

Article

The Impact of Climate Change on the State of Moraine Lakes in Northern Tian Shan: Case Study on Four Moraine Lakes

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Abstract

Glacial-lake outburst floods (GLOFs) threaten more than three million residents of south-east Kazakhstan, yet quantitative data on lake growth and storage are scarce. We inventoried 154 lakes on the northern flank of the Ile-Alatau and selected four moraine-dammed basins with the greatest historical flood activity for detailed study. Annual lake outlines (2016–2023) were extracted from 3 m PlanetScope imagery with a Normalised Difference Water Index workflow, while late-ablation echo-sounder surveys (2023–2024) yielded sub-metre bathymetric grids. A regionally calibrated area–volume power law translated each shoreline to water storage, and field volumes served as an independent accuracy check. The lakes display divergent trajectories. Rapid thermokarst development led to a 37% increase in the surface area of Lake 13bis, expanding from 0.039 km² to 0.054 km² over a 5-year period. In contrast, engineering-induced drawdown resulted in a 44% reduction in the area of Lake 6, from 0.019 km² to 0.011 km². Lakes 5 and 2, which are supplied by actively retreating glaciers, exhibited surface area increases of 4.8% and 15%, expanding from 0.077 km² to 0.088 km² and from 0.061 km² to 0.070 km², respectively. The empirical model reproduces field volumes to within $\pm 25\%$ for four lakes, confirming its utility for rapid hazard screening, but overestimates storage in low-relief basins and underestimates artificially drained lakes. This is the first study in Ile-Alatau to fuse daily 3 m multispectral imagery with ground-truth bathymetry, delivering an 8-year, volume-resolved record of lake evolution. The results identify Lake 5 and Lake 2 as priority targets for early-warning systems and demonstrate that sustained intervention can effectively suppress GLOF risk. Incorporating these storage trajectories into regional disaster plans will sharpen evacuation mapping, optimise resource allocation, and inform transboundary water-hazard policy under accelerating climate change.

Keywords: GLOFs; monitoring; remote sensing; climate change; empirical volume estimation; bathymetry



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1. Introduction

Over recent decades, the ecological landscape across the globe has been significantly disrupted by the consequences of global climate change, particularly environments in high-altitude regions like the mountains of central Asia and the Himalayas, which are extremely

susceptible to shifts in climate [1]. The most discernible changes resulting from climate change in these regions relate to the shrinking of glaciers, altering hydrological patterns, the rise in the number of glacial lakes, and escalated risks of glacier-related disasters [2]. These lakes, serving as vital freshwater reservoirs, are susceptible to alterations in volume and quality as a result of rising temperatures and changing precipitation patterns [3]. Especially, the expansion and evolution of the glacial lakes pose significant concerns, making them prone to glacial lake outburst floods (GLOFs), which can endanger regions both adjacent to and further downstream from these water bodies. A concerning trend in recent years involves GLOFs originating from the rupture of glacial lakes, exemplified by the 2016 Gongbatongsha GLOF in the Tibetan Himalayas and the 2023 South Lhonak GLOF in Sikkim, India [4,5]. While the Gongbatongsha flood submerged villages and agricultural land, upsetting livelihoods for thousands, the South Lhonak eruption destroyed vital infrastructure, including highways and hydroelectric plants, uprooting a huge number of people and causing significant economic losses. Therefore, analysing how climate change is affecting the characteristics of these lakes is crucial for understanding both the immediate and long-term ecological and socioeconomic repercussions on local communities.

The tracking and monitoring of glacial lakes in high mountainous regions is extremely challenging, given their severe weather, remote locations, and unapproachable terrains [6]. Although vital, traditional monitoring (in situ observation) is often expensive and demanding, particularly in remote and inaccessible mountainous areas where most glacial lakes are located. To overcome these challenges, geographic information systems (GIS) and remote sensing (RS) technologies offer efficient and promising tools for tracking spatiotemporal changes, mapping, and evaluating inaccessible environments [7,8]. These approaches offer a less resource-intensive and more scalable way to analyse lake properties and dynamics over extended periods and large areas. These methods provide spatially consistent information for detecting and monitoring glacial lake changes at regional and global scales [9]. They are optimal for monitoring seasonal analysis of the dynamics of water bodies, and also for calculating depth and volume, which is relevant for glacial lakes. By leveraging remote sensing data, integrated with in situ measurements and meteorological parameters, a comprehensive analysis of glacial lake dynamics can be accomplished, which provides crucial insights into the impact of climate change on the cryosphere and water resources of the region [10].

Driven by the advancement of remote sensing technology and the increased availability of high-quality satellite imagery, researchers have been able to conduct glacial lake research at efficient and unprecedented scales. Remote sensing is particularly useful for studying the effects of land use and land cover changes on hydrology in lake catchments, providing a thorough understanding of the patterns of hydrological response [11]. There are various studies that have utilised archival and current satellite data and aerial photographs to develop glacial inventories and explore the changing dynamics of glacial lakes. For instance, areas of the Tibetan Plateau [12], the Tian Shan [13], the Himalayas [10,14], Uzbekistan [15], Pakistan [16], and High-Mountain Asia, aside from the Altai and Sayan [17], have all had their glacial lake inventories created using multi-source remote sensing imagery. These inventories have proven to be a valuable source of information for identifying the spatiotemporal features of glacial lakes as well as how these lakes are responding to the consequences of climate change in these areas. Furthermore, Landsat satellite data are used to examine changes in glaciers and glacial lakes, showing that the areas of glaciers have decreased while the areas of glacial lakes have increased over time [18]. Various studies have employed remote sensing data to calculate the water indices [Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI)], which can be used to map water bodies [19,20], and to identify lake shorelines [21]. Authors

utilised Landsat imagery in combination with altimetry, and determined water levels from lake shoreline positions and provided information on lake water levels, as well as information on monitoring and forecasting lake floods on the Tibetan Plateau [22]. Water surface areas can be estimated using the MNDWI, with an average accuracy of 90.43% when compared with available high-resolution images [23]. When comparing water level fluctuations for analysis with climate data, a relationship was found between the reduction in lake surface area and increased evaporation, as well as decreased precipitation and a decrease in temperature during the studied period [23].

Furthermore, satellite-based remote sensing has been utilised to monitor the volume and water level changes of glacial lakes, which is often achieved through the integration of satellite imagery with digital elevation models [24]. Researchers utilized Sentinel-2 satellite images in combination with HydroWeb altimetry data to model changes in the volume of Lake Alakol in Kazakhstan [25]. In one study [10], the authors employed multi-temporal remote sensing images to determine the glacial lake volume by reconstructing the lake basin topography, then integrating the lake area over varying water levels. This approach is relevant to studying lakes located in remote areas that lack high-resolution topographic data [26]. Another study [27] estimated the volume of a glacial lake, Longbasaba, situated in the Himalayas, using depth data, GPS measurements from the field, and satellite images. To improve the accuracy of volumetric calculations, the authors conducted an analysis that incorporated lake area, length, width, bathymetric data, and the NDWI, derived from Landsat imagery [28]. As a result, they developed an equation that relates the volume of a glacial lake to its area and the ratio of its maximum length to maximum width. Although remote sensing techniques and geographic information systems have transformed research methodologies in glaciology and limnology, there are still challenges, particularly in High-Mountain Asia, due to rugged topography, cloud cover, and limited ground validation data [29]. Moreover, integrating remote sensing data with field observations and climate models can be challenging in terms of data processing, validation, and cross-validation. This highlights the need for methodological developments and improvements in remote sensing techniques, data processing algorithms, and validation strategies in order to strengthen the precision and reliability of glacial lake monitoring and assessment.

