ықтимал өсуін көрсетеді, бұл болжамды бақылау қажеттілігін растайды. Нәтижелер апат қаупін азайту, болжамдардың дәлдігін арттыру және күрделі геологиялық жағдайларда пайдалану қауіпсіздігін арттыру үшін ACMS және геомеханикалық модельдеу құралдарын біріктіруді қолдайды.

Кілт сөздер: деформациялық процестер, тау-кен массивтері, автоматтандырылған бақылау-өлшеу жүйелері, мониторинг, тау-кен жұмыстарының қауіпсіздігі, деформацияны болжау, геомеханикалық модельдеу.

А.Т. Койшыгарин, М.Б. Бахыт, Ж.К.Мукалиев
Казахский национальный университет имени аль-Фараби, г. Алматы Казахстан,
aibek-11-89@mail.ru, m.bakhyt66@gmail.com, zh_gis@mail.ru*

СОВРЕМЕННЫЕ ПОДХОДЫ К МОНИТОРИНГУ И АНАЛИЗУ ДЕФОРМАЦИОННЫХ ПРОЦЕССОВ

Аннотация

В данной статье рассматриваются современные подходы к мониторингу и анализу деформационных процессов при разработке месторождений открытым способом с использованием автоматизированных контрольно-измерительных систем (АСУ ТП). В исследовании представлена концептуальная и практическая основа для интеграции геотехнических датчиков, геодезического мониторинга и конечно-элементного моделирования в единую систему поддержки принятия решений. Для моделирования напряженно-деформированного состояния в условиях динамического нагружения используется гипотетический пример открытой шахты в Восточном Казахстане. Подробно описаны параметры моделирования и исходные данные, включая допущения о механических свойствах горных пород, граничных условиях и внешних факторах, таких как осадки и земляные работы. Результаты показывают потенциальное увеличение деформации в критических зонах на 25-30% в течение 5 лет, что подтверждает необходимость прогнозного мониторинга. Полученные результаты подтверждают необходимость интеграции ACMS и инструментов геомеханического моделирования для снижения рисков аварий, повышения точности прогнозов и повышения безопасности эксплуатации в сложных геологических условиях.

Ключевые слова: деформационные процессы, горные массивы, автоматизированные контрольно-измерительные системы, мониторинг, безопасность горных работ, прогнозирование деформаций, геомеханическое моделирование.

IRSTI 70.03.05, 89.57.35 **DOI** https://doi.org/10.37884/2-2025/47

A.A. Merekeyev [1,2], G.M. Iskaliyeva[1], A.B. Gaipova [1], A.A Amangeldi[1], MS. Sagat[1,2], N.K. Sydyk[1]*

[1]*«Ionosphere institute» LLP, Almaty, Republic of Kazakhstan, merekeev.aibek@gmail.com, igm.ionos@gmail.com*, arailym.geo@gmail.com, amangeldialimma@gmail.com, nurmahambet.s@gmail.com*
[2] *Al-Farabi Kazakh National University, Almaty, Kazakhstan, sagat.madina1@gmail.com*

METHODS OF MONITORING MORAINE LAKES IN CENTRAL ASIA UNDER CLIMATE CHANGE

Abstract

This article presents a comprehensive analysis of modern research methods for high-mountain glacial lakes in Central Asia under global warming conditions. Special attention is given to moraine lakes, which form due to glacier retreat and pose a significant hazard because of potential outburst events and associated debris flows. Key trends in glacial lake changes, their dynamic behavior, formation mechanisms, and current monitoring and risk assessment strategies are thoroughly examined.

Particular focus is placed on the use of remote sensing data (Landsat, Sentinel, Terra), which, in combination with geographic information systems (GIS), enables real-time monitoring of lake conditions, spatial and temporal dynamics, and risk assessment. The article also discusses approaches to estimating lake water volume using spectral indices (MNDWI, NDVI) and digital elevation models (DEMs).

The study summarizes research experience across major mountain systems, including the Himalayas, Pamirs, and Tien Shan. The advantages of satellite-based monitoring – such as efficiency and the ability to survey inaccessible regions – are highlighted alongside its limitations, including spatial resolution constraints, seasonal variability, and the need for ground-truth validation. The importance of integrating remote sensing with field-based observations for more accurate outburst risk assessment is emphasized.

The article presents specific case studies, including an inventory of 143 glacial lakes in the Shilik River basin and an analysis of the 2015 Bezymyannoye Lake outburst, which caused significant damage. The results have important practical implications for the development of early warning systems and risk management in mountainous areas. Given rising temperatures and accelerated glacier melt, the need for enhanced and integrated monitoring of glacial lakes is becoming increasingly urgent.

Keywords: *Moraine lakes, remote sensing, GIS, climate change, breakthrough hazard, debris flows, Central Asia, glaciers*

Introduction

Experience of studying high-mountain lakes.

Global warming is causing significant changes in the mountain ecosystems of Central Asia. Glaciers, key indicators of climate change, are shrinking, following the global trend. In Ile-Alatau, their area is shrinking by an average of 1 per cent per year, making the region one of the most vulnerable to glacier melt.

Rising temperatures increase the risks of floods and mudflows, contributing to the formation of moraine lakes. These reservoirs are formed by glacial deposits that retain water, but can collapse under the influence of precipitation or seismic activity, causing catastrophic mudslides.

