PAN
POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2024.151786
2024, No. 63 (X-XII): 19–24

Assessment of the current state and temporal changes of glacial-moraine lakes in the Central and Eastern part of the northern slope of the Ile Alatau, Kazakhstan

Ainur Mussina[1], Assel Abdullayeva*[1], Martina Barandun[2], Alessandro Cicoira[3], Marzhan Tursyngali[1]

[1] Al-Farabi Kazakh National University, Department of Meteorology and Hydrology, 050040, 71 Al-Farabi Ave., Almaty, Republic of Kazakhstan

[2] University of Fribourg, Department of Geosciences, CH-1700, 20 de l'Europe Ave., Fribourg, Switzerland

[3] University of Zurich, Department of Geography, CH-8006, 71 Rämistrasse, Zurich, Switzerland

* Corresponding author

RECEIVED 29.03.2024 ACCEPTED 09.08.2024 AVAILABLE ONLINE 08.11.2024

Highlights
- Analysed changes in 77 glacial-moraine lakes via remote data.
- Grasping lake formation and changes aids risk mitigation.
- Studied the importance of identifying temporal changes and features in glacial-moraine lakes
- Implementing effective measures to prevent and manage GLOFs.

Abstract: Retreat of glaciers and partial melting of permafrost moraines recorded since the 1970s, led to the formation and rapid accumulation of glacial-moraine lakes in Ile Alatau, Kazakhstan. For its part, there was a necessity to analyse hydrometeorological and morphometric data on the current state and temporal changes of moraine lakes. Maps provided comprehensive information about the state of moraine-glacial lakes to prevent and protect objects from the negative effects of mudflow hazards. In this regard, the purpose of the article is to prepare a systematic inventory as a result of the study, compare and analyse the changes and evolution of the lakes. The findings of this study show that the total number of moraine lakes increased over the study period from 20 in 1978 to 77 in 2021. It is visible that the glacial-moraine lakes are increasing in number and area, thereby posing possible mudflow hazards to the densely populated downstream land. The study on glacial-moraine lakes in the Ile Alatau region has practical value in several areas: it helps assess the risks of glacial lake outburst floods (GLOFs) and enables authorities to develop effective strategies for disaster management; it informs planners and developers about potential hazards; it provides valuable information for protecting sensitive ecosystems and maintaining the ecological balance of mountainous regions.

Keywords: earth's remote sensing data, glacial lake outburst flood, glacial-moraine lake inventory, number and area of moraine lakes

INTRODUCTION

Climate change has become a significant global problem in recent years, affecting both natural ecosystems and human societies. An unmistakable and highly impactful consequence of these alterations is the hastened withdrawal of glaciers worldwide. Glaciers, commonly known as the «canaries in the coal mine» for climate change, act as crucial indicators of the changes in worldwide and local climates (Linchenko *et al*., 2022; Moldasheva *et al*., 2023). The reduction in glacier mass is a result of increasing global temperatures and leads to a series of environmental effects such as the rise in sea levels, changes in the availability of freshwater, and modifications in the dynamics of river flow (Shahgedanova *et al*., 2020). The widespread occurrence of this phenomenon highlights the immediate necessity for thorough investigations into glacier retreat and its consequences.

In response to the current global warming the glacier located in the Ile Alatau, Kazakhstan shows a strong retreat. This retreat has been recorded since the 1950s (Aizen *et al*., 2016). The active occurrence of the process of retreat of glaciers is related to the seasonal and annual increase in air temperature (Deng, Chen and Liu, 2017). Since 1955, the rate of the glacial area's retreat was 0.76% per year, since the 1990s, its retreat rate has reached 1.13% (Severskiy *et al*., 2016). The retreat of glaciers in the Ile Alatau led to the appearance of young moraine sediments under them on the Earth's surface. This situation significantly changes the direction of cryogenic and post-cryogenic processes of young moraines.