This study has focused on the Ile-Alatau region in Kazakhstan, which presents a distinctive geographic setting that is essential for understanding the complex interactions between climate change, glacial dynamics, and alpine lake systems. This research aims to comprehensively analyse the impact of climate change on the state of glacial lakes, in particular, the moraine lakes in the Ile-Alatau region, by employing a combination of remote sensing techniques, field investigations, and meteorological data analysis. Specifically, the study assesses the spatiotemporal changes in four moraine lakes to characterise trends in lake expansion or contraction, and analyses alterations in lake bathymetry to evaluate changes in water volume and storage capacity. These observed lake dynamics are then systematically linked to patterns of glacier retreat and regional climatic trends to better understand their causal interrelationships. Finally, the research evaluates the applicability and accuracy of empirical methods for estimating lake volume to improve risk assessment and hydrological modelling in glacial environments. By adopting this holistic approach, the study aims to provide detailed insights into the impact of climate change on the state of glacial lakes in the region.

2. Study Area

The Ile-Alatau region is particularly sensitive to climatic shifts, making it a key area for assessing glacial lake evolution, hydrological hazards, and long-term environmental change in mountainous environments. Glacial lakes, particularly moraine-dammed lakes,

are prominent features of glaciated mountain regions and are highly sensitive to climate change [30]. The most dangerous moraine lakes in Kazakhstan are located in the Ile-Alatau mountain range, an area densely populated by more than three million residents [31]. This mountain range, stretching for 280 km and located at 43° north latitude and between 75–78° east longitude, creates unique conditions for the formation of glacial lakes due to its location and the dynamics of ice melting. The study area encompasses several moraine lakes situated within the various river basins of Ile-Alatau, including the Turgen, Issyk, Talgar, Kishi Almaty, Ulken Almaty, Kargaly, Aksay, Chemolgan, Kaskelen, and Uzun-Kargaly river systems. These river systems are characterised by complex hydrological regimes influenced by seasonal snowmelt, glacier melt, and precipitation patterns. This environment, marked by seasonal fluctuations, promotes the physical disintegration of rocks, generating loose debris that contributes to mudflows [32].

Ile-Alatau is a part of the Northern Tian Shan mountain range, which exhibits a continental climate characterised by cold winters and relatively warm summers. The snow accumulation period in this region lasts for about 9 months, starting in mid-September and ending in mid-June. The average air temperature recorded during the accumulation period fluctuates between -8 and -10 °C. The coldest months on average are January and February, with average monthly temperatures between -14 and -16 °C, and the lowest temperatures can fall to -32 °C and even lower. During this period, 700–800 mm of solid precipitation falls in the glaciers, with most of it falling at the end of the accumulation season, namely in April and May. The least amount of precipitation falls in January at only 20–30 mm (2–3 percent of the annual volume). This climate significantly influences the region's hydrology, particularly the formation and dynamics of glaciers and glacial lakes [33].

3. Methodology

The research methodology for this study involves a multifaceted approach. Initially, the selection of moraine lakes in the Ile-Alatau region, based on factors such as accessibility, size, and the availability of historical data to ensure a representative sample for analysis was conducted. Subsequently, high-resolution satellite imagery was acquired to analyse the spatial and temporal changes in lake area and glacier extent. Further, we utilised a well calibrated area–volume relation to translate each shoreline to volume, with field measurements providing error checks that bound our hazard-trend analysis.

3.1. Selection of Lakes

The selection of lakes for this study was a critical step in ensuring the relevance and reliability of the research findings. Ile Alatau has 10 river basins, stretching from east to west, including the Turgen, Issyk, Talgar, Kishi Almaty, Ulken Almaty, Kargaly, Aksay, Chemolgan, Kaskelen, and Uzun-Kargaly river systems. Glacial lake outbursts have been observed mainly in the central part of the ridge in the basins of the Ulken and Kishi Almaty, Talgar, and Issyk rivers. Several studies confirm that the number of glacial lakes and the number of lake outburst floods have increased in the Ile-Alatau range over the past few decades [31,33,34]. This is due to the acceleration of the warming process and the degradation of glaciers. New lakes have begun to appear in the periglacial zone, and existing ones, especially periglacial lakes, are rapidly increasing in size. Researchers have highlighted the rise of glacial lakes and the expansion of total lake areas in the Kyrgyz and Teskey ranges [35].

For the initial detection and inventory of moraine-dammed lakes on the northern slope of the Ile-Alatau, we used the dataset compiled by Kapitsa et al. [36], which is based on detailed interpretation of satellite imagery and field surveys. This baseline inventory

was refined and updated through the analysis of Sentinel-2 imagery, allowing for more precise delineation of lake boundaries. The resulting inventory was further validated using field observations and data from specialists of the State Institution “Kazselezashchita,” an organisation under the Ministry for Emergency Situations of the Republic of Kazakhstan responsible for monitoring the hazard potential of moraine-dammed lakes and implementing preventive measures.

The final dataset comprised of 154 lakes situated at elevations ranging from 2700 m to 3980 m (Figure 1). These lakes collectively span a total area of 2.28 km², with an average individual lake size of 0.015 km². A notable concentration of 69 of these lakes (45%) was found in the 3500–3700 m altitude range, accounting for 0.938 km² (41%) of the total lake area. The lakes varied significantly in size: 39 lakes were smaller than 1000 m²; 69 lakes ranged from 1000 m² to 10,000 m²; 22 lakes were between 10,000 m² and 20,000 m²; 14 lakes measured 20,000 m² to 50,000 m²; and 10 lakes were between 50,000 m² and 100,000 m². When categorised by volume, the distribution highlighted potential risks. 50 lakes had a volume under 10,000 m³, for example, and these are generally considered safe, i.e., they are unlikely to cause significant damage if they burst. However, a significant number of lakes posed a greater risk: 52 lakes had a volume between 10,000 m³ and 50,000 m³; 22 lakes ranged from 50,000 m³ to 100,000 m³; 15 lakes had a volume of 100,000 m³ to 200,000 m³; and 14 lakes exceeded 200,000 m³. According to the results of a study of glacial lake outburst flood events, the most dangerous lakes have certain characteristics: a volume exceeding 100,000 m³, location as proglacial lakes, and dams consisting of moraine with an ice core [31,34].

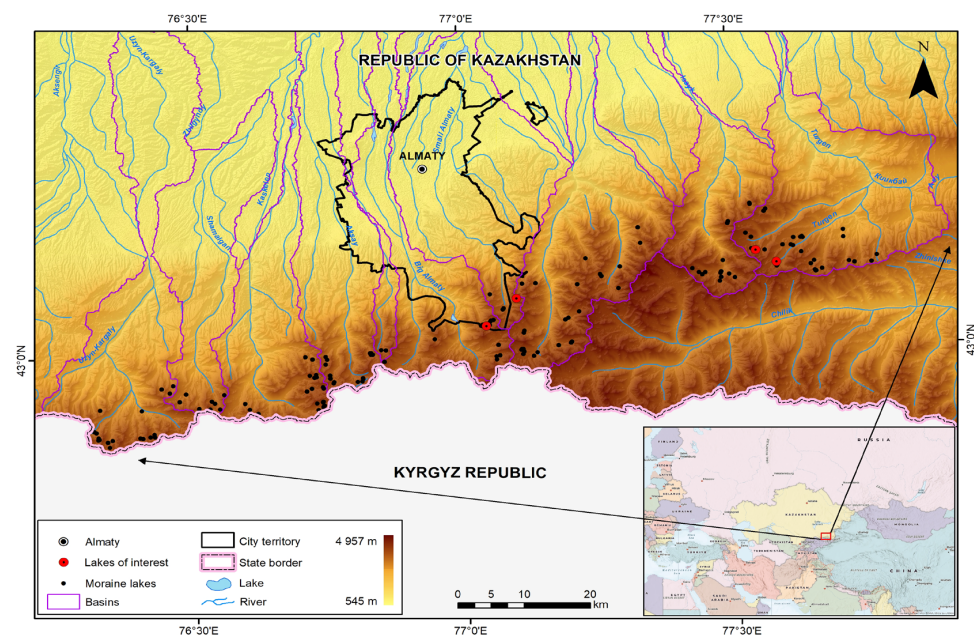


Figure 1. Distribution of moraine lakes in Ile-Alatau.