Almaty, which is in a high-risk zone, is regularly exposed to mudslides. Over the past 160 years, there have been six major mudslides resulting in destruction. One example was the breakthrough of the Bezymyannoye moraine lake in 2015, the breakthrough of the moraine lake caused the release of 40,000 m^3 of water, flooding neighbourhoods along the Kargalinka River, but human casualties were avoided. Recent events, such as the mudflows in Almaty in July 2023, caused by abnormal heat and increased precipitation, emphasise the importance of studying the condition of glaciers and moraine lakes. Precipitation levels in the mountains ranged from 7 to 72 millimetres, which significantly increases the likelihood of mudflows.

In view of the above, the study and mapping of moraine lakes is relevant for risk assessment and development of preventive measures, which contributes to the protection of the environment and safety of the population of Almaty region. Modern technologies, including satellite and meteorological monitoring, allow studying the formation of moraine lakes, their parameters and the influence of climatic factors. Aerospace monitoring provides rapid tracking of changes, improving risk management. Comprehensive data analysis helps to identify patterns in the glacier-marine-lake system, predict threats and develop effective protective measures.

Use of remote sensing and GIS data

In recent decades, remote sensing (RS) data in conjunction with geographic information systems (GIS) have become an important tool for studying moraine lakes, especially in the face of ongoing climate change. These techniques provide up-to-date, objective, rapidly georeferenced information that is critical for effective response to emergencies such as glacial lake outbursts. This is particularly important to ensure rapid response to critical situations, including lake outbursts and subsequent debris flows.

Remote sensing techniques allow analysing the dynamics of water bodies, calculating their depth and volume, which is particularly important for inaccessible moraine lakes [1] and facilitating the study of changes in both the area and depth of aquatic ecosystems, as well as estimating their volumetric capacity, which is a critical aspect for remote mountainous areas [1]. Optical satellite images from platforms such as Landsat and Terra are commonly used to delineate lake boundaries and conduct extensive inventories. Spectral indices (e.g., MNDWI) and water masking algorithms are used to accurately detect water bodies, allowing pixels corresponding to water surfaces to be precisely identified. This is important given that water bodies have low reflectance, making them difficult to detect compared to other natural elements [2].

Since 1950, more than 40 cases of moraine lake outbursts caused by the destruction of glacial dams have been recorded in South-East Kazakhstan. The continuing retreat of glaciers leads to an increase in the number of such lakes, which increases the risks of catastrophic outbursts. In this regard, studies aimed at estimating their water volumes, peak discharge [1] and mudflow activity, taking into account the world experience, remain relevant.

Satellite monitoring facilitates documentation of the stages of moraine lake development and their peak formation, which is extremely important for predicting debris flow phenomena. For example, remote sensing methods have been effectively used to catalogue glacial lakes in the Zhetysu-Alatau Range [3], estimating their area, number and morphological characteristics.

Studies in Patagonia and the Baikal region illustrate the usefulness of aerospace data for debris flow risk assessment and flood modelling. In the Pamirs, remote sensing technologies have been used to monitor glacier dynamics and detect newly formed high mountain lakes. Optical satellite images were used to determine the current extent of glaciers and water bodies, while radar images (SAR) played an important role in calculating the height of the fern line and modelling the behaviour of glacial masses. Integration of SRTM data with interferometric techniques has improved the topography of moraine dams, which is crucial for assessing their stability.

In the Himalayas, remote sensing techniques have recorded a 2.7% reduction in glaciers between 1997 and 2007, as well as a decrease in snow cover. The assessment of Lonak Lake showed an increase due to glacier degradation. Satellite monitoring has also quantified changes in glacier mass balance and growth in the volume of glacial lakes, which emphasises the need for continuous monitoring of these phenomena.

The growth of moraine lakes due to glacier ablation is relevant for Almaty. In the context of global warming, their condition, especially in high-mountainous areas, needs to be constantly monitored using space technologies [4]. In the Shilik River basin, 143 moraine lakes with a total area of 5.71 km² have been identified [5]. Their inventory was carried out on the basis of satellite image interpretation and GIS-analysis. The key parameter is the change in the volume of lakes, which determines their bursting hazard.

Assessment of reserve volume of lakes includes water level analysis, bathymetric maps and remote sensing methods. In researchers applied satellite data to determine the reserve volume of breach prone lakes by considering the area, length, dam height and water level. The study applied the reserve volume determination method based on the parameters of lake dams and water level. Radar images (SAR) were used for modelling the boundaries of water bodies using the transformation method [6], which allows to specify the waterline position and dynamics of water masses.

In addition, snow cover assessment is an important component of hydrological regime monitoring. According to NOAA/AVHRR, the application of the normalised differential snow index (NDSI) showed that the timing of snow loss in Kazakhstan has increased by one week over the last three decades. These results are confirmed by meteorological measurements carried out by Kazgidromet.

Thus, the application of remote sensing methods and geoinformation systems for monitoring moraine lakes in Central Asia represents a promising direction to improve the understanding of processes related to climate change and its impact on ecosystems in the region. These approaches can significantly improve the efficiency of risk management and ensure the safety of the local population.

The use of remote sensing and GIS technologies has proven highly effective for monitoring moraine lakes in remote mountainous regions of Central Asia. These methods provide essential data for assessing lake dynamics, predicting outburst risks, and supporting early warning systems amid ongoing climate change. Integration of optical, radar, and topographic satellite data enhances the accuracy of lake volume estimations and contributes to disaster risk reduction strategies.

Experience in determining the volume of water in glacial lakes

The volume of moraine lakes is a key indicator of their bursting hazard. The potential reserve volume, defined as the difference between the maximum and actual volumes, is an important criterion for risk assessment. Water volume estimation is based on water level change data, bathymetric and topographic maps, but these are costly to obtain.