Studies of the formation, temporal changes, and morphometric characteristics of glacial-moraine lakes in Kazakhstan have been conducted since the late 20th century (Mussina, Abdullayeva and Barandun, 2022; Asanova *et al*., 2023). Tokmaganbetov (2010) considered the modern evolution of glacial-moraine lakes of the Kishi Almaty river basin taking into account the morphometric characteristics of glacial-moraine lakes. The results of the work of glaciologists showed that the formation of glacial-moraine lakes was related to the degradation of glaciers (Amin *et al*., 2020; Mussina *et al*., 2023).

As a result of increasing lake formation, water level and the water volume of glacial-moraine lakes the potential to evolve to a mudflow hazard has increased (Barandun *et al*., 2020; Barandun and Pohl, 2023). Modern dangerous exogenous processes, such as mudflows, landslides, and river erosion depend upon a variety of terrain forms, and geological and climatic conditions of territories (Baymoldayev *et al.*, 2018). The main signs of the possibility of a catastrophic GLOFs are the rising size of the depression due to an increase of the water surface area, an anomaly inflow of water causing its overflow through the natural dam and an increase in the temperature of the water in the lake (Nematov *et al*., 2023).

Applying modern software, the temporal changes of moraine lakes is monitored by high-resolution satellite images. The use of GIS technologies, remote sensing of the Earth and the latest software most effectively affects the quality of informed decision-making when managing mudflow risks in the moraine-glacier complex, and, importantly, the evolution of cartographic materials of an analytical nature (maps of the location of moraine lakes and glaciers, maps of mudflow hazard and mudflow risk) used to prevent and protection of socio-, techno- and ecosphere objects from the negative impact of mudflow phenomena (Mussina and Zhanabayeva, 2016).

In this regard, the main purpose of the article is to prepare a systematic inventory including the temporal changes and the current state of glacial-moraine lakes located in the Ulken Almaty and Kishi Almaty basins in the central part, Talgar and Esik basins in the eastern part of the Ile Alatau.

MATERIALS AND METHODS

STUDY AREA

The study area includes the river basins of Ulken Almaty, Kishi Almaty, Talgar, and Esik, located in southeastern Kazakhstan. These river basins originate in the northern slopes of the Trans-Ili Alatau mountain range, which is part of the Tian Shan mountains. The region features a mix of high mountain terrains, deep valleys, and diverse ecosystems. The study area on the northern slope of the Ile Alatau experiences harsh climatic conditions, with seasonal fluctuations in temperature and precipitation. The region's river regime includes mixed glacial-rain floods and stable winter snowfall. Physical weathering of rocks due to melting ice and snow, extreme temperatures, and extreme weathering results in the formation of loose clastic sediments, which contribute to mudflows. The Ile Alatau region is experiencing the formation of new moraine areas due to glacial erosion, characterised by frontal ridges reaching 150–200 m. The study area, which includes 91.63 km^2 of new moraines with buried glaciers from the Little Ice Age, is at the highest mudflow hazard.

DATA COLLECTION

During the inventory of the lakes, satellite images were taken for July–August, which is a relatively dry season, when the minimum limit of snow reserves is observed. In addition, the period from 1978 to 2021 was selected to determine the temporal changes of moraine lakes of the concerned area. The selection of these dates and years for inventory of glacial-moraine lakes is explained by the minimum limit of cloud and snow layers at the source of selection and the high quality of the images.

In the study of glacial-moraine lakes, the Multispectral Scanner System (MSS) satellite images were used for 1978, the Thematic Mapper (TM) for 1990, the Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) Landsat for 1990, and the Sentinel-2 satellite images for 2021. In addition, data from the Alos Palsar, launched by the Japan Aerospace and Exploration Agency (JAXA), was used as a numerical model of the terrain to capture the study area on the map surface. In this regard, images of high and medium spatial resolution of 10, 30 and 60 m taken by the Sentinel-2 and the Landsat space satellites were used as the main data source for the study area. The reliability of the identification of glacial-moraine lakes with the help of selected images is determined by the spatial imaging capability.