Building on this regional context, we selected four moraine lakes (Figures 2 and 3) for detailed case studies. These lakes are situated in different river basins of the Ile-Alatau range, and each lake exhibits distinct characteristics in terms of size, morphology, and glacial influence. The following lakes were selected as reference outburst-hazardous lakes for monitoring for a comprehensive assessment of the dynamics of changes in their areas: Moraine Lake No. 13 bis in the Ulken River basin of Almaty, Moraine Lake No. 6 in the Kishi River basin of Almaty, and Moraine Lake No. 2 and Moraine Lake No. 5 in the Turgen River basin.

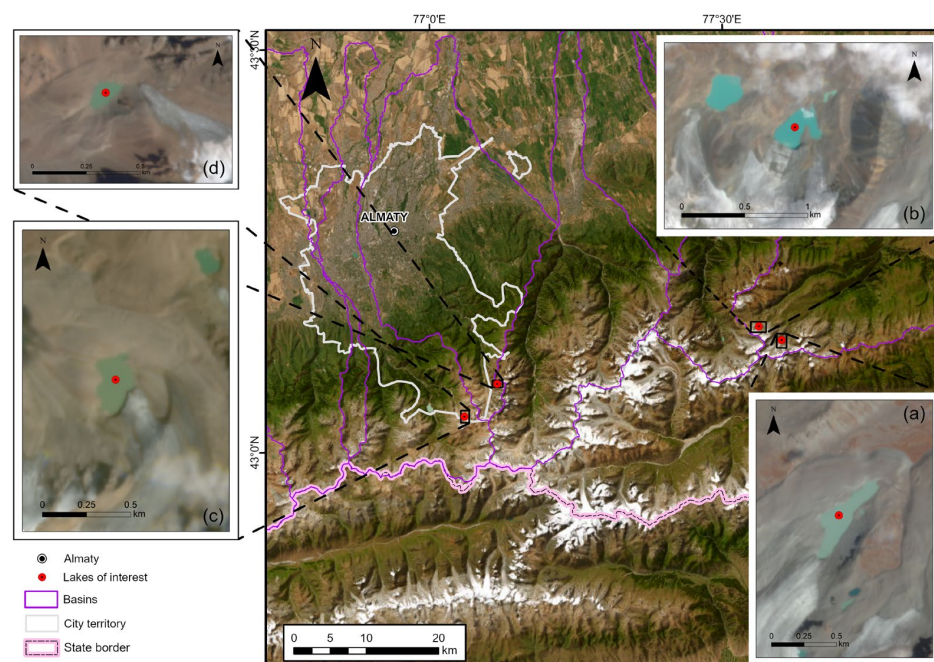


Figure 2. Location of the studied moraine lakes: (a) Lake no. 5; (b) Lake no. 2; (c) Lake no. 13 bis; (d) Lake no. 6.

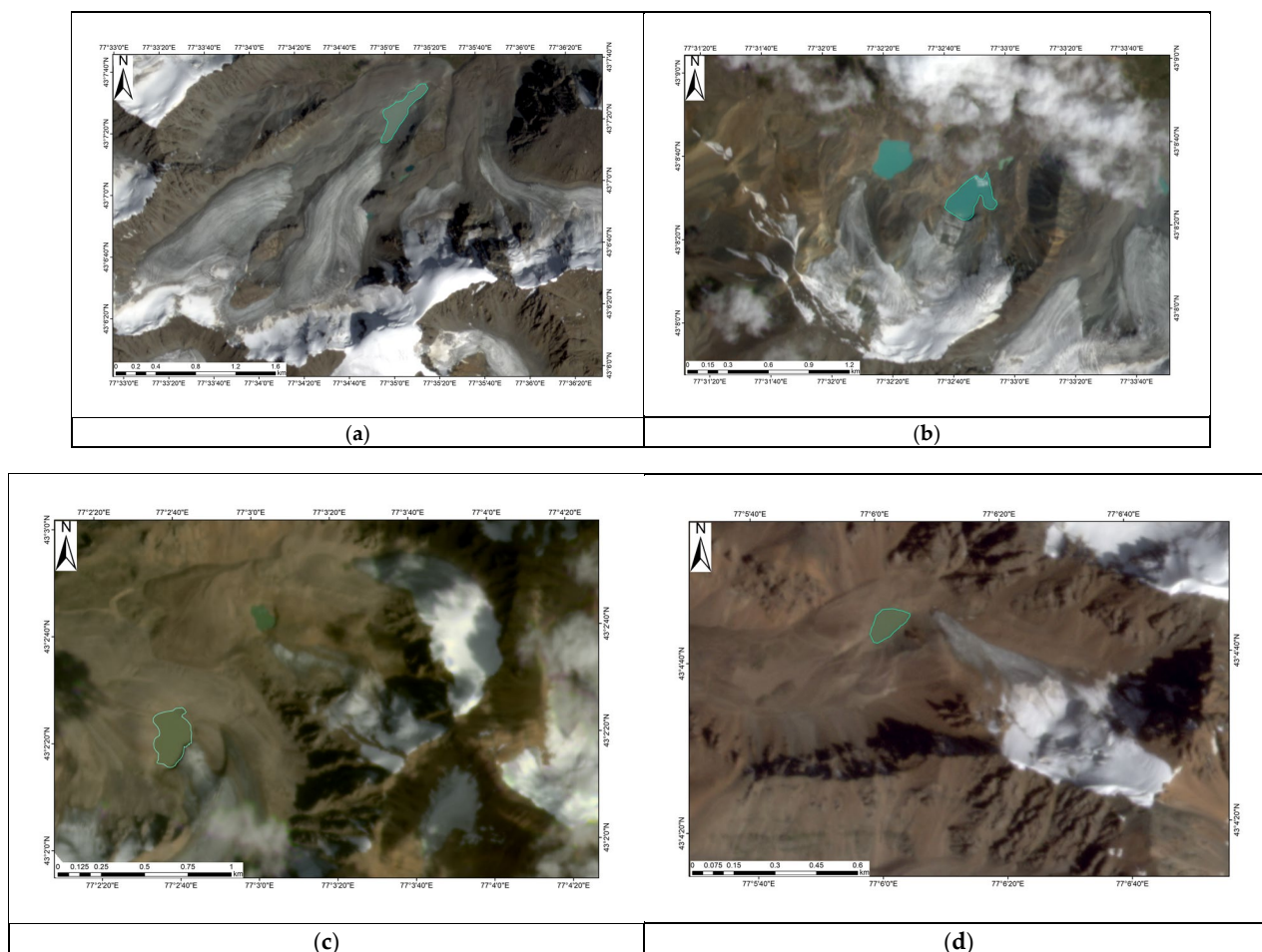


Figure 3. Latest true colour images of the moraine lakes procured from PlanetScope, with the study areas for the four lakes: (a) Lake no. 5; (b) Lake no. 2; (c) Lake no. 13 bis; (d) Lake no. 6, indicated by boxes in Figure 2.

Table 1 provides the information regarding river basins in which selected lakes are located, along with the approximate coordinates of the lakes. This selection ensures that the study captures the variability inherent in moraine lake systems across the region.

Table 1. General information about the studied moraine lakes.

