood wave caused by a rock and ice avalanche), (2) melting of ice within the dam or forming the dam, (3) blocking of or (4) extension of subsurface outflow tunnels or (5) long-term dam degradation (Clague and Evans, 2000; Richardson and Reynolds, 2000; Mergili and Schneider, 2011; Emmer, 2017). Several researchers provided schemes for the assessment of hazard and danger of different moraine-dammed glacial lakes (e.g. Huggel et al., 2002; Janský et al., 2010; Bolch et al., 2011; Wang et al., 2012; Emmer and Vilímek, 2013; Fujita et al., 2013; Allen et al., 2019). While all approaches have certain differences, they share the consideration of the characteristics of the lake and its changes, the characteristics and stability of the dam, the downstream path and the potential of trigger mechanisms from the surrounding rock slopes. While the different indicators can be assessed objectively to different extents, expert driven subjective decisions have to be made for a final classification. The indicators identified for SE Kazakhstan above are in general in line with the indicators of the published studies and moreover, benefit from the detailed observations made in the study area. The existing studies in SE Kazakhstan revealed also that lake outbursts triggered by rock/ice avalanches are rather uncommon in contrast to other regions like the Himalaya and were therefore not considered. However, with increasing lake area and numbers of the lakes as well the increased occurrence of lakes in higher hypsometric levels the possibilities of GLOF triggering due to mass movements into the lakes is increasing. Therefore, the probability of mass movements into the lakes should be considered in future studies of this region. It should further be noted that the criteria identified in Section 3.3 are suitable to assess the lake hazard level (i.e. the GLOF frequency and magnitude). The danger level of the lakes (i.e. considering also the exposure to the presence of people, livelihoods, environmental services, infrastructure and other resources that could be adversely affected by a potential hazard) was mainly identified based on the location of the lakes, past outburst events, the discharge mechanisms and the calculated peak discharges. Modelling of the outburst path and the affected areas as suggested and applied by different studies (e.g. Huggel et al., 2003; Bolch et al., 2011; Wang et al., 2015; Allen et al., 2019) were rarely applied in the study region. We therefore encourage the re-evaluation of the hazard criteria and the modelling of the outburst paths and the affected areas and apply it consistently for the whole study area to obtain a consistent inventory of hazardous and dangerous MGL across the study region.

## 6.5. Mitigation measures

In case a significant danger and risk level is identified for a specific lake, measurements to mitigate the risk are needed. The best mitigation measure is to significantly reduce the likelihood of an outburst by emptying or strongly lowering the water level of the lake. This is usually associated with strong efforts and high costs as the lakes are in remote areas and a strong reduction relies on the creation of artificial outflow channels. The review of preventive measures of lakes in various countries as well as experience and experiments in south-east Kazakhstan showed that the implementation of preventive measures for emptying the MGL is associated with significant risk if evacuation channels are

**Fig. 14.** Tsho Rolpa Spillway panorama ("© Reynolds International Ltd, 2016").

dug in the ridges of melting ice-cored terminal moraines and may not prevent an outburst. Lakes have outburst during preventive works in several countries including Norway, Peru and Switzerland (Liestol, 1956; Lliboutry et al., 1977; Röthlisberger, 1971). Kazakhstan has faced a similar example. The water level of a lake №13 in upper Kumbelsu River (Ulken Almaty River basin) was lowered in 1976 and 1977 by an artificial channel in the dam. In the afternoon of August 3 of 1977, the lake burst. In just over 20 min, more than 88,000 $m^3$ of water drained and the peak discharge reached 180–210 $m^3/s$. The event caused a series of debris flows with a maximum discharge up to 10,000 $m^3/s$ of the largest wave which exited the mountain valley and hit parts of the outskirts of Almaty city (Esenov and Degovets, 1979). In addition to significant material damage, the debris flow caused human casualties. Therefore, work to deepen the drainage system should include the strengthening of the existing drainage systems. But even then the water level can only be lowered by few meters without incalculable risks. A typical example is Tsho Rolpa Lake, upstream the Rolwaling Khola River in the Himalayas. The lake was lowered and the outflow stabilised (Fig. 14) but the lake still contains a substantial volume of water and a model showed that even a partial lake outburst (39.4 million $m^3$) would still lead to a peak discharge close to 34,234 $m^3/s$, for a 30 m wide rupture (Shrestha et al., 2013).

A safer solution is the use of pumps and siphons for pumping out lake water. But it is not a guaranteed solution to eliminate MGL discharge as the water level can be reduced by a few meters only. However, it is considered as an effective tool in combination with other engineering measures. In general, preventive measures aimed at emptying the lakes of morainic-glacial complexes require greater compliance with increased requirements for safety.