MAPPING OF GLACIAL-MORAINE LAKES AND DEVELOPMENT OF INVENTORY

The studied glacial-moraine lakes were identified using by normalised difference water index (*NDWI*) (EOSDA, 2021). The *NDWI* index is a normalised index of the relationships between visible green and near-infrared spectral bands that indicate water bodies, as well as inhibit vegetation and other soil features. Determination of lakes by values marked as a positive range of the *NDWI* index and mapping of glacial-moraine lakes using a numerical model of the terrain were carried out using the ArcGIS 10.8 program. Firstly, segmentation was performed on Landsat and Sentinel-2 satellite images to obtain preliminary results of mapping glacial-moraine lakes in the study area. Secondly, digitisation of each lake was carried out for each of the studied years by analysing the preliminary obtained results. Based on spectral reflection, some shaded areas were mistakenly classified as glacial-moraine lakes. For this reason, adjustments were made as a result of comparing incorrectly classified or identified lakes with images from the Google Earth application. In the course of the study, errors in mapping the area of glacial-moraine lakes were evaluated according to the method proposed by Hanshaw and Bookhagen (2014).

After the mapping work was carried out, the following characteristics were assigned to each lake as an attribute for the development of an inventory to assess the current state and temporal changes of glacial-moraine lakes of the central and eastern part of the northern slope of the Ile Alatau:

1) name of glacial-moraine lakes,
2) coordinates of the location of glacial-moraine lakes in latitude and longitude,
3) altitude values of glacial-moraine lakes in m a.s.l.,
4) area of glacial-moraine lakes:
   a) <5,000 m^2,
   b) 5,000–20,000 m^2,
   c) >20,000 m^2.

RESULTS

CURRENT STATE AND TEMPORAL CHANGES OF GLACIAL-MORAINE LAKES

This study examines the temporal variations and features of 77 glacial-moraine lakes in the Central and Eastern regions of the Northern slope of Ile Alatau, Kazakhstan, by utilising remote sensing data. The data indicates that the number of moraine lakes has risen from 20 in 1978 to 77 in 2021. Additionally, the total area covered by these lakes has increased by 160%, from 193.3 km^2 in 1978 to 503.9 km^2 in 2021, with a margin of error of 16 and 1.5% respectively. Detailed information on glacial-moraine lakes' temporal changes for the five time periods are summarised in Table 1.

Uncertainties of areas for Landsat-2 with a resolution of 60 m showed in the range of 11–22% in 1978, for Landsat-5 and Landsat-7 with a resolution of 30 m – 4–13% in 1990, 3–9% in 1999. Results of Sentinel-2 showed fewer uncertainties in the

Table 1. Changes in number, area and evolution in study basins from 1978 to 2021

Study year	Study area	Total lakes	Area (m^2)						Intensity of temporal changes according to 1978 (% per year)		Uncertainties (%)
			<5,000		5,000–20,000		>20,000		total area (m^2)	%	
			count	m^2	count	m^2	count	m^2			
1978	Ulken Almaty	7	2	5,400	5	47,600	–	–	53,000	–	11
	Kishi Almaty	4	1	1,800	3	24,800	–	–	26,600	–	22
	Talgar	5	2	5,700	1	7,400	2	51,600	64,700	–	20
	Esik	4	–	–	4	48,600	–	–	48,600	–	14
1990	Ulken Almaty	9	6	17,500	3	31,100	–	–	48,600	–0.64	5.7
	Kishi Almaty	4	2	4,650	2	18,600	–	–	23,250	–0.97	12.7
	Talgar	15	8	20,500	6	57,900	1	66,100	144,500	9.49	4.1
	Esik	7	4	9,350	3	44,250			53,600	0.79	8.9
1999	Ulken Almaty	10	8	20,400	1	6,100	1	22,950	49,450	–0.3	5.1
	Kishi Almaty	5	2	3,800	2	11,400	1	20,800	36,000	1.61	4.8
	Talgar	20	13	30,300	4	30,250	3	114,250	174,800	7.74	3.1
	Esik	8	5	9,800	3	38,700	–	–	48,500	–0.01	9.1
2013	Ulken Almaty	11	6	11,250	3	44,200	2	61,750	117,200	3.36	3.6
	Kishi Almaty	4	1	2,700	2	17,300	1	22,450	42,450	1.66	9.1
	Talgar	23	12	28,800	7	73,850	4	153,800	256,450	8.23	2.5
	Esik	14	10	19,600	4	42,300	–	–	62,000	0.77	6.3
2021	Ulken Almaty	21	14	26,400	5	52,950	2	76,550	155,900	4.41	0.6
	Kishi Almaty	5	3	6,900	2	21,600	–	–	28,500	0.16	3.5
	Talgar	29	21	44,300	6	66,750	2	103,850	214,900	5.28	0.8
	Esik	22	17	30,000	5	74,650	–	–	104,650	2.62	1.4