Name of the Lake	River Basin	Geographic Coordinates	
		Latitude	Longitude
Moraine Lake No. 13 bis	Ulken Almaty	43°2′21.29″	77°2′35.46″
Moraine Lake No. 6	Kishi Almaty	43°4′43.27″	77°6′0.36″
Moraine Lake No. 2	Turgen	43°8′30.31″	77°32′50.69″
Moraine Lake No. 5	Turgen	43°7′27.20″	77°35′9.50″

The selected areas span the three river basins with the greatest historical outburst activity, thus capturing the east–west hydro-climatic gradient of the Ile-Alatau range. Moreover, they display contrasting morphometries from a shallow, periodically draining thermokarst basin (Lake 6, 12 m max. depth) to a rapidly deepening composite lake (Lake 5, 30 m).

3.2. Data Collection

Historical satellite images of the selected lakes in different years were acquired to determine the dynamics of changes in the areas of moraine lakes. Our study primarily utilised PlanetScope imagery to collect data for a selected group of moraine lakes. PlanetScope is a constellation of 130 satellites capable of capturing images of the entire Earth’s surface daily, covering up to 200 million km² per day. Each PlanetScope image has a resolution of approximately 3 m per pixel, providing high detail and accuracy in the visual data [37,38]. The dataset spans three sensor generations—PS2, PS2.SD, and PSB.SD—providing four to eight spectral bands (RGB-NIR plus coastal blue, green-I, yellow, and red-edge in the PSB.SD series) that enable robust water-index extraction and cross-sensor radiometric harmonisation. All scenes were orthorectified to WGS-84/UTM 43 N with sub-pixel planimetric accuracy and passed through Planet’s automated atmospheric-correction pipeline, ensuring radiometric consistency across the 8-year record.

We specifically downloaded PlanetScope imagery from 2016 to 2023. The year 2016 marked the first year that imagery was available for our study sites. To maintain consistency, we used images captured between 20 August and 10 September for each year of the study period. This specific timeframe was selected because it represents the period of maximum ice melting in the study area, which typically occurs from late July to early August. Details about the PlanetScope imagery used for these lakes are provided in Table 2. These data, sourced from the Planet Developers website (<https://developers.planet.com>) (accessed on 17 August 2025), were crucial for tracking changes in the area of the selected lakes.

Furthermore, to obtain the volume and depth statistics required for assessing the current state of these lakes, field bathymetric data were gathered for the lakes in the summer during the late-ablation seasons of 2023 and 2024 using a portable echo-sounder. The bathymetric surveys provide essential data for estimating lake volumes and depth variations, which are critical for assessing the risk of potential GLOFs. This method allowed us to map the lake bottoms accurately.

Table 2. Dataset Details for PlanetScope Imagery.

Dataset	Date of Receipt of Images	PlanetScope Image ID	Image Source
Lake No. 13 bis Lake No. 6	21 August 2016	1308e343-0959-4e1f-9dfe-5cd614106fe3	PS Scene
	27 August 2017	b5469de2-9202-4d57-805f-57f9f3f91313	
	20 August 2018	4d6964f9-cefc-43c9-9c94-a582f61015a8	
	26 August 2019	91fbacc6-6da1-4c09-803b-78b5f71b4faa	
	23 August 2020	01fb2da7-e737-42e2-8cd9-899f49c7e3aa	
	22 August 2021	c8fe4309-90f6-4eef-af11-a695dd8a46b1	
	23 August 2022	79784655-7a0c-4ba0-bac8-322458ea77b4	
	23 August 2023	ff5ebd42-e566-4ac7-834d-1f86d3624d68	
Lake No. 5 Lake No. 2	27 August 2016	488b5c8a-baf6-498f-b3f1-8539ecd6faa1	PS Scene
	27 August 2017	11cf980e-7609-4608-bef7-5b3f749aa335	
	23 August 2018	1d297f71-5143-4458-8e10-d2ffb3f5c9f1	
	26 August 2019	d9bde865-5895-4744-8305-07b17765d754	
	24 August 2020	b823d7b2-4f4b-4580-bd1b-99fef51dc457	
	23 August 2021	48f82968-6154-4b48-ae2f-2f2eefe06fb9	
	22 August 2022	27adf1e6-0dbb-490f-8627-d68376006699	
	21 August 2023	a718fa93-644f-4c42-9c32-f58180769028	

3.3. Data Processing and Analysis

Satellite-derived planimetric metrics and field bathymetry were integrated through a multi-stage workflow. First, cloud-free PlanetScope Level-3B scenes (2016–2023) were atmospherically verified and ortho-rectified to WGS-84/UTM 43T. Water bodies were extracted using the Normalized Difference Water Index [29]. NDWI is calculated using the following equation:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (1)$$

where Green represents the green band and NIR represents the near-infrared band of the satellite imagery [39]. The binary NDWI layer was vectorised in ArcGIS 10.8 and polished by visual interpretation and, later, lake area, perimeter, length, width, and water-surface altitude were calculated with sub-pixel precision.

Second, echo-sounder soundings acquired in 2023 and 2024 were cleaned for spike noise, speed-of-sound variations, and jitter, then interpolated in Surfer 10 software to 1 m digital bathymetric models. Volumes and maximum and mean depths were derived by numerical integration under the PlanetScope shoreline; cross-line residuals never exceeded 0.22 m, ensuring planimetric-altimetric consistency with the satellite record.

Thirdly, to estimate lake volumes from remote sensing data, we utilised an empirical relationship between lake area and volume. This empirical relation is based on bathymetric measurements of 32 lakes in the Zailiysky and Dzungarian Alatau, part of the Tian Shan mountain system [36]. The original study acquired the data at the end of the ablation season, between late August and September. Lake depth was measured using echo soundings along profiles, and volumes were derived using Surfer software. The empirical formula is expressed as follows:

$$V_s = 0.036A^{1.49} \quad (2)$$

where V is the lake volume (m^3) and A is the lake area (m^2). The average depth (D) of the lake can then be calculated as follows:

$$D = 0.036A^{0.49} \quad (3)$$

Using these equations, we were able to estimate lake volumes and average depths based on the area measurements obtained from remote sensing data. This method is particularly useful for estimating lake volume changes over time, using satellite imagery [40].

Lastly, to evaluate the accuracy of the volume estimates obtained from the empirical formula, we compared them to volumes derived from field bathymetric data. We calculated the error between the bathymetrically obtained volume (V_0) and the volume calculated for satellite data (V_s) using the following equation:

$$Error = \frac{(V_0 - V_s)}{(V_s)} \times 100 \quad (4)$$

The calculated errors were then classified into three categories:

- Predicted (0–24% error): high accuracy;
- Moderately unpredictable (25–49% error): satisfactory, but not perfect, model performance;
- Unpredictable (>50% error): low prediction accuracy.

This error classification system allowed us to assess the performance of the empirical formula. Therefore, we could determine the reliability of the volume estimates derived from remote sensing data [41–43].

4. Results

4.1. Bathymetry of Moraine Lakes

Ground-based bathymetric survey is essential in collecting the bathymetric data of the moraine lakes, and is used to analyse the morphometry of the lake [44]. These surveys conducted in the summers of 2023 and 2024 provided detailed depth measurements for the selected moraine lakes. Table 3 presents the results of ground-based studies of reference moraine lakes, including the following parameters: volume, area, length, width, and the maximum depth of the lake. The morphometric characteristics of these moraine lakes have been highlighted in Figure 4. These parameters play a key role in understanding the hydrological and glaciological processes occurring in moraine lakes and can be used to assess the risk of lake outbursts and predict the consequences of such events [45].

Table 3. Information regarding the morphometrics of moraine lakes under study.