In the study, remote sensing methods are applied to determine the reserve volume of high-mountain lakes. The following parameters were used: area, length, height and water level at the dam. Space images allowed digitising the contours of lakes and constructing a vertical relief profile using DEM. The accuracy of calculations increases when morphometric and genetic characteristics of lakes are considered. The accuracy of calculations is increased by considering morphometric and genetic characteristics of lakes.

The accuracy of water level measurement is critical for water resources management. In [14], water level fluctuations in narrow bodies of water were analysed using SAR data (TerraSAR, COSMO-SkyMed). Waterline and water body boundary determination was performed using the Hough transform algorithm. In the absence of a detailed DEM, a simplified method with a constant slope was used.

Multispectral imagery, water surface delineation methodologies and the construction of physical models of aquatic systems have also been used to estimate water volume in glacial lakes. However, without in situ measurements of water levels, accurate estimation of underwater topography is difficult, making it difficult to apply the developed methodologies to lakes where measurement data are not available.

The application of remote sensing (RS) techniques plays a key role in the study of water resources, especially in high altitude lake environments. In particular, lake shorelines are determined using normalised water difference index (MNDWI), whereas NDVI and NDWI show comparatively less efficiency. Estimation of reservoir depth and volume is based on previously developed methodologies; however, the authors emphasise the need for ground-based measurements to validate remotely sensed data, especially when assessing potential stocking volumes as indicators of flood risk.

Remote data have also been used to estimate water levels in Lake Pukod (India) using SWOT [7] and on the Tibetan plateau where Landsat altimetry eliminated systematic errors. In a study Shanlong Lu, the water volume in Lake Baiyandian was calculated based on multispectral images, water surface boundary delineation and construction of a physical model of the water body.

It is important to note that during the calculations without field measurements of water level it is impossible to reliably estimate the underwater topography, which limits the application of the developed methods in unmeasured lakes. For example, in a case study of Longbasaba lake from Xiaojun Y, the volume of the potentially dangerous Longbasaba Lake in the Himalayas was estimated, which is of great importance for predicting possible floods.

Thus, the peculiarities of multi-year variability of the regime of high-altitude reservoirs can be revealed using remote sensing and GIS technologies. Remote sensing techniques, such as the use of normalised difference water index, are actively used to monitor and assess the condition of moraine lakes. In the context of climate change, it is also important to consider geographic information systems (GIS) and remote sensing techniques to assess the risks associated with glacial lake outbursts.

Remote sensing (RS) techniques play a key role in the study of water resources including high altitude lakes. In a study Svirepov S., using Mongun-Taiga massif (Altai) as an example, the lake shoreline was delineated using MNDWI, whereas NDVI and NDWI were less effective. Estimation of the depth and volume of water bodies was based on previously developed methods [8], but the authors emphasise the need for ground-based measurements to verify remote sensing data, especially when calculating the potential reserve volume as an indicator of breakthrough hazard.

Paper [8] describes the methodology for estimating this parameter using Terra satellite radiometric data and DEMs (SRTM 4.1, ASTER DEM G2). The analyses of lake morphometry were performed in GLOBAL MAPPER and ArcGIS and included calculation of area, length, absolute height of the water's edge and dam. The depth of the lake, according to the findings, is maximum near its centre and is approximated by a semi-ellipse.

A study by Pamir presents a methodology for calculating the parameters of glacial lake outbursts, including area, volume and maximum outburst discharge. Empirical formulae relating volume to area and depth were obtained for 141 lakes. And in northern Pakistan, glacial lake outburst scenarios were analysed considering extreme floods using GIS, remote sensing and ground data [9].

The area of lakes was determined using multispectral images, and the volume was calculated using the TIN model, considering field measurements of water level. The historical stock dynamics of the lakes since 1984 was studied in [10] using Landsat, Sentinel-2, altimetry (Topex/Poseidon, Jason-1/2/3, Sentinel-3, ICESat-2) and the HydroLAKES project. The HydroLAKES geostatistical approach demonstrated more accurate estimates of water volumes compared to GLOBathy, and data processing algorithms compensated for gaps caused by cloud cover.

To increase the frequency of water volume measurements, a data gap-filling algorithm was implemented to eliminate omissions caused by atmospheric events. The HydroLAKES geostatistical method showed more accurate results compared to GLOBathy and was used to assess the dynamics of water reserves [10].

In China, a new approach to estimation of water reserves of high-mountain lakes considering geomorphology has been proposed. In work in the central Himalayas [11], a model was developed to classify moraine lakes (contact and non-contact with glaciers) using the threshold R - the ratio of maximum lake width to length. This made it possible to typify lakes and improve the estimation of their volumes.

Chinese scientists have also developed a method to scale the volume of moraine dammed lakes in the Himalayas based on bathymetry and topographic data. For water bodies without direct measurements, the volume was estimated by interpolation using key parameters (area, length, width). The methodology based on the Normalised Difference Water Index (NDWI) allowed the lakes to be divided according to their contact with the glacier and simplified the size calculation. However, the volume refinement is associated with the uncertainty of lake boundaries, which was considered in the models [12].

When constructing empirical area-volume or depth-volume relationships, the question of choosing reliable parameters remains open. A study by Muñoz et al. [13] found that the mean depth parameter gives more accurate estimates of volume, similar findings are presented by Kapitsa et al. [14].

The complex morphological characteristics of glacial lakes make it difficult to establish a direct relationship between their parameters and water volume. The empirical equations used are not always effective for supraglacial and relief complex lakes. The presence of ice under the bottom may lead to overestimation of calculated depth and volume values.