Source: own study.

range of 0.6–3.0 in 2021. The average error observed when measuring the area of glacial-moraine lakes for each study area is shown in Table 1. The accuracy of lake measurements is influenced by the spatial resolution, the date of receipt of images, geometric and radiometric corrections, and mapping methods. Since the error was estimated using half a pixel multiplied by the perimeter, the error was higher for small glacial-moraine lakes.

FACTORS INFLUENCING THE TEMPORAL CHANGES OF GLACIAL-MORAINE LAKES

One of the features of climatic factors contributing to the formation of lakes is the positive air temperature over a long period. In this regard, the analysis of the duration of positive degree days in the Central part of the Northern slope of the Ile Alatau in the period from 1950 to 2020 was carried out using data from Mynzhylky station. The Mynzhylky meteorological station is located at an altitude of 3017 m a.s.l., which contributes to obtaining more reliable data on changes in air temperature and precipitation. The duration of positive degree days for the research period was from June until the first decade of September (Fig. 1). The average duration of positive degree days' sum for the studied area during the period 1950–2020 made up 106 days.

The analysis of the data of the summer period for 50 years from 1970 to 2020 shows a linear trend of temperature increase according to data received from the Mynzhylky meteorological station (Fig. 2a). Linear trend provide visual information about

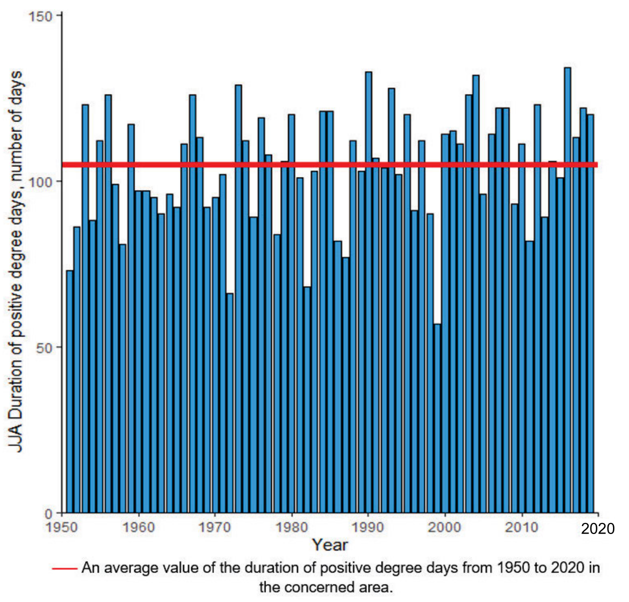

Fig. 1. Duration of positive degree days of the concerned area for the period from 1950 to 2020; JJA = June, July, August; source: own study

the gradual increase from the average of June-August air temperatures over the past decades. Each rolling ten years was considered to estimate the growth rate of the average air temperature indicators obtained for June–August. Also, a change in the precipitation regime was investigated. In contrast to the air temperature, no clear trend could be identified for the change in the precipitation in the study area for 50 years (Fig. 2b).