River Basin	Name of the Lake	Lake Volume, m ³	Lake Area, m ²	Length, m	Width, m	Maximum Depth, m
Ulken Almaty	Moraine Lake No. 13 bis	154,500	57,570	370	353	15
Kishi Almaty	Moraine Lake No. 6	64,500	15,900	237	113.1	12
Turgen	Moraine Lake No. 2	715,300	68,700	407	231	27.3
Turgen	Moraine Lake No. 5	1,109,000	89,800	740	225	30

These ground-based surveys have provided the basic data that are used to analyse the current state of moraine lakes and to assess their potential hazards. It was observed that most of the lakes lie between 3585 m and 3680 m above mean sea level, yet their morphometry spans an order of magnitude. Lake No. 5 (Turgen basin, 3585 m) possesses both the greatest surface area ($8.98 \times 10^4 \text{ m}^2$) and depth ($h_{\max} \approx 30 \text{ m}$), yielding the largest observed water volume ($1.11 \times 10^6 \text{ m}^3$) and confirming its status as the primary outburst threat. Lake No. 2, situated at an altitude of 3680 m, is nearly as voluminous ($7.15 \times 10^5 \text{ m}^3$) but achieves this with a markedly smaller planform ($6.87 \times 10^4 \text{ m}^2$) thanks to a sharply incised basin 27.3 m deep, demonstrating how confined morphologies can concentrate hazard potential.

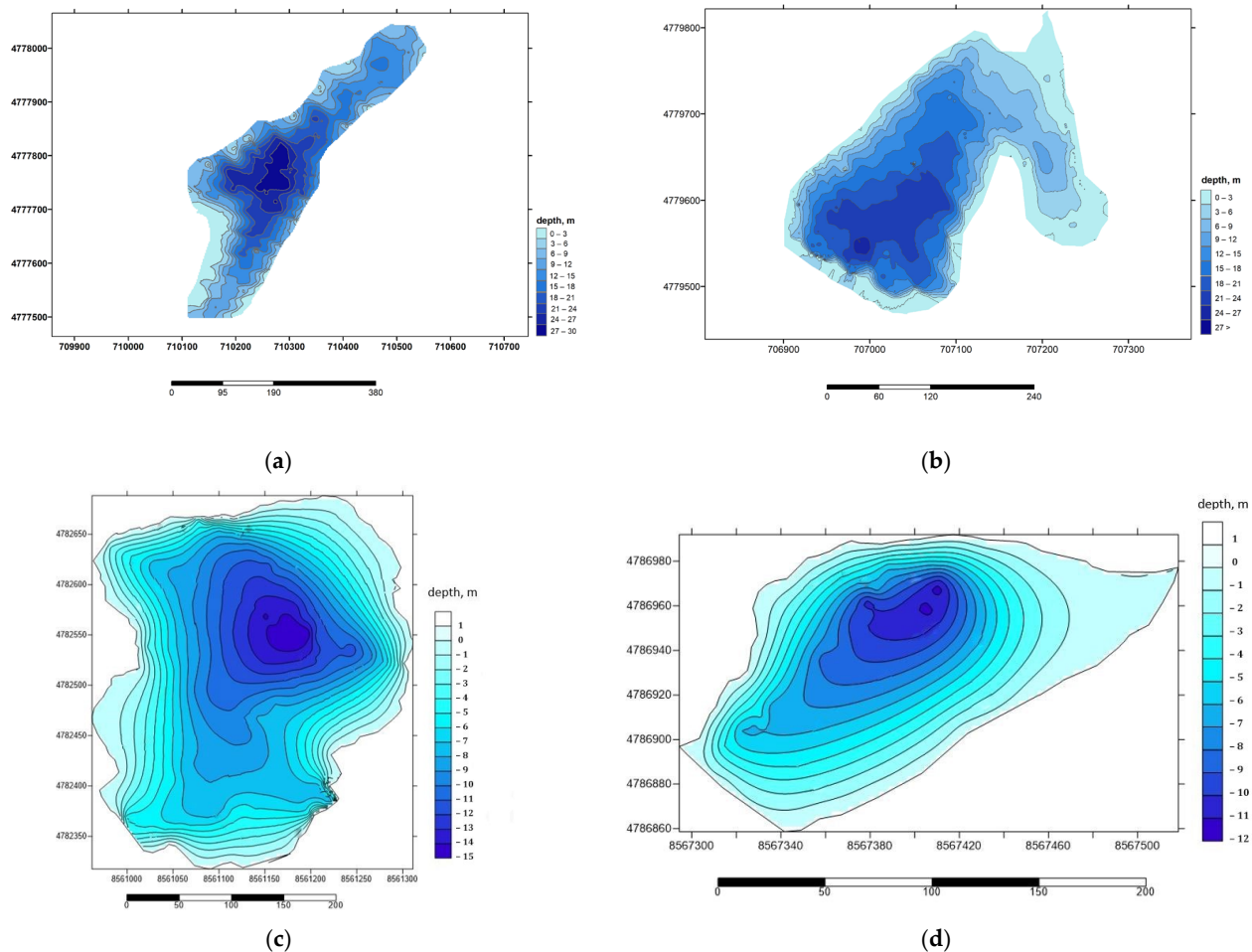


Figure 4. Morphometric characteristics of the lakes under study: (a) Lake no. 5; (b) Lake no. 2; (c) Lake no. 13 bis; (d) Lake no. 6.

Lake No. 6, located in the Kishi Almaty river basin at 3606 m, is both the shallowest and smallest (volume = $6.45 \times 10^4 \text{ m}^3$; area = $1.59 \times 10^4 \text{ m}^2$; $h_{\text{max}} = 12 \text{ m}$). This lake is a non-stationary lake where water fills periodically, mainly in summer, due to snow and glacier melting. Lake No. 13 bis, located in the Ulken Almaty river basin at 3554 m, typifies a rapidly expanding thermokarst lake, although its present volume ($1.55 \times 10^5 \text{ m}^3$) and depth ($\approx 15 \text{ m}$) are modest.

4.2. Characteristics and Dynamics of Individual Moraine Lakes

A comprehensive analysis of the selected moraine lakes in the Ile-Alatau was conducted based on satellite imagery from 2016 to 2023. This section highlights the key findings, focusing on area changes, volume estimation, and the overall dynamics of each lake. Remote sensing data, combined with field measurements, provided valuable insights into the behaviour of these lakes in response to changing climatic conditions. Understanding these dynamics is crucial for assessing and mitigating the risks associated with glacial lake outburst floods in the region [46].

To understand the temporal changes in the area of moraine lakes, PlanetScope scenes for the late-ablation seasons of 2016–2023 were transformed into NDWI rasters, which were initially histogram-partitioned into seven equal-interval classes. Visual inspection showed that Class 7—representing the darkest, water-rich bin—most effectively isolated moraine lakes while minimising the presence of spurious pixels. Therefore, this class was

vectorised to yield annual lake polygons. Figure 5 illustrates the NDWI classification for all four moraine lakes, and Figure 6 plots the dynamics of changes in their areas.