Glacial lake outbursts pose a significant threat, which requires their prediction and comprehensive prevention measures. Sub-pond lakes are formed in areas of glacial retreat, and when they exceed critical depths they can expand, increasing flood risk. In the Himalayas, flood risk assessments, including prediction of lake growth, are being carried out.

A method for estimating the depth and volume of glacial lakes has been developed in the Indian Himalayas that takes into account glacier velocity, slope and laminar ice flow [30]. Using subpixel correlation of Landsat panchromatic images (15 m) and a laminar flow model, ice thickness distribution and bed topography were estimated. The volume of South Lhonak Lake calculated by this method was confirmed by echosounder measurements with an error of about 9%.

Methods for estimating lake volume make extensive use of optical and microwave satellite imagery. Approaches based on topographic data, including the triangulated irregular network (TIN) method, are considered to be the most accurate. However, in inaccessible areas, the development of remote sensing methods that take into account the dynamics of water volumes is relevant.

In the Tien Shan, the lake area was analysed based on Landsat (30 m), Keyhole data (1.8 m) and the ERA5-Land and TerraClimate climate series. Evaporation was found to be a key factor in the shrinking of lowland lakes, while proglacial lakes are expanding due to warming. A Bayesian BE-GLAV model considering the bottom shape and lake parameters was proposed for proglacial lakes in Asia [2]. Comparison with 10 models showed that Zhang's scaling models (minimum error 0.1%) and Kapitsa's model (error <10%)) gave the best results [14]. BE-GLAV exhibits errors ranging from 1-61% and allows for depth estimation along the centreline of the lake, making it an alternative to scaling methods in hard-to-reach regions.

Based on remote sensing of lake area, an empirical relationship for volume prediction has been developed based on the approaches of O'Connor (2001), Hooggel (2002) and Evans (1986). However, the versatility of these models is limited by the complex morphology of glacial lakes, which requires adaptation to local conditions.

In [15], glacial lakes were investigated in the context of climate change and outburst risk. Lakes were classified according to their position relative to glaciers and their parameters were estimated using Sentinel-2, Landsat 5 images and GIS methods. Mapping was performed using MNDWI and NDWI water indices.

Accurate estimation of water volume in moraine lakes is essential for assessing the risk of glacial lake outbursts. Remote sensing technologies, including multispectral and radar imagery combined with DEM data and empirical models, provide a practical alternative to field measurements, especially in hard-to-reach mountainous areas. However, in situ data remain crucial for improving the reliability of volume assessments due to the complex morphometry of glacial lakes.

Integrated Glacial Lake Hazards and Risk Assessment

Glacial lakes are key sites in the context of climate change and natural risks. In the Himalayas and Tibet, the threat of lake outbursts and their consequences have been investigated.

In the Indian Himalayas, risks for lakes >0,05 km² were assessed by modelling moraine, avalanche and rockfall stability using Landsat 5 and Aster data. Depth and volume were calculated using the Cook and Quincy equations, and inundation probabilities were calculated using the Monte Carlo method (MC-LCP).

In southeastern Tibet, GLOF incidents threatening infrastructure are increasing due to glacier shrinkage. Combining GIS, SAR and InSAR helps to identify landform deformations and potential landslides.

In the Pamirs, Landsat 7 and Terra satellite images are used to analyse the albedo of glaciers, which allows remote monitoring of their condition and impact on moraine lakes.

The impact of permafrost thawing on glacial lake growth and GLOF risk was modelled in the Northern Tien Shan. Lakes No. 23 and No. 122 were found to be the most dangerous [15]. However, the methodology is limited to the assessment of dam stability and material composition.

In Cordillera Blanca, qualitative, semi-quantitative and quantitative risk assessment methods were tested for six moraine-dam lakes, each with different advantages depending on the parameters of the analysis.

A new model for assessing the risk of glacial lake outburst in the Rongxer watershed (Himalaya, southern Tibet) is proposed [17]. GIS, hydrological models and Landsat TM/ETM/OLI (30 m) data for five periods were used. Risk assessment included analyses of dam slope, catchment area and lake typology (supraglacial, glacial, unconnected, non-glacial). ALOS DEM satellite data (12.5 m) allowed to determine the height of the lakes and to model the consequences of a possible breach on downstream areas.

A classification system including three criteria was used to select potentially dangerous glacial lakes:

– Lakes overlapped by end moraine, which may lead to dam failure;

– Lakes in contact with glaciers or less than 500 m from the upper glacier and fed by glacial meltwater;

– Lakes larger than 0.1 square kilometres.

The GLOF risk assessment was conducted in three steps: glacial lake hazard assessment, impact assessment and risk assessment. The expert analytic hierarchy process (AHP) was used to determine the weighting of the different hazard indicators, and each parameter was categorised using the geometric interval method. The resulting numerical values were categorised into five risk levels: very low (0.25-0.40), low (0.40-0.55), medium (0.55-0.70), high (0.70-0.85) and very high (>0.85) [16].

An inventory of glacial lakes in the western Himalayas [18] was conducted using Sentinel-2 data. The breakout risk assessment used an analytical hierarchical process, water indices and manual editing. The main risk factors were lake area and expansion rate, distance from the glacier, and slope between them.

Lakes were categorised by risk level: low (<0,06 km²), medium (0,06-0,1 km²), высокий (>0.1 km²). Expansion rate was estimated from satellite images (>100% – high, 50-100% – moderate, <50% – low). Glacier contact increases the risk of GLOF: contacted – high risk, <500 м – moderate, >500 m – low risk.