The positive results of preventive work can be demonstrated by several lakes in the study basins. One such example is Lake No. 13-bis in the Ulken Almaty river basin, which has undergone rapid development over the past ten years and poses a danger of a GLOF to Almaty city. This lake was formed in the 1990s at the Sovetov 2 No. 89 glacier and did not pose any danger until 2000, but was regularly monitored by the Kazakhstan State Agency for Mudflow Protection (KSAMP). In 2010, the lake's area had increased by 1100% compared to 1990, to a total of 40,500 m^2. Since then, KSAMP has recognised the lake as a potential mudflow hazard and has implemented preventive measures, including the installation of siphons and an evacuation channel, which successfully lowered the lake's water level by 7.7 m. However, with the arrival of glacial flow, the lake's size and characteristics continued to grow, reaching 54,800 m^2 in 2020, a 1600% increase compared to 1990.

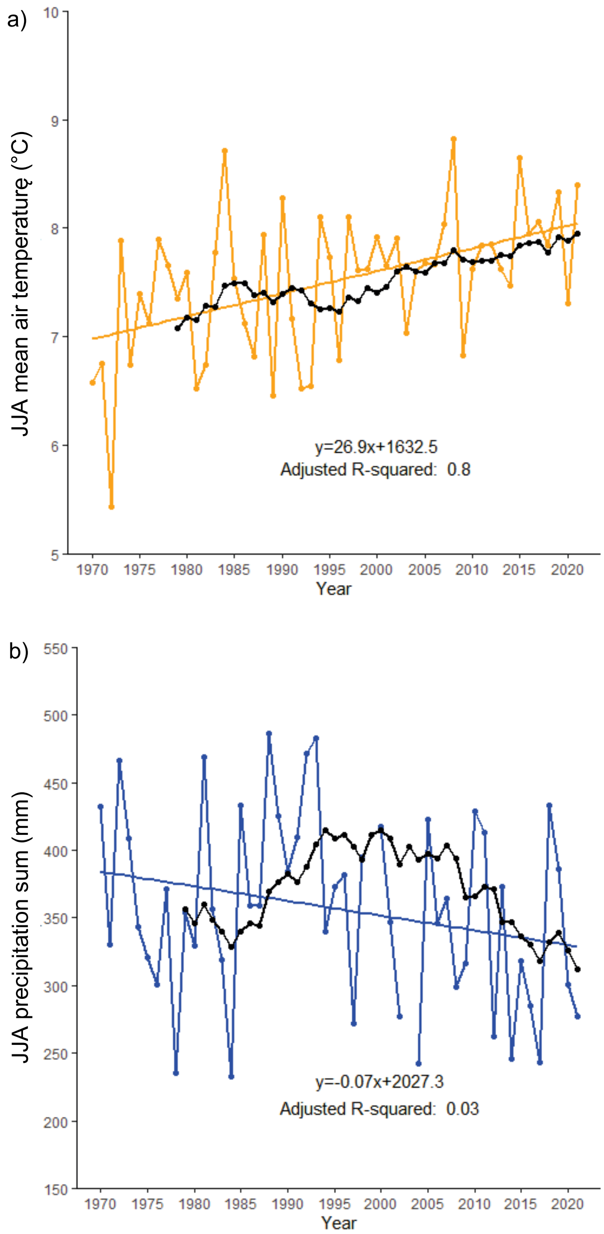

Fig. 2. Linear trends of: a) annual means of monthly (JJA) air temperatures; b) annual (JJA) precipitation sums for 1970–2020; JJA = June, July, August; the black line in both graphs represents a smoothed version of the data, reducing short-term fluctuations to highlight longer-term trends in temperature and precipitation; source: own study

Another lake where preventive work has been carried out is glacial-moraine lake No. 6 in the Kishi Almaty River basin, which is characterised by its rapid formation. According to KSAMP's exploration work in 1978, the lake's area was 5,200 m^2. By 2021, satellite images showed that the lake's area had decreased by 47%. The use of preventive measures to decrease the water levels in the lakes means that they are not reliable indicators of climate change in the study area. Preventive measures have also been implemented in two other mudflow hazard lakes in the Talgar and Esik basins. In 1978, KSAMP's preventive work showed that the area of Lake No. 8 in the Talgar basin was 18,900 m^2. By 2021, the lake's area had increased by 240%. Similarly, glacial-moraine lake No. 23, located in the Esik basin, has increased by 1,460% since 1978.