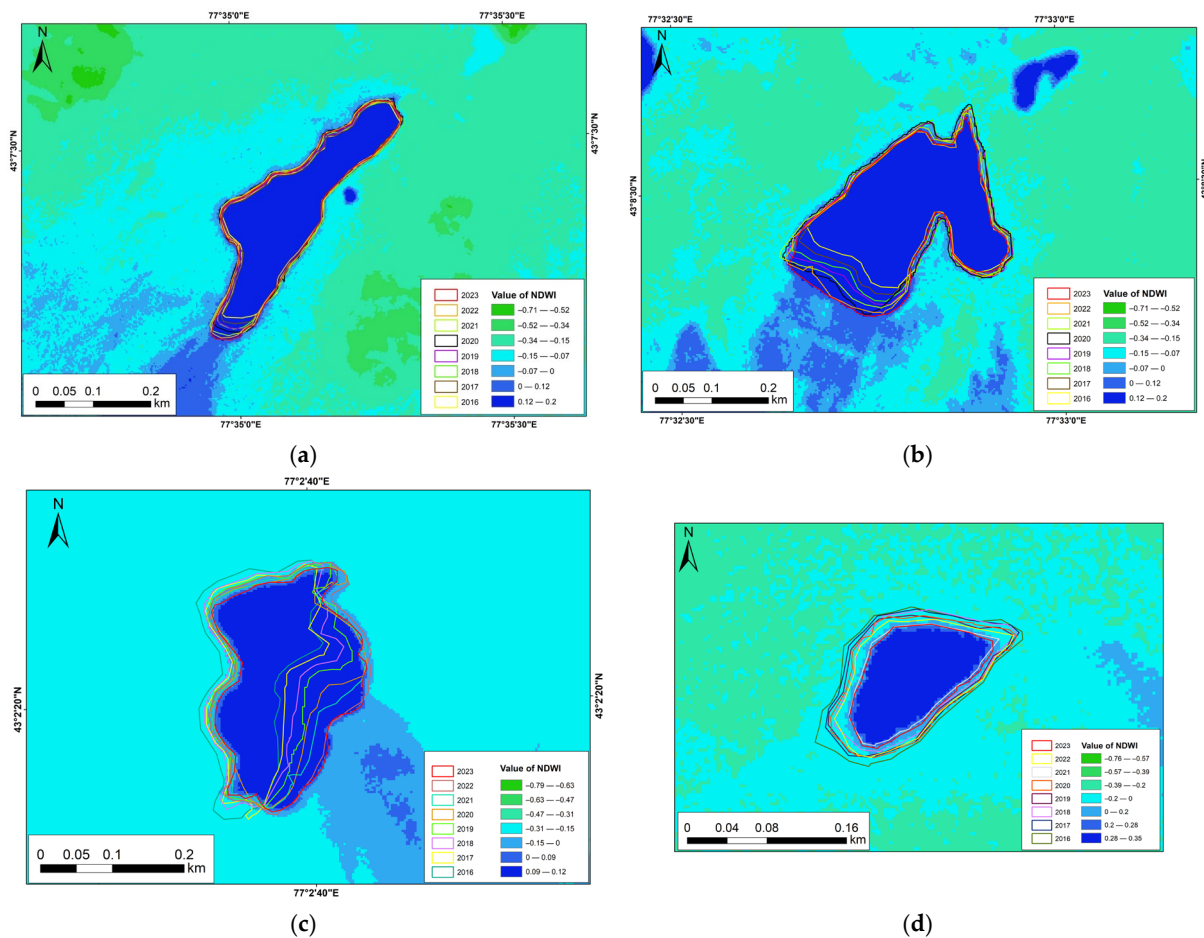


Figure 5. NDWI results of four moraine lakes using high-resolution PlanetScope images: (a) Lake no. 5; (b) Lake no. 2; (c) Lake no. 13 bis; (d) Lake no. 6.

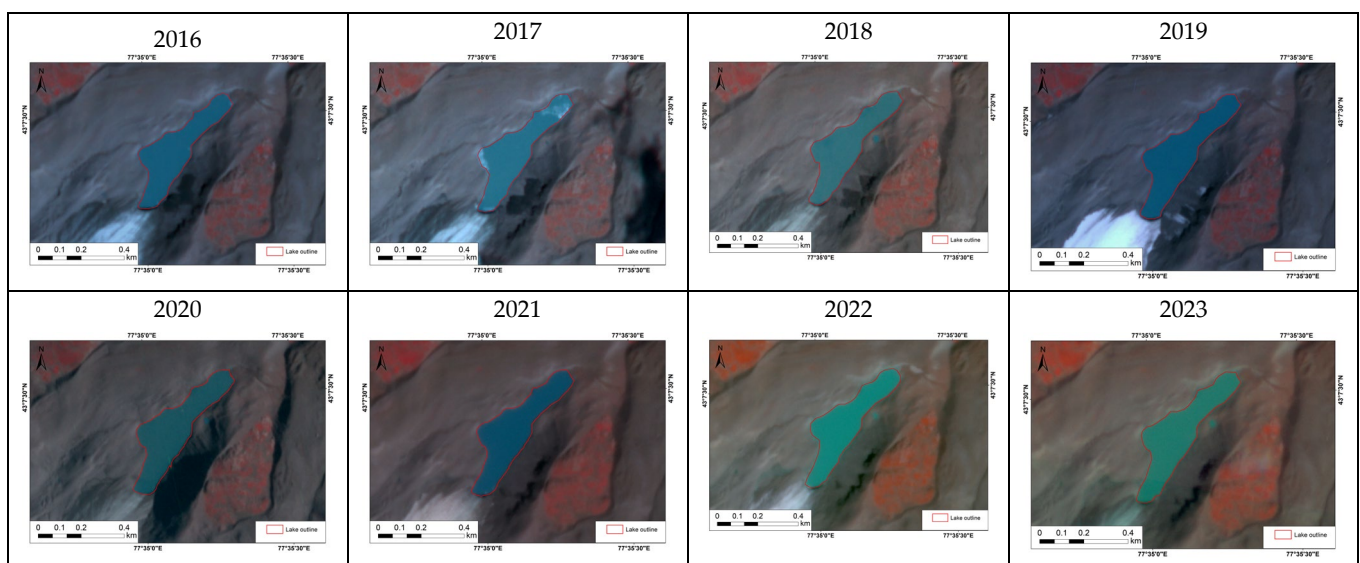


Figure 6. PlanetScope false-colour composites of Lake No. 5 (2016–2023) with lake outlines derived from remote sensing classification.

For the automated extraction of water surfaces, the NDWI was calculated for each pixel of the PlanetScope imagery. The initial seven-class NDWI partitioning followed approaches adopted in several authoritative studies [47–49], as it allows for differentiating clear water, turbid water, and nearshore areas, thereby reducing the likelihood of misclassification compared with binary segmentation.

Building on previous findings, Ji et al. [50] modelled NDWI using spectral data from Landsat ETM+, SPOT-5, ASTER, and MODIS, and concluded that NDWI offers the most stable threshold values among tested indices, recommending its use for water surface mapping when thresholds are adapted to scene-specific conditions. For high-resolution data (SPOT-5 and WorldView, which share spatial and spectral similarities with PlanetScope), subsequent studies reported threshold values in the range of 0.25–0.40, depending on region and season [51,52]. These authors emphasised that a universal fixed threshold is undesirable; instead, thresholds should be adapted by analysing the NDWI histogram for each scene in the context of regional spectral characteristics.

In the present study, the optimal NDWI threshold for each lake and each year was further refined using the Otsu method, implemented in Google Earth Engine. This automated approach minimises within-class variance, removes subjectivity from threshold selection, and adapts to interannual and seasonal spectral variability. The resulting thresholds ranged from 0.10 to 0.30 (Figure 5), consistent with values previously reported for high-resolution datasets, including SPOT-5 and WorldView [50,53].

In order to validate the extracted shorelines, we visually compared them with PlanetScope true-colour composites. Figure 6 presents a time series of images for Lake No. 5 for all study years, including RGB composites with overlaid boundaries derived from the remote sensing analysis. Lake No. 5 was selected due to its pronounced interannual variability, making it a suitable case to illustrate the robustness of the automated delineation.