In case a glacial lake was identified as having a high danger and risk but a significant lowering of the lake level is either too costly or associated with too high risks either construction measures to reduce the affected areas (which have been initiated in SE Kazakhstan as early as the 1930s) or installing an early warning systems (Reynolds, 1995; Huggel et al., 2020a, 2020b) should be considered.

## 7. Conclusions

The genesis, evolution and distribution of the MGLs in the study area show their close relationship to the general trend of glacier retreat and to comparable moraine-glacial complexes in various mountain systems of the Earth. Despite the general increase in the number and surface area of glacial lakes associated to glacier recession we did not find an increase in outburst activity. Analyses of statistical data on documented glacial debris flows and floods in South-East Kazakhstan has revealed two stages of outburst activity of the MGL – with many outbursts occurring in the second half of the 20th century and only few after 2000. At the same time, we found that the total number of lakes slightly increased between 1970 and 2019, despite the disappearance of many lakes as a result of outbursts or evolutionary changes. Due to the retreat of glaciers and the further reduction of their total area, new lakes formed in recent years and the glacial-lake ratio (area of glacial lakes vs. glacier area) increased significantly over the same period. There are indications of an increase in the potential debris flow hazard in recent years, as new MGLs form and existing glacial lakes grow. It should specifically be noted that the new lakes develop at higher hypsographic levels. Such MGLs and their possible drainage represent a major threat due to their greater potential energy. However, despite a large number of recorded GLOF events, glacial debris flows did not occur in all cases, since their formation also requires appropriate conditions in underlying mountain valleys (potential debris flow material, natural debris flow channels, favourable conditions for watering of loose sediments, and significant slopes of the beds).

One of the most important causes of outbursts is the failure of the moraine-dams. Data from direct observations and results from land surveys of debris flow traces allowed us to identify three main mechanisms of the MGL outburst events in our study area: surface path via open channels, underground path through ice tunnels (old drainage channels) as well as via rupture in melted moraines. The greatest threat of MGLs stems from discharge via ice tunnels and, especially, through ruptures in melting moraines. In these cases, powerful outburst waves form at the peak of water discharge from the lake, causing debris flows in the lower valleys due to erosion, caving and shear processes. These can cover distances of tens of kilometres and lead to destruction of infrastructure, objects and settlements and can even cause human casualties. Depending on the type of MGL and mechanisms for emptying the lake basins, floods form during breakouts, which differ not only in quantitative characteristics of drainage process, but also in forms of hydrographs. A determining factor for glacial debris flows is the maximum (peak) discharge, which for conditions of the research area may exceed the usual glacier runoff by more than two orders of magnitude. Empirical relationships between lake volume and peak water discharge during the outburst events are of great practical significance in assessing MGL outburst hazard in Kazakhstan. Most proposed formulae to estimate the water volume based on the surface area provide reasonable estimates but calibrating the formula using measurements in the study area is advantageous. The well-known Clague-Mathews equation for determining maximum discharge during the outburst through an ice tunnel, proved suitable for evaluating the characteristics of relatively small-volume MGLs in south-eastern Kazakhstan. In general, this connection between flood volume and peak discharge is also observed for outburst cases with different triggers; both when ice masses or rock (debris) collapse into lakes, as well as the moraine dam's loss of stability. Further direct observations of lake drainage are of special significance to further refine the modelling.

The differences in genesis, evolution, hydrological regime and mechanisms of the MGL outburst events in south-east Kazakhstan shown in this study require different approaches to planning and implementing preventive measures on modern moraines. Identified features of the outburst events allow us to give predictive scenarios for development of debris flow, to justify the planning and implementation of appropriate preventive measures.

Preventive measures aimed at emptying the lakes of morainic-glacial complexes, which are currently being carried out, require greater compliance with increased requirements for safety.

The investigation of glacial lakes using a multi-method approach, including remote sensing, field work and simplified models (cf. Fig. 2), has proven to be suitable to detect potentially dangerous glacial lakes and plan mitigation measures. To further improve the knowledge and the assessment of the hazard and danger of the glacial lakes it is necessary to conduct focused studies on moraine-dammed glacial lakes, glacial-moraine complexes, ice-cores of water-retaining moraine dams, runoff channels and filtration zones, as well as the provision of measures to protect the lake dam's integrity. This should include investigations using multi-temporal high-resolution images and digital elevation models and detailed in-situ investigations (such as geophysical investigations and drilling of rock/ice cores) to plan during mitigation measures but also during preventive construction work. In combination with the presented analyses, these studies and measurements can serve as a basis for a long-term forecast of increased glacial debris flows and floods activity in the study area.