In the Shek basin (upper Indus) [19], the GLOF risk was comprehensively assessed using high-resolution satellite imagery, ALOS/PALSAR and CRU data. The sensitivity assessment considered lake, dam and glacier feeding parameters.

Climate change is increasing the risk of glacial lake outbursts, threatening populations in the Karakoram Himalaya and Hindu Kush. The study determined the depth, volume, pressure and height of potentially dangerous lakes using spectral indices.

An inverse relationship between lake volume and glacier surge velocity was found: surge velocity controls water depth and volume. Geometric estimation is reliable in the absence of field data. A critical GLOF threshold is identified: depth >0.60 m and pressure >510 kPa.

Remote sensing techniques and analytical processes help to analyse risks. Regular monitoring is necessary to prevent catastrophic consequences. Climate change is transforming glacial ecosystems, changing the geomorphology of high mountain regions. The increasing number of glacial lakes, especially in the Himalayas and Central Asia, requires comprehensive monitoring and analysis of GLOF (glacial lake hydraulic outburst) risks [7,40]. Effective GLOF risk management requires not only scientific research, but also cooperation between government agencies, local communities and scientific organizations. The development of adaptation strategies based on monitoring data and traditional knowledge will minimize impacts on the population living near glacial lakes [14].

Remote sensing and GIS methods allow to effectively analyses the morphometric characteristics of lakes (area, volume, depth, shoreline shape) and assess their stability. Deep lakes with high water pressure on the dams are at increased risk of breach. It is important to note that even relatively small changes in the morphology of a lake can significantly affect its stability, emphasizing the need for multi-level and multi-criteria risk assessment methods.

In addition to morphometric characteristics, climatic factors also play a crucial role in glacial lake dynamics. Studies show that increasing temperatures and decreasing precipitation accelerate glacier melt, contributing to an increase in lake area and volume. This emphasises the need to integrate climate models with geomorphological studies to better predict future changes.

Further research should focus on the comprehensive integration of different risk assessment methods to develop effective GLOF prevention and mitigation measures. In the context of ongoing climate change, regular monitoring of glacial lakes becomes a key element in ensuring the safety and sustainable development of mountain regions.

Research shows that the increasing number of glacial lakes and their potential threats, such as dam breaches, require a comprehensive approach to risk assessment, including the use of remote sensing and geographic information systems. Effective management of GLOF risks necessitates collaboration between scientific organizations, local communities, and government agencies to develop adaptation strategies and minimize impacts on the population.

Discussion and Results

Global climate change, including an imbalance between precipitation and potential evaporation, has favoured glacier retreat and the formation of many moraine-podded glacial lakes over the last century. These lakes have become the subject of intense scientific study in mountainous regions of the world. The first references to glacial lakes in the Zailiyskiy Alatau date back to the beginning of the 20th century [5]. Breakthroughs of these lakes in the past caused devastating floods and mudflows, causing serious damage to both people and infrastructure. Although the number of outbursts has decreased since the early 21st century, the continued retreat of glaciers at high altitudes is creating new lakes, which, combined with their high potential energy, makes the risks of future outbursts increasingly urgent.

Studies in the Zailiyskiy Alatau have attracted the attention of many scientists [1,3, 5,14]. With the advent of new remote sensing technologies, artificial intelligence and specialised software solutions, the development of methods for monitoring and modelling of glacial lakes has become more effective. The use of multi-temporal Landsat space images makes it possible to track both the early stages of formation and the stages of maximum development of lakes, which may pose a threat to the formation of debris flows.

Classical remote sensing and geoinformation technologies have proven useful for monitoring glacial lakes. However, there are a number of limitations that need to be considered:

1. Spatial resolution. Many high-altitude lakes are small and located in complex terrain, requiring very high-resolution imagery for accurate interpretation.

2. Cloud cover. Frequent clouds in mountainous regions limit the availability of high-quality cloud-free imagery, which is critical for lake mapping.

3. Seasonal variations. High-altitude lakes are subject to significant seasonal variations such as freezing and thawing, making data interpretation difficult.

Using altimetry provides information on elevation and water level dynamics, but the technology also faces certain challenges:

1. Accuracy. Detecting small changes in water level requires highly accurate data, which can be difficult in complex topography.

2. Temporal resolution. The limited revisit time of traditional altimetry missions can impact the frequency of measurements.

Artificial intelligence and machine learning systems are becoming increasingly common for automated lake mapping. However, there are challenges:

1. Training data. AI models require large amounts of labeled data, which may not be available for remote high-altitude lakes.

2. Complex terrain. Varied mountain topography can complicate the algorithms' work, reducing classification accuracy.

Unmanned aerial vehicles (UAVs) provide high spatial resolution and flexibility in data collection, but they also have their limitations:

1. Operational restrictions. Weather conditions and regulations may limit the use of UAVs, especially in remote and high-altitude areas.

2. Data processing. Processing large amounts of data is computationally intensive and can be time-consuming.

Determining the water volume of moraine-dammed or glacial lakes is critical to understanding their hydrological dynamics, potential hazards, and response to climate change. In recent decades, researchers have used both direct and remote sensing techniques to estimate lake volumes.

Direct bathymetric surveys using echosounder or sonar equipment provide accurate depth measurements, which is an advantage of this method. However, it is expensive and time-consuming, especially for large or remote lakes, and is limited in spatial coverage.

Geographic information system (GIS)-based methods use digital elevation models to model the lake basin and calculate volume based on water surface area. This method is cost-effective, but its accuracy depends on the quality of the data, and it assumes a constant lake shape, which may not always be the case.

Satellite altimetry allows tracking changes in water surface elevation, which is useful for trend analysis. However, this method also has limitations related to spatial resolution and the need for ground truthing.