The measurement of moraine lake areas is inherently subject to uncertainties, primarily due to the effect of pixel discretisation in shoreline delineation. To quantitatively assess these uncertainties, the method proposed by Hanshaw and Bookhagen [53] was applied, which accounts for such factors and is widely used in contemporary studies, including that of Javed et al. [54]. The analysis revealed an inverse relationship between lake area and relative error: larger lakes exhibit lower uncertainty, whereas smaller water bodies are more affected by classification errors.

Out of a total sample of 182 lakes, 159 have an area exceeding 1000 m², with 122 of these objects exhibiting relative errors below 10%, corresponding to an acceptable accuracy level for monitoring purposes. The mean area across the sample was 16,624.42 m².

Four lakes selected for detailed analysis, each with an area greater than 15,000 m², demonstrated low uncertainty values. The average errors for these lakes were 3.65% (Lake 6), 2.53% (Lake 13 bis), 2.10% (Lake 5), and 2.16% (Lake 2). These estimates were incorporated into the construction of area dynamics graphs, where vertical error bars in Figure 7 represent the magnitude of calculated uncertainty for each temporal observation. Detailed lake area values with corresponding uncertainty intervals for the period 2016–2023 are presented in Table 4, appended to Figure 7. This approach enables the distinction of statistically significant changes from variations attributable to methodological errors.

Accounting for uncertainties substantially enhances the reliability of moraine lake dynamics analysis and facilitates a more accurate assessment of the associated hydrological risks.

The annual dynamics of moraine lakes observed from satellite imagery reveal contrasting and distinct patterns for each lake. In the case of Lake No. 5, sharp fluctuations in area are observed throughout the period. Its footprint jumped from 0.077 km² in 2016 to a peak of 0.091 km² in the warm summer of 2020, contracted during the cooler, drier

2022 season (0.078 km²), and partially rebounded to 0.081 km² in 2023, giving a net 8-year gain of 4.8%. The fluctuations mirror year-to-year differences in glacier meltwater supply and testify to the lake's sensitivity to short climate pulses. While Lake No. 2 followed a more graduated curve, with the area expanding steadily from 0.061 km² to 0.075 km² by 2020, it fell during the relatively cool 2021 season and stabilised near 0.070 km² in 2023. This could be attributed to the basin's narrowness and depth, where even modest areal growth can translate into marked volume increments, reinforcing its outburst potential.

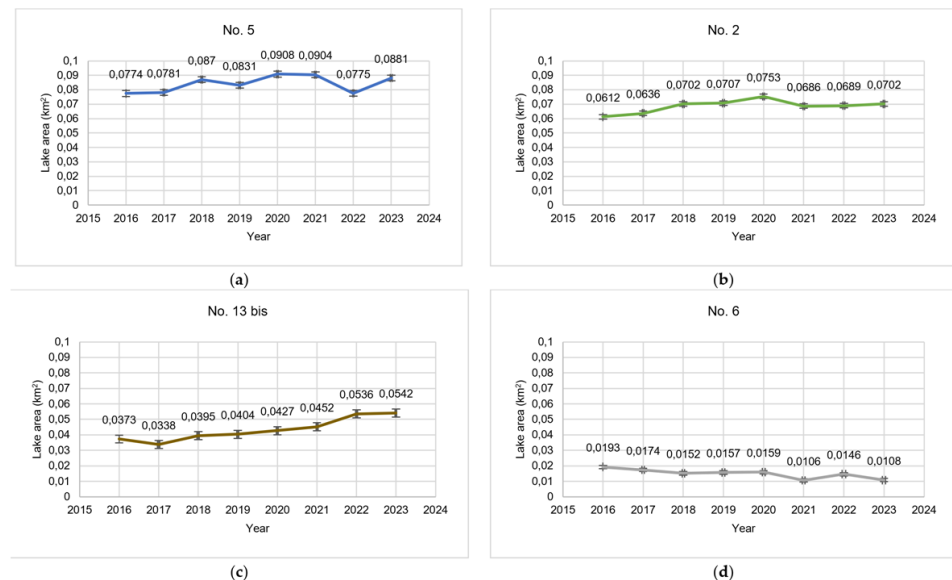


Figure 7. Variability in lake area (in square km) of our four moraine lakes over the past 8 years: (a) Lake no. 5; (b) Lake no. 2; (c) Lake no. 13 bis; (d) Lake no. 6.

Table 4. Uncertainty in lake area as a present of the total lake area.

Lake	2016	2017	2018	2019	2020	2021	2022	2023
Lake no. 6	3.19%	3.30%	3.56%	3.51%	3.56%	4.27%	3.65%	4.17%
Lake no. 13 bis	2.81%	3.10%	2.64%	2.68%	2.51%	2.40%	2.04%	2.04%
Lake no. 5	2.17%	2.19%	2.02%	2.10%	2.03%	2.00%	2.24%	2.06%
Lake no. 2	2.23%	2.23%	2.06%	2.07%	2.21%	2.15%	2.22%	2.07%

In the Ulken Almaty basin, Lake 13 bis exhibited the fastest proportional growth: NDWI polygons document an expansion from 0.039 km² (2018) to 0.054 km² (2023), a 37% surge driven by rapid thermokarst of the ice-cored frontal moraine as Glacier “Sovetov 2” retreats. The steady, monotonic trend indicates the continuing mass loss of the parent glacier rather than short-term hydrometeorological forcing. Conversely, Lake No. 6 (Kishi Almaty) shrank almost continuously because of repeated engineering measures being taken to empty it to ensure safety and prevent possible floods. Its surface fell from 0.019 km² in 2016 to just 0.011 km² in 2023, a 44% reduction that aligns with the documented pumping and cutting of a spillway channel to lower the hazard level.

Taken together, the NDWI-derived area histories confirm that lakes fed by actively retreating glaciers or undergoing thermokarst (13 bis, 2, 5) continue to gain size, though with differing volatility. Moreover, engineered intervention can override climatic drivers and reverse the natural trajectory (lake 6). When coupled with the bathymetry-based volume estimates presented earlier, these findings allow a calibrated assessment of evolving GLOF risk across the Ile-Alatau reference sites.

4.3. Quantifying Area-to-Volume Dynamics for Outburst Forecasting

Lacking continuous in situ hydrometric measurements, changes in parameters, including depth and storage volume, can be estimated via empirical scaling relations based on the lake area. To determine the volume and depth from our satellite imagery data, we employed the empirical relation derived by Kapitsa et al. [36]. They established this relationship, which links lake area to volume, by analysing bathymetric measurements from 32 lakes, located in the Zailiysky and Dzungarian Alata regions of Kazakhstan.

Applying the empirical relationships formulated by Kapitsa et al. [36] to the PlanetScope-derived surface areas yields volume and depth estimates that agree well with our 2024 bathymetric surveys for the moraine lake. Table 5 provides the information related to the parameter values obtained from empirical formula and the ground surveyed bathymetric data for our four moraine lakes. It can be observed that, for Lakes 5 and 2, the model under-predicts storage by 22.5% and 12.8%, respectively, while, for thermokarst-dominated Lake 13 bis, it over-predicts by a comparable 12.7%. These errors lie within the $\pm 25\%$ uncertainty band generally accepted for first-order GLOF appraisals and confirm that, where basin geometry conforms to the depth–area scaling implicit in the formulated relation, a single late-season PlanetScope scene can provide a serviceable proxy for field-measured volume.

Table 5. Comparison between values obtained from empirical formula and bathymetric data.