This approach can also be extended and adjusted to other study regions and include more triggering factors such as rock-ice avalanches, but could be complemented by investigations of the impact on the downstream area by including more physically-based models of outburst floods and debris flows.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

We thank the scientific editor for the general support and the anonymous reviewers for their critical but supportive comments which helped to significantly improve the quality of this paper. We furthermore thank Gregoire Guillet and Owen King for proofreading.

## References

Aizen, V.B., Aizen, E.M., Melack, J.M., 1995. Climate, snow cover and runoff in the Tien Shan. Water Resour. Bull. 31 (6), 1113–1129.

Allen, S.K., Zhang, G., Wang, W., Yao, T., Bolch, T., 2019. Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. Sci. Bull. 64, 435–445. https://doi.org/10.1016/j.scib.2019.03.011.

Baimoldayev, T.A., Vinokhodov, V.N., 2007. Kazsekezashita – Operational measures before and after disaster. - Almaty, p. 283 (in Russian).

Benn, D.I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D., Thompson, S., Toumi, R., Wiseman, S., 2012. Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. Earth Sci. Rev. 114, 156–174. https://doi.org/10.1016/j.earscirev.2012.03.008.

Bhattacharya, A., Bolch, T., Mukherjee, K., King, O., Menounos, B., Kapitsa, V., Neckel, N., Yang, W., Yao, T., 2021. High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. Nat. Commun. 12, 4133. https://doi.org/10.1038/s41467-021-24180-y.

Bizhanov, N.K., Vinokhodov, V.N., Kulmakhanov Sh, K., Nurlanov, M.T., Popov, N.V., 1998. Safety and Control of Glacial Debris Flows in Kazakhstan. - Almaty, Gylym, p. 102 (in Russian).

Bolch, T., 2007. Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. Glob. Planet. Chang. 56 (1–12), 2007. https://doi.org/10.1016/j.gloplacha.2006.07.009.

Bolch, T., Gorbunov, A.P., 2014. Characteristics and origin of rock glaciers in Northern Tien Shan (Kazakhstan/Kyrgyzstan). Permafr. Periglac. Process. 25 (4), 320–332. https://doi.org/10.1002/ppp.1825.

Bolch, T., Marchenko, S.S., 2009. Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions. In: Braun, L., Hagg, W., Severskiy, I.V., Young, G.J. (Eds.), Selected papers from the Workshop "Assessment of Snow, Glacier and Water Resources in Asia" held in Almaty, Kazakhstan, 28-30 Nov. 2006. IHP/HWRP-Berichte 8, pp. 132–144.

Bolch, T., Peters, J., Pradhan, B., Yegorov, A.B., Buchroithner, M.F., Blagoveshchenskiy, V.P., 2011. Identification of potentially dangerous glacial lakes in the northern Tien Shan. Nat. Hazards 59 (3), 1691–1714.

Bolch, T., Shea, J.M., Liu, S., Azam, F.M., Gao, Y., Gruber, S., Immerzeel, W.W., Kulkarni, A., Li, H., Tahir, A.A., Zhang, G., Zhang, Y., 2019. 2019. Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In: Wester, P., Mishra, A., Mukherji, A., Shrestha, A.B. (Eds.), The Hindu Kush Himalaya Assessment: Mountains, Climate Change. Sustainability and People. Springer International Publishing, Cham, pp. 209–255.

Buckel, J., Otto, J.C., Prasicek, G., Keuschnig, M., 2018. Glacial lakes in Austria - distribution and formation since the Little Ice Age. Glob. Planet. Chang. 164, 39–51. https://doi.org/10.1016/j.gloplacha.2018.03.003.

Carrivick, J.L., Tweed, F., 2016. A global assessment of the societal impacts of glacier outburst floods. Glob. Planet. Chang. 144, 1–16.

Cenderelli, D., Wohl, E.E., 2001. Peak discharge estimates of glacial-lake outburst floods and "normal" climatic floods in the Mount Everest region, Nepal. Geomorphology 40, 57–90.

Chen, F., Zhang, M., Guo, H., Allen, S., Kargel, J.S., Haritashya, U.K., Watson, C.S., 2021. Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017. Earth Syst. Sci. Data 13, 741–766. https://doi.org/10.5194/essd-13-741-2021.

Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat. Sci. Rev. 19 (17–18), 1763–1783.

Clague, J.J., Mathews, W.H., 1973. The magnitude of jökulhlaups. J. Glaciol. 12 (66), 501–504.