The use of modern remote sensing (RS) and geographic information systems (GIS) plays a critical role in monitoring the condition of moraine lakes, especially in high-mountain areas. Each method has its own advantages and disadvantages, which highlights the need to integrate data and methods to improve the accuracy of monitoring and managing the condition of high-mountain lakes.

The importance of continuing research in this area lies in the need for sustainable water management and minimization of environmental risks. Modern RS methods in combination with traditional approaches significantly improve the accuracy of assessing the volumes and outburst hazard of moraine lakes. This, in turn, is key to effective water management and the prevention of potential natural disasters.

Thus, the use of RS technologies not only expands the possibilities for assessing the condition of high-mountain lakes, but also improves the monitoring of their potential hazard. This highlights the importance of integrating modern technologies into water resources management processes to prevent negative impacts associated with changes in lake ecosystems.

Gratitude: This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21882365).

References

1. Medeu, A. R., Popov, N. V., Blagovechshenskiy, V. P., Askarova, M. A., Medeu, A. A., Ranova, S. U., Kamalbekova A., Bolch, T. Moraine-dammed glacial lakes and threat of glacial debris flows in South-East Kazakhstan //Earth-Science Reviews. – 2022. – T. 229. – P. 103999.
2. Gantayat P., Sattar, A., Haritashya, U. K., Watson, C. S., & Kargel, J. S. (2024). Bayesian Approach to Estimate Proglacial Lake Volume (BE-GLAV) //Earth and Space Science. – 2024. – T. 11. – №. 6. – C. e2024EA003542.
3. Kaiheng Hu, Xiaopeng Zhang, Manish Raj Gouli, Shuang Liu, Yong Nie. Retrospective analysis and hazard assessment of Gega glacial lake in the eastern Himalayan syntaxis //Natural Hazards Research. – 2022. – T. 2. – №. 4. – P. 331-342.
4. Wang X, Xiaoyu Guo, Chengde Yang, Qionghuan Liu, Junfeng Wei, Yong Zhang, Shi-yin Liu, Yanlin Zhang, Zong-li Jiang, Zhiguang Tang. Glacial lake inventory of high-mountain Asia in 1990 and 2018 derived from Landsat images //Earth System Science Data. – 2020. – T. 12. – №. 3. – P. 2169-2182.
5. Dildabekova S. N., Isanova G. T., Raimbekova Z. T., Musina A. K., Kasenov M. K. Inventory of Glacier-Moraine Lakes in the Shilik River Basin and Analysis of Their Spatial Distribution //Journal of Geography & Environmental Management. – 2022. – T. 65. – №. 2.
6. Lee Y. K., Hong S. H., Kim S. W. Monitoring of water level change in a dam from high-resolution sar data //Remote Sensing. – 2021. – T. 13. – №. 18. – P. 3641
7. Akhilesh S. Nair, Nitish Kumar, J. Indu, B. Vivek. Monitoring lake levels from space: preliminary analysis with SWOT //Frontiers in Water. – 2021. – T. 3. – P. 717852.
8. Shugar D., Burr A., HaritashyaU.K., Kargel J., WatsonC.S., KennedyM.C., Bevington A.R., Betts R.A., Harrison S., Strattman K. Rapid worldwide growth of glacial lakes since 1990 //Nature climate change. – 2020. – T. 10. – №. 10. – P. 939-945.
9. Amin M., Bano D., Hassan Sh., Goheer M., Khan A., Khan M., Hina S. Mapping and monitoring of glacier lake outburst floods using geospatial modelling approach for Darkut valley, Pakistan //Meteorological Applications. – 2020. – T. 27. – №. 1. – P. e1877.
10. Jiawei Hou, Albert I.J.M. Van Dijk, Luigi J. Renzullo, Pablo R. Larraondo. GloLakes: a database of global lake water storage dynamics from 1984 to present derived using laser and radar altimetry and optical remote sensing //Earth System Science Data Discussions. – 2022. – T. 2022. – P. 1-20.
11. Miaomiao Qi, Shiyin Liu, Yongpeng Gao, Fuming Xie, Georg Veh, Letian Xiao, Jinlong Jing, Yu Zhu, Kunpeng Wu. A mathematical model to improve water storage of glacial lakes

prediction towards addressing glacial lake outburst floods //Hydrology and Earth System Sciences Discussions. – 2024. – T. 2024. – P. 1-28.

12. Miaomiao Qi, Shiyin Liu, Kunpeng Wu, Yu Zhu, Fuming Xie, Huian Jin, Yongpeng Gao, Xiaojun Yao. Improving the accuracy of glacial lake volume estimation: A case study in the Poiqu basin, central Himalayas //Journal of Hydrology. – 2022. – T. 610. – P. 127973.

13. R. Muñoz, Ch. Huggel, H. Frey, A. Cochachin, W. Haeberli. Glacial lake depth and volume estimation based on a large bathymetric dataset from the Cordillera Blanca, Peru //Earth surface processes and landforms. – 2020. – T. 45. – №. 7. – P. 1510-1527.

14. V. Kapitsa, M. Shahgedanova, N. Kasatkin , I. Severskiy, M. Kasenov, A. Yegorov and M. Tatkova. Bathymetries of proglacial lakes: a new data set from the northern Tien Shan, Kazakhstan //Frontiers in Earth Science. – 2023. – T. 11. – P. 1192719.

15. Sarwar M., Mahmood S. Exploring potential glacial lakes using geo-spatial techniques in Eastern Hindu Kush Region, Pakistan //Natural Hazards Research. – 2024. – T. 4. – №. 1. – P. 56-61.