In summary, the preventive measures implemented by KSAMP have been successful in mitigating the potential hazards posed by several glacial-moraine lakes in the study area. However, the continued growth of some lakes, such as Lake No. 13-bis, highlights the need for ongoing monitoring and observation to ensure the safety of surrounding communities and infrastructure.

DISCUSSION

After conducting this study, it is important to examine the opinions of other scholars on this issue. The assessment and dynamics of the glacial flow of rivers on the Northern slope of Ile Alatau in the context of global warming were conducted by a group of scientists, including Chigrinets *et al.* (2020), who collected and analysed glacio-hydrometeorological data, such as glacier morphometry, air temperature, rainfall, and river runoff. By analysing the collected data, the researchers were able to assess the changes in glacial flow over time, particularly in the context of global warming. In addition to studying the dynamics of glacial runoff, the researchers proposed new dependencies and formulae.

The impact of future climate change and glaciers on river runoff in the Northern Tien Shan region was investigated by a group of scientists, including Shahgedanova *et al.* (2020). The research findings indicate that glaciers in the region are expected to undergo rapid retreat until the 2050s, followed by a stabilisation phase, except in the case of the HadGEM8.5 scenario, where retreat continues. Projections suggest a substantial reduction in glacier volume by 38–50% and a decrease in glacier area by 34–39%. The consequences of these changes in glacial dynamics are particularly significant for river discharge. Catchments with lower glacier coverage, ranging from 2–4%, are anticipated to experience a considerable decline in total river discharge during the months of July and August, with projections indicating a reduction of 20–37%. This decline in river discharge highlights the profound impact of glacier retreat on water resources in the affected regions (Skarbøvik *et al.*, 2010; Barandun *et al.*, 2021; Easa *et al.*, 2024). These findings underscore the urgent need for effective water resource management strategies to address the potential consequences of glacier retreat on hydrological regimes, water availability, and ecosystem dynamics in the Northern Tien Shan region.

Severskiy *et al.* (2016) observed that the highest rate of mass loss of glaciers is typical for the period from 1973 to 1991 and from 2005 to 2015, which contributed to the decrease in the surface of the glacier by an average of 0.38 m per year. Glacier activity is an indicator of the response to climate change because an increase in the average annual temperature over the past hundred years with an intensity of less than 1°C was enough to reduce the glaciation of the mountains of southeastern Kazakhstan by more than a third. Wang *et al.* (2019) revealed that an increase in temperature by +1 K reduced the proportion of snowfall by half, thereby affecting the accumulation of glacier mass and surface albedo. Changing glacier mass balance can influence the formation of glacial-moraine lakes in the Ile Alatau importantly, cause the formation of GLOFs of origin in the concerned territory due to the rise of their water levels. The research by Vanderwall *et al.* (2024) highlights that the retreat of glaciers, driven by climate change, results in significant alterations to the lake ecosystems, including changes in nutrient concentrations, water temperature, and the composition of aquatic communities.

To further investigate the state and temporal changes of glacial-moraine lakes in the northern slope of Ile Alatau, a comprehensive monitoring program should be implemented, involving remote sensing data, field surveys, and measurements. Climate and meteorological data should be analysed to understand the influence of temperature, precipitation patterns, and other climatic factors on lake dynamics. Hydrological models should be developed to simulate inflow and outflow dynamics, incorporating factors like glacier meltwater, precipitation, evaporation, and groundwater inputs to better understand lake behaviour and forecast future changes. Detailed geomorphic mapping of the lake basins and their surroundings using high-resolution satellite imagery and field surveys should be also performed. This can help identify landforms, sediment deposits, and drainage patterns associated with glacial-moraine lakes. Such expanded research would enhance the understanding of these dynamic systems and contribute to better management and mitigation strategies for the associated risks.