Clague, J.J., O'Connor, J.E., 2015. Glacier-related outburst floods. In: Haeberli, W., Whiteman, C. (Eds.), Snow and Ice-Related Hazards, Risks, and Disasters. The Netherlands, Amsterdam, pp. 487–519.

Cook, S.J., Quincey, D.J., 2015. Estimating the volume of Alpine glacial lakes. Earth Surf. Dynam. 3 (559–575), 2015. https://doi.org/10.5194/esurf-3-559-2015.

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. Geol. Soc. Am. Bull. 7, 1054–1068.

Dokukin, M.D., Khatkutov, A.V., 2016. Lakes at the Small Azau glacier on Elbrus: dynamics and outbursts. Ice and snow 56 (4), 472–479 (in Russian).

Dokukin, M.D., Savernyuk, E.A., Bagov, A.M., Markina, A.V., 2012. On the restructuring of the hydrographic network of the northeastern foot of the Elbrus (river basins of Birjaly-Su and Kara-Kaya-Su). Ice snow 2 (118), 23–30 (in Russian).

Duysenov, E.D., 1971. Debris flows in the Zailiskiy Alatau. - Ed. "Kazakhstan", Alma-Ata, p. 191 (in Russian).

Emmer, A., 2017. Glacier Retreat and Glacial Lake Outburst Floods (GLOFs). In: Cutter, S.L., et al. (Eds.), Oxford Research Encyclopedia of Natural Hazard Science. Oxford University Press, pp. 1–38. https://doi.org/10.1093/acrefore/9780199389407.013.275.

Emmer, A., Vilímek, V., 2013. Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). Nat. Hazards Earth Syst. Sci. 13 (6), 1551–1565.

Esenov, U.E., Degovets, A.S., 1979. Debris flows of 1977 on the Bolshaya Almatinka River and protection tasks of Almaty. Issues of anti-mudflow measures. Alma-Ata 213–222 (in Russian).

Evans, S.G., 1986a. Landslide damming in the· Cordillera of Western Canada. In: Schuster, A.L. (Ed.), Landslide Dams: Processes, Risk, and Mitigation: American Society of Civil Engineers Geotechnical Special Publication No. 3. American Society of Civil Engineers, pp. 111–130.

Evans, S.G., 1986b. The maximum discharge of outburst floods caused by the breaching of man-made and natural dams. Can. Geotech. J. 23, 385–387. https://doi.org/10.1139/t86-053.

Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Molg, T., Bolch, T., Vorogushyn, S., Guntner, A., 2015. Substantial glacier mass loss in the Tien Shan over the past 50 years. Nature Geosci 8, 716–722. https://doi.org/10.1038/ngeo2513.

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A.B., Sawagaki, T., Yamanokuchi, T., 2013. Potential flood volume of Himalayan glacial lakes. Nat. Hazards Earth Syst. Sci. 13, 1827–1839. https://doi.org/10.5194/nhess-13-1827-2013.

Gardelle, J., Arnaud, Y., Berthier, E., 2011. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Glob. Planet. Chang. 75 (47–55), 2011.

Gardner, A.S., Moholdt, G., Cogley, J.G., Wouters, B., Arendt, A.A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W.T., Kaser, G., Ligtenberg, S.R.M., Bolch, T., Sharp, M.J., Hagen, J.O., van den Broeke, M.R., Paul, F., 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science 852–857. https://doi.org/10.1126/science.1234532.

Gerasimov, V.A., 1978. Catastrophic phenomena of the northern slope of the Greater Caucasus associated with glacial processes. Mater. Glaciol. Studies (MGI) 32, 71–76 (in Russian).

Glaciological Dictionary, 1984. Glaciological Dictionary - Leningrad. Cambridge University Press, p. 528.

Golubev, G.N., 1974. Features of Glacial Lakes Dicharges of Various Types. - Materials Glaciological Studies, Vol. 24.M, pp. 155–163 (in Russian).

Gorbunov, A.P., Severskyi, E.V., 2001. The debris flow of Almaty and its surroundings. Almaty 78 (in Russian).

Gorbunov, A.P., Severskiy, E.V., Titkov, S.N., 1996. Geokriologichesije Uslovija Tjan-Shanja i Pamira (Permafrost conditions of Pamir and Tien Shan). Institut Merzlotovedenija, Rassiyskaja Akademija Nauk, Irkutsk, p. 196 [in Russian].

Grabs, W.E., Hanish, J., 1993. Objectives and prevention methods for glacier lakes outburst floods (GLOF). – Snow and Glacier Hydrology (Proceedings of the Kathmandu Symposium, November 1992). IAHS Publ. №218.