16. Zhang S., Nie Y., Zhang H. Glacial Lake Changes and Risk Assessment in Rongxer Watershed of China–Nepal Economic Corridor //Remote Sensing. – 2024. – T. 16. – №. 4. – P. 725.

17. Suresh Das, Soumik Das, Sandip Tanu Mandal, Milap C Sharma. Inventory and GLOF susceptibility of glacial lakes in Chenab basin, Western Himalaya //Geomatics, Natural Hazards and Risk. – 2024. – T. 15. – №. 1. – P. 2356216.

18. Abid Farooq Rather, Rayees Ahmed, Changhyun Jun, Sayed M. Bateni, Pervez Ahmed, Riyaz Ahmad Mir. Understanding glacial lake evolution and the associated GLOF hazard in the Shyok catchment of the Upper Indus Basin using geospatial techniques //Natural Hazards Review. – 2024. – T. 25. – №. 3. – P. 04024014.

19. Nazir Ahmed Bazai, Paul A. Carling, Peng Cui, Hao Wang, Zhang Guotao, Liu Dingzhu, Javed Hassan. Predicting the risk of glacial lake outburst floods in Karakorum //EGUsphere. – 2024. – T. 2024. – P. 1-22.

А.А. Мерекеев[1,2], Г.М. Искалиева[1*],А.Б. Гаипова[1], Ә.А. Амандельді[1], М.С. Сағат[1,2], Н.Қ. Сыдық[1]

[1] *«Ионосфера институты» ЖШС, Алматы қ., Қазақстан Республикасы,* *merekeev.aibek@gmail.com, igm.ionos@gmail.com*, arailym.geo@gmail.com, amangeldialimma@gmail.com, nurmahambet.s@gmail.com*

[2] *әл-Фараби атындағы Қазақ ұлттық университеті, , Алматы қ Қазақстан Республикасы, sagat.madina1@gmail.com*

ОРТАЛЫҚ АЗИЯДАҒЫ МОРЕНАЛЫҚ КӨЛДЕРДІ КЛИМАТТЫҢ ӨЗГЕРУІ ЖАҒДАЙЫНДА МОНИТОРИНГТЕУ ӘДІСТЕРІ

Аңдатпа

Мақалада жаһандық жылыну жағдайында Орталық Азиядағы биік таулы мұздық көлдерді зерттеудің заманауи әдістеріне жан-жақты талдау берілген. Мұздықтардың шегінуі нәтижесінде пайда болатын және жойқын жарылыстар мен соған байланысты қауіпті сел тасқындарының болуы мүмкін болғандықтан айтарлықтай қауіп төндіретін мореналық көлдерге баса назар аударылды. Мұздық көлдерінің өзгеруінің маңызды тенденциялары, олардың динамикалық қасиеттері мен қалыптасу механизмдері, сондай-ақ мониторинг пен тәуекелді бағалаудың басым стратегиялары мұқият талданды.

Географиялық ақпараттық жүйелермен ұштастыра отырып, мұздық көлдердің жай-күйін нақты уақыт режимінде бағалауға, олардың кеңістіктік және уақыттық динамикасын бақылауға және ықтимал ошақтармен байланысты тәуекелдерді бағалауға мүмкіндік беретін қашықтықтан зондтау деректер жинақтарын (Landsat, Sentinel, Terra) пайдалануға айтарлықтай көңіл бөлінді. Спектрлік индекстер (MNDWI, NDVI) және сандық биіктік үлгілері арқылы көлдердің су көлемін есептеу әдістері қарастырылған.

Мақалада Гималай, Памир және Тянь-Шаньды қоса алғанда, әртүрлі тау жүйелеріндегі мұздық көлдерді зерттеу тәжірибесі жинақталған. Спутниктік мониторингтің жоғары тиімділік және жету қиын аймақтарды қамту мүмкіндігі сияқты артықшылықтары, сондай-ақ оның деректердің кеңістіктік рұқсатымен байланысты шектеулері, маусымдық өзгерістер және оларды валидациялау қажеттілігі талданады. Көлдің жарылуымен байланысты тәуекелдерді дәлірек бағалау үшін қашықтықтан зондтауды жерүсті далалық зерттеулермен біріктіретін кешенді тәсілдің маңыздылығы атап өтіледі. Мұздық көлдердің жағдайын бақылау мен бағалаудың заманауи технологияларын сәтті қолданудың нақты мысалдары келтірілген. Атап айтқанда, Шілік өзені алабындағы 143 көлдің тізімдемесі қаралып, 2015 жылы айтарлықтай жойылуға әкеп соққан Безымянное көліндегі серпіліс оқиғасы талданды.

Алынған нәтижелер таулы аймақтарда ерте хабарлау және табиғи тәуекелдерді басқару жүйесін дамыту үшін маңызды практикалық мәнге ие. Жылдық орташа температураның жоғарылауы және мұздықтардың жылдам еруі жағдайында мұздық көлдеріне егжей-тегжейлі мониторинг жүргізу қажеттілігі ерекше өзекті болып отыр, бұл қашықтықтан зондтау әдістерін одан әрі жетілдіруді және оларды жерүсті бақылаулармен біріктіруді талап етеді.

Кілт сөздер: Мореналық көлдер, Жерді қашықтықтан зондтау, ГАЖ, климаттың өзгеруі, жарылыс қаупі, сел тасқындары, Орталық Азия, мұздықтар.