CONCLUSIONS

The findings revealed that glacial-moraine lakes were a manifestation of complex processes occurring at elevations ranging from 3000 to 3800 meters. These lakes are influenced by various factors such as hydrology, meteorology, geomorphology, and geology. It is noteworthy that glacial lake outburst floods pose a severe threat to Almaty City, which has a population of 2 million people. Therefore, understanding the formation conditions, temporal changes, and prospects of glacial-moraine lakes becomes crucial in mitigating the risks associated with hazardous exogenous processes.

Therefore, the knowledge acquired from this research can enhance the overall comprehension of glacial-moraine lake dynamics, the factors that impact their development, and the potential risks they present. This information can be used to enhance mitigation and adaptation strategies in other regions that are also dealing with comparable challenges.

ACKNOWLEDGMENTS

The authors gratefully acknowledge to RSE Kazhydromet for the provided meteorological data on the Mynzhylky meteorological station and the Ministry of Emergency Situations of the Republic of Kazakhstan for the results of bathymetric surveys conducting after the preventive measures.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Aizen, E.M. *et al.* (2016) "Abrupt and moderate climate changes in the mid-latitudes of Asia during the Holocene," *Journal of Glaciology*, 62(233), pp. 411–439. Available at: https://doi.org/10.1017/jog.2016.34.

Amin, M. *et al.* (2020) "Mapping and monitoring of glacier lake outburst floods using geospatial modelling approach for Darkut valley, Pakistan" *Meteorological Applications*, 27(1), e1877. Available at: https://doi.org/10.1002/met.1877.

Asanova, E. *et al.* (2023) "Morphometric characters of the whitefish ludoga (*Coregonus lavaretus ludoga*) in connection with the lake Issyk-Kul ecological and geographical conditions and its introduction," *E3S Web of Conferences*, 380, 01018. Available at: https://doi.org/10.1051/e3sconf/202338001018.

Barandun, M. *et al.* (2020) "The state and future of the cryosphere in Central Asia," *Water Security*, 11, 100072. Available at: https://doi.org/10.1016/j.wasec.2020.100072.

Barandun, M. *et al.* (2021) "Hot spots of glacier mass balance variability in Central Asia," *Geophysical Research Letters*, 48(11), e2020GL092084. Available at: https://doi.org/10.1029/2020GL092084

Barandun, M. and Pohl, E. (2023) "Central Asia's spatiotemporal glacier response ambiguity due to data inconsistencies and regional simplifications," *The Cryosphere Discussions*, 17(3), pp. 1343–1371. Available at: https://doi.org/10.5194/tc-17-1343-2023.

Baymoldayev, T.A. *et al.* (2018) "Prostranstvenno-vremennoy analiz raspredeleniya selevykh yavleniy i puti preduprezhdeniya i snizheniya ikh razrushitel'nykh vozdeystviy v gornykh i predgornykh rayonakh Kazakhstana [Spatial-temporal analysis of the mudflow phenomena distribution and ways of preventing and reducing their destructive effects in mountainous and foothill areas of Kazakhstan]," in S.S. Chernomorets and G.V. Gavardashvili (eds.) *Selevyye potoki: katastrofy, risk, prognoz, zashchita. Trudy 5-y Mezhdunarodnoy konferentsii [Debris flows: disasters, risk, forecast, protection. Proceedings of the 5th International Conference]*. Tbilisi, Georgia, 1–5 October 2018. Tbilisi: Publishing House "Universal", pp. 262–270.

Chigrinets, A.G. *et al.* (2020) "Evaluation and dynamics of the glacial runoff of the rivers of the Ile Alatau northern slope in the context of global warming" *International Journal of Engineering Research and Technology*, 13(3), pp. 419–426. Available at: https://dx.doi.org/10.37624/IJERT/13.3.2020.419-426.

Deng, M., Chen, N. and Liu, M. (2017) "Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo Valley, south-eastern Tibetan Plateau," *Natural Hazards and Earth System Sciences*, 17(3), pp. 345–356. Available at: https://doi.org/10.5194/nhess-17-345-2017.

Easa, H.K. *et al.* (2024) "Sustainability in irrigation practices through 5G optimization of water resources," in *Conference of Open Innovation Association, FRUCT*. Tampere: IEEE Computer Society, pp. 201–210. Available at: https://doi.org/10.23919/FRUCT61870.2024.10516407.