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. Ann. Glaciol. 4, 85–90.

Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A., Emmer, A., Glasser, N., Haritashya, U.K., Klimeš, J., Reinhardt, L., Schaub, Y., Wiltshire, A., Regmi, D., Vilímek, V., 2018. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. Cryosphere 12, 1195–1209.

Huggel, C., Kääb, A., Haeberli, W., Krummenacher, B., 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. Nat. Hazards Earth Syst. Sci. 3, 647–662.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing-based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can. Geotech. J. 39, 316–330.

Huggel, C., Allen, S., Wymann von Dach, S., Dimri, A.P., Mal, S., Linbauer, A., Salzmann, N., Bolch, T., 2020a. An integrative and joint approach to climate impacts, hydrological risks and adaptation in the Indian Himalayan region. In: Dimri, A.P., Bookhagen, B., Stoffel, M., Yasunari, T. (Eds.), Himalayan Weather and Climate and their Impact on the Environment. Springer International Publishing, Cham, pp. 553–573.

Huggel, C., Cochachin, A., Drenkhan, F., Fluixá-Sanmartín, J., Frey, H., García Hernández, J., Jurt, C., Muñoz, R., Price, K., Vicuña, L., 2020b. Glacier Lake 513, Peru: Lessons for early warning service development. WMO Bull. 69, 45–52.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., Kääb, A., 2021. Accelerated global glacier mass loss in the early twenty-first century. Nature 592, 726–731. https://doi.org/10.1038/s41586-021-03436-z.

Inland Waters Directorate, 1977. Report on the influence of glaciers on the hydrology of streams affecting the proposed Alcan pipeline route. Glaciology Division, Inland Waters Directorate, Fisheries and Environment Canada, Ottawa, Canada, p. 38.

Ives, J.D., Shrestha, R.B., Mool, P.K., 2010. Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. ICIMOD.

Janský, B., Sobr, M., Engel, Z., 2010. Outburst flood hazard: case studies from the Tien-Shan Mountains, Kyrgyzstan, Limnologica. Ecol. Manag. Inland Waters 40, 358–364. https://doi.org/10.1016/j.limno.2009.11.013.

Kapitsa, V.P., Shagedanova, M.V., Usmanova, Z.S., Seversky, I.V., Blagoveshchensky, V. P., Kasatkin, N.E., 2018. Glacial lakes of the Ile (Zailiysky) Alatau: state, modern -change changes, probable risks. Georisk 68–78 (in Russian).

Kapitsa, V., Shahgedanova, M., Severskiy, I., Kasatkin, N., White, K., Usmanova, Z., 2020. Assessment of changes in Mass Balance of the Tuyuksu Group of Glaciers, Northern Tien Shan, between 1958 and 2016 using Ground-based Observations and Pléiades Satellite Imagery. Front. Earth Sci. 8, 259. https://doi.org/10.3389/feart.2020.00259.

Karamanov, U.K., Degovets, A.S., 1992. Attention: debris flow!. In: Almaty, p. 47 [in Russian].

Kasatkin, N.E., Kapitsa, V.P., 2009. The morainic lakes dynamics in the Ile Alatau. In: Materials of the International Conference "Mitigation of natural hazards in mountain areas", Bishkek, Kyrgyzstan, 15.-18.9.2009, 55–58.

Kavetsky, S.P., Gulina, V.R., 1964. Debris flows in the area of glaciers, the possibility of forecasting and combatting against it. Mater. Glaciol. Studies (MGI). 9, 99–102. Moscow. (in Russian).

Kavetsky, S.P., Smirnov, I.P., 1957. Mudflows of non-storm origin. Trans. KazNIGMI no. 9, 43–52 (in Russian).

Keremkulov, V.A., 1985. Morphometric characteristics and classification of moraine lakes. Mudflows 36–47. Sat No. 9, Moscow. (in Russian).

Keremkulov, V.A., Kirenskaya, T.L., 1985. On the prediction of moraine lakes outburst. In: Debris Flows, pp. 84–92. Sat No. 9, Moscow. (in Russian).

Keremkulov, V.A., Tsukerman, I.G., 1984. A model of catastrophic emptying the lake via a breach in the body of a bulkhead composed of loose fragments. In: Sat 8 "Debris flows", Moscow, Gidrometeoizdat, pp. 92–108 (in Russian).

Keremkulov, V.A., Tsukerman, I.G., 1985. Model for emptying a moraine lake through a grotto. In: Sat 9, "Debris flows", Moscow, Gidrometeoizdat, pp. 59–70 (in Russian).