А.А. Мерекеев[1,2], Г.М. Искалиева[1*], А.Б. Гаипова[1], Ә.А. Амандельді[1], М.С. Сағат[1,2], Н.Қ. Сыдық[1]

[1] ТОО «Институт ионосферы», г. Алматы, Республика Казахстан,
merekeev.aibek@gmail.com, igm.ionos@gmail.com, arailym.geo@gmail.com, amangeldialimma@gmail.com, nurmahambet.s@gmail.com*

[2] Казахский национальный университет им. аль-Фараби, г. Алматы , Республика Казахстан, sagat.madina1@gmail.com

МЕТОДЫ МОНИТОРИНГА МОРЕННЫХ ОЗЁР ЦЕНТРАЛЬНОЙ АЗИИ В УСЛОВИЯХ ИЗМЕНЕНИЯ КЛИМАТА

Аннотация

В статье представлен комплексный анализ современных методов исследования высокогорных ледниковых озер Центральной Азии в условиях глобального потепления. Основное внимание уделялось моренным озерам, которые возникают в результате отступления ледников и представляют значительный риск из-за возможности катастрофических взрывов и связанных с ними опасных селевых потоков. Были тщательно проанализированы важные тенденции изменений в ледниковых озерах, их динамических свойствах и механизмах образования, а также преобладающие стратегии мониторинга и оценки рисков.

Значительное внимание уделялось применению наборов данных дистанционного зондирования (Landsat, Sentinel, Terra), которые в сочетании с географическими информационными системами позволяют в реальном времени оценивать состояние ледниковых озер, отслеживать их пространственную и временную динамику и оценивать риски, связанные с потенциальными вспышками. Рассматриваются методики расчета водного объема озер с применением спектральных индексов (MNDWI, NDVI) и цифровых моделей рельефа.

В статье обобщен опыт исследований ледниковых озер в различных горных системах, включая Гималаи, Памир и Тянь-Шань. Проанализированы преимущества спутникового мониторинга, такие как высокая оперативность и возможность охвата труднодоступных территорий, а также его ограничения, связанные с пространственным разрешением данных, сезонными изменениями и необходимостью их валидации. Подчеркивается значимость комплексного подхода, сочетающего дистанционные методы с наземными полевыми исследованиями для более точной оценки рисков, связанных с прорывами озер. Приведены конкретные примеры успешного применения современных технологий для мониторинга и оценки состояния ледниковых озер. В частности, рассмотрена инвентаризация 143 озер в бассейне реки Шилик, а также проанализирован случай прорыва озера Безымянное в 2015 году, приведший к значительным разрушениям.

Полученные результаты имеют важное практическое значение для разработки систем раннего предупреждения и управления природными рисками в горных регионах. В условиях роста среднегодовых температур и ускоренного таяния ледников необходимость детального мониторинга ледниковых озер становится особенно актуальной, что требует дальнейшего совершенствования методов дистанционного зондирования и их интеграции с наземными наблюдениями.

Ключевые слова: Моренные озера, ДЗЗ, ГИС, изменение климата, прорывоопасность, селевые потоки, Центральная Азия, ледники

IRSTI 68.47.94; 68.47.15; 68.47.33 **DOI** https://doi.org/10.37884/2-2025/48

Zh.M. Baigazakova[1], M. Yerzhankyzy[1], O.T. Mukhametzhanova[1], Zh.T. Bukabayeva[2], O. Adalkan[1]*

[1]Shakarim University, Semey, Kazakhstan, jadi-2-92@mail.ru, Marzhan-erzhankyzy@mail.ru, nu_rai@mail.ru, oral.adalkan@mail.ru*
[2]Alikhan Bokeikhan University, Semey, Kazakhstan, zhanilxan79@mail.ru

FOREST ECOSYSTEMS OF EAST KAZAKHSTAN IN THE SYSTEM OF WATER BALANCE REGULATION AND SOIL EROSION PROTECTION

Abstract

The article examines the impact of forest ecosystems in Eastern Kazakhstan on the regulation of water balance and protection of soils from degradation. Experimental studies have been conducted to assess the water retention capacity of soils, the level of erosion and the dynamics of humidity in various forest formations. The results show that forests play an important role in stabilizing the hydrological regime and preventing erosion processes. Remote sensing data and GIS technologies have been applied to analyze vegetation cover density, soil moisture indices, and NDVI values, which provides a comprehensive assessment of ecosystem health. The study also examines the role of tree and shrub composition in erosion resistance, highlighting the importance of mixed forest formations in increasing soil stability. The results highlight the need for sustainable forest management practices and afforestation strategies to mitigate land degradation and improve regional water conservation efforts. Analysis of precipitation infiltration and evapotranspiration rates shows that forests contribute to maintaining stable groundwater levels, reducing the risk of droughts and floods in adjacent agricultural and urban areas. The study concludes with recommendations for adaptive management strategies for forest conservation, including afforestation using native species, controlled grazing methods, and the implementation of solutions based on natural factors to enhance landscape resilience. These findings serve as the basis for the development of a comprehensive policy aimed at preserving the ecological functions of forests in Eastern Kazakhstan and ensuring long-term environmental sustainability.

Keywords: *forests, water balance, soil erosion, soil degradation, East Kazakhstan.*

Introduction

Forest ecosystems play a key role in ensuring the sustainability of natural landscapes, shaping water balance, and preventing soil degradation [1]. In Eastern Kazakhstan, where the continental climate prevails with sharp temperature fluctuations and uneven precipitation distribution, forest conservation is a critically important aspect of the ecological stability of the region [2]. In recent decades, active land development, deforestation and climate change have led to an increased risk of soil erosion and a decrease in their water retention capacity [3].