EOSDA (2021) *Normalized Difference Water Index (NDWI)*. EOS Data Analytics. Available at: https://eos.com/make-an-analysis/ndwi/ (Accessed: February 16, 2024).

Hanshaw, M.N. and Bookhagen, B. (2014) "Glacial areas, lake areas, and snow lines from 1975 to 2012: Status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru," *Cryosphere*, 8(2), pp. 359–376. Available at: https://doi.org/10.5194/tc-8-359-2014.

Linchenko, V. *et al.* (2022) "Zelena enerhetyka: problemy okhorony navkolyshn'oho seredovyshcha [Green energy: Problems of environmental protection]," *Ekolohichna bezpeka ta zbalansovane resursokorystuvannya [Ecological Safety and Balanced Use of Resources]*, 13(2), pp. 58–68. Available at: https://doi.org/10.31471/2415-3184-2022-2(26)-58-68.

Moldasheva, R. *et al.* (2023) "Method for controlling phytoplankton distribution in fresh open water," *International Journal of Environmental Studies*. Available at: https://doi.org/10.1080/00207233.2023.2249791.

Mussina, A.K., Abdullayeva, A.S. and Barandun, M. (2022) "The importance of conducting research methods to assess the state of glacial-moraine lakes," *News of the National Academy of Sciences of the Republic of Kazakhstan*, 6(456), pp. 147–155. Available at: https://doi.org/10.32014/2518-170X.245.

Mussina, A.K. *et al.* (2023) "Mountain resilience: A tool for mudflow risk management in the Ile Alatau mountains, Kazakhstan," *Mountain Research and Development*, 43(1), pp. 1–10. Available at: https://doi.org/10.1659/MRD-JOURNAL-D-22-00004.

Mussina, A.K. and Zhanabayeva, Zh.A. (2016) "GIS-technology in the management of mudflow risk," *Journal of Geography and Environmental Management*, 42(1), pp. 140–146.

Nematov, D.D. *et al.* (2023) "A detailed comparative analysis of the structural stability and electron-phonon properties of ZrO2: Mechanisms of water adsorption on t-ZrO2 (101) and t-YSZ (101) surfaces," *Nanomaterials*, 13(19), 2657. Available at: https://doi.org/10.3390/nano13192657.

Severskiy, I. *et al.* (2016) "Changes in glaciation of the Balkhash-Alakol basin, central Asia, over recent decades," *Annals of Glaciology*, 57(71), pp. 382–394. Available at: https://doi.org/10.3189/2016AoG71A575.

Shahgedanova, M. *et al.* (2020) "Emptying water towers? Impacts of future climate and glacier change on river discharge in the northern Tien Shan, Central Asia," *Water*, 12(3), 627. Available at: https://doi.org/10.3390/w12030627.

Skarbøvik, E. *et al.* (2010) "Harmonised monitoring of Lake Macro Prespa as a basis for integrated water resources management," *Irrigation and Drainage Systems*, 24(3–4), pp. 223–238. Available at: https://doi.org/10.1007/s10795-010-9099-1.

Tokmaganbetov, T.G. (2010) "Sovremennaya evolyutsiya lednikovo-morennykh ozer Zailiyskogo Alatau [Modern evolution of glacial-moraine lakes of the Ile Alatau]," *Nauka o Zemle*, 3, pp. 83–87. Available at: http://nblib.library.kz/elib/library.kz/journal/Tokmagambetov.pdf (Accessed: February 16, 2024).

Vanderwall, J.W. *et al.* (2024) "Mountain glaciers influence biogeochemical and ecological characteristics of high-elevation lakes across the northern Rocky Mountains, USA," *Limnology and Oceanography*, 69(1), pp. 37–52. Available at: https://doi.org/10.1002/lno.12434.

Wang, R. *et al.* (2019) "Spatial heterogeneity in glacier mass-balance sensitivity across high mountain Asia," *Water*, 11(4), 776. Available at: https://doi.org/10.3390/w11040776.