Khanal, N.R., Hu, J.-M., Mool, P., 2015. Glacial lake outburst flood risk in the Poiqu/Bhote Koshi/Sun Koshi River Basin in the Central Himalayas. Mount. Res. Dev. 35, 351–364. https://doi.org/10.1659/MRD-JOURNAL-D-15-00009.

Kirenskaya, T.L., Stepanov, B.S., Khonin, R.V., 1977. Debris Flow in the Bolshaya Almaty Basin August 19, 1975 - Sat. Mudflows No. 2, Moscow, pp. 115–119 (in Russian).

Kobrushko, S.S., Stavissky, Y.S., 1978. Glacial lakes of Kyrgyzstan and their role in formation of mudflows. In: Materials Glaciological Studies, Vol. 32. Moscow, pp. 59–62 (in Russian).

Kolotilin, N.F., 1959. Geological conditions for formation of some debris flows of local manifestation (on the example of mudflow in the valley of the Malaya Almatinka River in August 7, 1956). -Materials of the IV All-Union Conference on Mudflows - Alma-Ata, Ed. Academy of Sciences of the Kazakh SSR, pp. 40–51 (in Russian).

Kotlyakov, V.M., Komarova, A.I., 2012. Explanatory bilingual dictionary of Geography. - Moscow, 752 s.

Liestol, Q., 1956. Glacier-dammed lakes in Norway. Nor. Geogr. Tidsskr. 15 (3–4), 122–149.

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M.F., Allen, S., 2016. Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya–Karakoram region. Ann. Glaciol. 57, 117–130.

Lliboutry, L., Arnao, B.M., Pautre, A., Schneider, B., 1977. Glaciological Problems set by the control of dangerous lakes in Cordillera Blanka, Peru. J. Glaciol. 18 (79), 239–254.

Marchenko, S.S., Gorbunov, A.P., Romanovsky, V.E., 2007. Permafrost warming in the Tien Shan Mountains, Central Asia. Glob. Planet. Chang. 56 (3–4), 311–327. https://doi.org/10.1016/j.gloplacha.2006.07.023.

Markov, I.N., Popov, N.V., 1980. Dynamics of Lakes in the Chilik river basin. And the possibilities of their breakthrough. - Mudflows, Sat 4, Moscow, pp. 107–113 (in Russian).

Medeu, A.R., Kirenskaya, T.L., Blagoveshchensky, V.P., Askarova, M.A., 2015. Glacial debris flow in the Kargaly river basin (Ile Alatau) July 23, 2015 - Geography and Ecology Issues. No. 4, pp. 73–80 (in Russian).

Medeu, A.R., Blagoveshchensky, V.P., Baimoldaev, T.A., Kirenskaya, T.L., Stepanov, B.S., 2018. Debris flows of the South-East Kazakhstan, Vol. 2, p. 288. Part 2, Almaty. (in Russian).

Mergili, M., Schneider, J.F., 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Nat. Hazards Earth Syst. Sci. 11, 1447–1462.

Mukherjee, K., Bolch, T., Goerlich, F., Kutuzov, S., Osmonov, A., Pieczonka, T., Shesterova, I., 2017. Surge-type glaciers in the Tien Shan (Central Asia). Arct. Antarct. Alp. Res. 49, 147–171. https://doi.org/10.1657/AAAR0016-021.

Narama, C., Severskiy, I., Yegorov, A., 2009. Current state of glacier changes, glacial lakes, and outburst floods in the Ile Ala-Tau and Kungöy Ala-Too ranges, northern Tien Shan Mountains. Aust. Geogr. Stud. 84, 22–32.

Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y., Song, C., 2017. A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. Remote Sens. Environ. 189, 1–13. https://doi.org/10.1016/j.rse.2016.11.008.

O'Connor, J.E., Hardison, J.H., Costa, J.E., 2001. Debris flows from failures of Neoglacial-age moraine dams in the three Sisters and Mount Jefferson Wilderness areas, Oregon, US Department of the Interior, US Geological Survey, Professional Paper 1606, p. 93. https://doi.org/10.3133/pp1606.

Palgov, N.N., 1958. Modern glaciation in the Zailiysky Alatau. - Alma-Ata. Ed. Academy of Sciences of the Kazakh SSR, p. 313 (in Russian).

Plekhanov, P.A., 1977. Glacial debris flow in August 19, 1975 in Bolshaya Almaty River basin. - Snow avalanches and glaciers of Kazakhstan. Alma-Ata 144–154 (in Russian).

Plekhanov, P.A., Sudakov, P.A., Tokmagambetov, G.A., 1975. Debris flow's causes and processes of formation on the Malaya Almatinka River. July 15. In: 1973 - "Bulletin of the Academy of Sciences of the Kazakh SSR", No. 4, pp. 25–35 (in Russian).

Plekhanov, P.A., Sudakov, P.A., Tokmagambetov, G.A., 1977. Glacial debris flow on the Zharsay River. 3 / UII, pp. 165–178 (in Russian).

Popov, N.V., 1978. Debris flows in the Bolshaya Almaty River basin in August 3–31, 1977. In: XV All-Union Scientific and Technical Conference on Anti-Mudflow Measures: Abstracts - September 27–28, 1978, Vol. 1, Tashkent (in Russian).

Popov, N.V., 1981. Quantitative assessment and causes of mudflow formation in the Zharsai River basin. - Problems of anti-mudflow measures. Alma-Ata 158–166 (in Russian).

Popov, N.V., 1984. Glacial debris flow on July 23, 1980 on the Kaskelen River in the Trans-Ili Alatau. - Sat "issues of anti-debris flow measures". "Kazakhstan", Alma-Ata 222–230 (in Russian).

Popov, N.V., 1986a. Methods of combating the glacial debris flows of an outburst character. - issues of anti-debris flow measures. Alma-Ata 56–62 (in Russian).

Popov, N.V., 1986b. Study on the lakes of glacial zone in the South-East of Kazakhstan in order to assess the possibility of their breakthroughs and monitor debris flow hazard. In: Abstract of the Dissertation for the Degree of Candidate of Geographical Sciences, Moscow (in Russian).

Popov, N.V., 1987. Outburst glacial debris flows and combating them in the mountains of the Northern Tien Shan. In: Materials of Glaciological Studies, Moscow, Vol. 59, pp. 188–193 (in Russian).

Popov, N.V., 1988. Features of morphometry of glacial and moraine lakes in Zailiysky Alatau. In: Problems of anti-mudflow measures. Alma-Ata, pp. 31–37 (in Russian).

Popov, N., 1991. Assessment of glacial debris flow hazard in the north Tien-Shan. In: Proceedings of the Soviet-China-Japan Symposium and Field Workshop on Natural Disasters, 2–17 Sept. 1991, pp. 384–39.

Popov, N., 1997. Glacial debris-flows mitigation in Kazakhstan: assessment, prediction and control. In: Proceedings of the 1st International Conference on Debris-Flow Hazard Mitigation: Mechanics, Prediction and Assessment, San Francisco, California, 7–9 Aug. 1997. Edited by C.-L. Chen. ASCE, New York, N.Y, pp. 113–122.

Popov, V.I., Stepanov, B.S., Mochalov, V.P., Khonin, R.V., Markov, I.N., Golubovich, V. A., Bekarevich, V.E., 1980. Debris Flows August 3-31, 1977 Bolshaya Almaty. - Debris flows No. 4, Moscow, pp. 57–63 (in Russian).

Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Thai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N. M., 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Reynolds, J.M., 1995. Glacial-lake outburst floods (GLOFs) in the Himalayas: an example of hazard mitigation from Nepal. Geosci. Develop. 2, 6–8, 1995.

Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Quat. Int. 65/66 (1), 31–47.

Röthlisberger, F., 1971. Massnahmen gegen die Ausbrüche eines Gletschersees ob Saas-Balen (Grubengletscher). Schweizerische Bauzeitung 89 (40), 999–1003.

Rounce, D.R., McKinney, D.C., Lala, J.M., Byers, A.C., Watson, C.S., 2016. A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. Hydrol. Earth Syst. Sci. 20 (9), 3455–3475. https://doi.org/10.5194/hess-20-3455-2016.

Severskiy, I.V., Vilesov, E.N., Armstrong, R., Kokarev, A., Kogutenko, L., Usmanova, V., Morozova, V., Raup, B., 2016. Changes in glaciation of the Balkhash–Alakol basin, central Asia, over recent decades. Ann. Glaciol. 51, 382–394. https://doi.org/10.3189/2016AoG71A575.

Shean, D.E., Bhushan, S., Montesano, P., Rounce, D.R., Arendt, A., Osmanoglu, B., 2020. A systematic, regional assessment of High Mountain Asia glacier mass balance. Front. Earth Sci. 7, 363. https://doi.org/10.3389/feart.2019.00363.

Shrestha, B.B., Nakagawa, H., Kawaike, K., Baba, Y., Zhang, H., 2013. Glacial hazards in the Rolwaling valley of Nepal and numerical approach to predict potential outburst flood from glacial lake. Landslides 10 (3), 299–313. https://doi.org/10.1007/s10346-012-0327-7.

Shugar, D.H., Burr, A., Haritashya, U.K., Kargel, J.S., Watson, C.S., Kennedy, M.C., Bevington, A.R., Betts, R.A., Harrison, S., Strattman, K., 2020. Rapid worldwide growth of glacial lakes since 1990. Nat. Clim. Chang. https://doi.org/10.1038/s41558-020-0855-4.

Shusharin, V.I., Markov, I.N., 1976. Observation for glacial debris flow formation in the Middle Talgar River basin. In: "Debris flows" № 1, Moscow, pp. 98–108 (in Russian).

Shusharin, V.I., Popov, N.V., 1981. Development of debris flow in the Middle Talgar River basin. – Problems of anti-debris flow measures. Alma-Ata 153–157 (in Russian).

Tokmagambetov, G.A., Sudakov, P.A., Plekhanov, P.A., Golubovich, V.A., 1978. The mode of melt water flow on moraines and the water-regulating ability of moraine deposits. In: Bulletin of the Academy of Sciences of the Kazakh SSR No. 10, pp. 60–68 (in Russian).

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Clim. Change 2, 725–731. https://doi.org/10.1038/nclimate1592.

Tokmagambetov, G.A., Sudakov, P.A., Plekhanov, P.A., 1980. Glacial lakes in the Zailiskiy Alatau. - Materials of Glaciological Studies. Issue 39, 63–68 (in Russian).

Veh, G., Korup, O., von Specht, S., Roessner, S., Walz, A., 2019. Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. Nat. Clim. Chang. 9, 379–383.

Vilesov, E.N., 2018. Change in the Size and Condition of Kazakhstani glaciers Over 60 years (1955-2015). - Ice and Snow, T. 58, No. 2, pp. 159–170 (in Russian).

Vinogradov, Yu.B., 1977. Glacial Outburst Floods and Debris Flows. - Leningrad. in Russian, p. 156.

Vinogradov, Yu.B., Zems, A.E., Khonin, R.V., 1976. Debris flow on July 15, 1973 in Malaya Almatinka. In: Sat Mudflows No. 1, Moskow, pp. 60–73 (in Russian).

Walder, J.S., Costa, J.E., 1996. Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. Earth Surf. Process. Landf. 21, 701–723.

Wang, S., Zhang, T., 2013. Glacial lakes change and current status in the central Chinese Himalayas from 1990 to 2010. J. Appl. Remote. Sens. 7 (1), 073459 https://doi.org/10.1117/1.JRS.7.073459.

Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J., Han, Y., 2012. An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. Nat. Hazards Earth Syst. Sci. 12, 3109–3122. https://doi.org/10.5194/nhess-12-3109-2012.

Wang, X., Ding, Y., Liu, S., Jiang, L., Wu, K., Jiang, Z., Guo, W., 2013. Changes of glacial lakes and implications in Tian Shan, Central Asia, based on remote sensing data from 1990 to 2010. Environ. Res. Lett. 8, 44052.

Wang, W., Xiang, Y., Gao, Y., Lu, A., Yao, T., 2015. Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas. Hydrol. Process. 29, 859–874.

Wang, X., Guo, X., Yang, C., Liu, Q., Wei, J., Zhang, Y., Liu, S., Jiang, Z., Tang, Z., 2020. Glacial lake inventory of high-mountain Asia in 1990 and 2018 derived from Landsat images. Earth Syst. Sci. Data 12, 2169–2182. https://doi.org/10.5194/essd-12-2169-2020.

Wangchuk, S., Bolch, T., 2020. Mapping of glacial lakes using Sentinel-1 and Sentinel-2 data and a random forest classifier: strengths and challenges. Sci. Remote Sens. 100008 https://doi.org/10.1016/j.srs.2020.100008.

Westoby, M.J., Glasser, N.F., Brasington, J., Hambrey, M.J., Quincey, D.J., Reynolds, J. M., 2014. Modelling outburst floods from moraine-dammed glacial lakes. Earth Sci. Rev. 134, 137–159. https://doi.org/10.1016/j.earscirev.2014.03.009.

Wilson, R., Harrison, S., Reynolds, J., Hubbard, A., Glasser, N.F., Wündrich, O., Iribarren, Anacona P., Mao, L., Shannon, S., 2019. The 2015 Chileno Valley glacial lake outburst flood, Patagonia. Geomorphology 332, 51–65.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., Cogley, J.G., 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature. https://doi.org/10.1038/s41586-019-1071-0.