Lake No. 5			
	Square	Volume	Maximum depth
Bathymetric data (3 July 2024)	89,800 m ²	1,109,000 m ³	30 m
PlanetScope (3 July 2024)	89,447 m ²	1,117,524 m ³	
Error:		0.77%	
Lake No. 2			
	Square	Volume	Maximum depth
Bathymetric data (13 July 2024)	68,700 m ²	715,300 m ³	27.3 m
PlanetScope (1 August 2024)	72,164 m ²	823,850 m ³	
Error:		15.2%	
Lake No. 13 bis			
	Square	Volume	Maximum depth
Bathymetric data (1 August 2024)	95,281 m ²	596,844 m ³	15 m
PlanetScope (1 August 2024)	75,933 m ²	885,614 m ³	
Error:		48.3%	
Lake No. 6			
	Square	Volume	Maximum depth
Bathymetric data (18 June 2024)	15,900 m ²	64,500 m ³	12 m
PlanetScope (20 June 2024)	11,539 m ²	60,997 m ³	
Error:		5.4%	

In contrast, the repeatedly drained Lake 6 is underestimated by 58.7% because the empirical curve cannot accommodate abrupt anthropogenic draw-downs. By integrating these calibrated estimates with the NDWI-based area histories, we obtain a temporally resolved picture of water-storage evolution that feeds directly into peak-discharge calculations and, ultimately, into a more nuanced ranking of outburst hazards across the range. Changes

in lake area can be identified by comparing satellite images of the area, which can also be used to infer the lake depth, volume, and likely flood exposure [55].

5. Discussion

The present study combined detailed field surveys and satellite observations to illuminate the evolving characteristics of moraine-dammed lakes in the Ile-Alatau range. The results reveal pronounced variability in lake morphometry and dynamics even among lakes at similar elevations, underscoring the complex interplay of local factors. For instance, Lake No. 5 and Lake No. 2 were both high-volume, hazardous lakes, yet their basin shapes differed (broad vs. narrow), affecting how area growth translated to volume. Meanwhile, Lake No. 13 bis showed rapid expansion due to thermokarst processes, and Lake No. 6 demonstrated how human intervention can drastically alter a lake's trajectory. These findings underscore the importance of integrated approaches for understanding glacial lake behaviour under climate warming—a trend that is driving an overall increase in glacial lake number and size in high-mountain regions. As glaciers retreat and permafrost degrades, new proglacial lakes form and existing lakes grow, heightening the potential for unstable moraine dam [56]. In this context, our study provides timely insights that not only document how specific lakes have changed in the past decade, but also calibrate remote sensing techniques against in situ data to better assess current lake volumes and, by extension, possible outburst flood volumes.

Our observations align with regional and global patterns of glacial lake development. In the Tian Shan (which includes the Ile-Alatau), and across the Himalaya range, numerous studies have reported an increase in both the number and total area of glacial lakes over recent decades as a result of glacier melt. For example, in the neighbouring Djungarskiy (Jetyysu) Alatau range of Kazakhstan, the number of lakes increased by ~6% (2002–2014) and dozens of newly formed lakes were identified as potentially hazardous [56]. Authors identified 50 moraine-dammed lakes in that region whose outburst could threaten the surrounding areas and downstream communities [36]. Similarly, our identification of Lake No. 5 (with $\sim 1.11 \times 10^6 \text{ m}^3$ volume) as a primary outburst threat is consistent with such hazard-screening efforts. The net area changes we recorded—for instance, Lake No. 5's ~5% area gain from 2016 to 2023—are modest in comparison to some dramatic cases in the Himalaya range [57,58], yet they mirror the general trajectory of climate-driven lake growth. Notably, Lake No. 13 bis's 37% surge in area (2018–2023) is indicative of the rapid expansion observed in newly formed or recently exposed proglacial lakes. Such high growth rates have also been observed in other glacierised regions when a glacier recedes from its moraine, allowing a small lake to enlarge quickly in the newly de-iced basin. On the other hand, the shrinkage of Lake No. 6 due to artificial drainage underscores that direct human intervention can override climatic trends—a phenomenon also documented elsewhere. In Nepal, for example, the dangerous Tsho Rolpa lake was rapidly expanding (from 0.23 km^2 in 1958 to $\sim 1.55 \text{ km}^2$ by 1999) until engineering works in 2000 lowered its water level to reduce GLOF [59]. Lake No. 6's repeated pumped draw-downs are a smaller-scale analogue of this strategy, highlighting a shared recognition across Asia that certain lakes require active management.

It is worth noting that, while our study lakes are relatively small compared to Himalayan giants like Tsho Rolpa or Imja Tsho, even moderate-sized lakes can pose severe local hazards. Historical outburst floods in the High-Mountain Asia region have demonstrated that a breach of a lake with tens or hundreds of thousands of cubic meters can wreak devastation [60]. Recent examples include the 2022 Shisper lake outburst in Pakistan and the 2023 South Lhonak lake outburst in India, which underscore that outburst events are not isolated [61,62]. Our findings, in line with these studies, reinforce that continuous

monitoring and risk assessment are imperative even for smaller moraine-dammed lakes, as they are part of a broader pattern of increasing GLOF threat under climate change. In the context of Central Asia, our approach complements previous regional research by providing ground-truthed volume estimates. Earlier work in the Tian Shan largely focused on inventories and qualitative assessments [63–65]. By measuring bathymetries and comparing them with satellite-based estimates, we address a key gap noted in the literature; that is, the scarcity of depth and volume data for alpine areas. This allows for more confident application of empirical area–volume models, which have been developed for Central Asia and the Himalayas, but always carry uncertainties. In fact, consistent with findings elsewhere, we observed that simple area–volume scaling performs well for typical steep-walled lakes but can significantly misestimate volumes for anomalously shallow or human-modified lakes [56]. Such comparison with other studies highlights both the promise and the problems of extrapolating our results: the general trends (lake growth, hazard potential) concur with broad-scale assessments, but it must always be taken into account that the unique geomorphology of each lake is significant.

The insights from this study carry important implications for various stakeholders tasked with managing glacial lake hazards. For regional authorities and planners, our lake inventory and volumetric assessments provide a scientific basis for prioritising risk reduction measures. For example, knowing that Lake No. 5 contains an order of 10^6 m³ of water, and is fed by an actively retreating glacier, signals that this lake warrants regular surveillance and potentially an early warning system. The concerned state authorities can integrate this data into their hazard rankings to decide on the appropriate levels of monitoring and possible mitigation. Moreover, the utilisation of an empirical area-to-volume model for calculations from remote sensing imagery offers a low-cost way to track lake growth where fieldwork is difficult. Volumes accurate to roughly $\pm 25\%$ can be fed directly into GLOF hydrodynamic and dam-breach models, sharpening emergency-planning scenarios and identifying evacuation zones.

Communities that reside in the surrounding and downstream areas of these lakes are also critical stakeholders who benefit from this research. Our findings highlight which lakes are gaining volume rapidly or reaching thresholds of concern, information that should be incorporated into community-based disaster risk reduction. Making these results accessible through open portals, workshops, and participatory monitoring helps translate scientific assessment into local preparedness. On a broader scale, our Ile-Alatau case study has relevance for other parts of High-Mountain Asia: it demonstrates how combining ground truth (bathymetry) with satellite monitoring can inform adaptation strategies. Comprehensive information about the effectiveness of remote sensing techniques for monitoring and assessing glacial lake outburst floods (GLOFs) is demonstrated by the authors [66]. Although the geomorphology and climatic specifics differ from the Himalayas or Pamirs, the underlying principles apply broadly, and our methodology is transferable to other regions facing similar challenges. For international organisations and researchers, our work contributes to the growing body of knowledge on climate change impacts in Central Asia, a region where data is often scarce.

Despite the valuable insights gained, our study has several limitations that must be acknowledged. First, the scope of our lake sample is limited as we focused on four reference lakes, which may not capture the full diversity of moraine-dammed lake behaviour in the Ile-Alatau. Another limitation could be the temporal coverage, since our satellite-based area analysis spanned 2016–2023 with one image per year, meaning intra-annual variability (like short-term filling and draining events or peak monsoon impacts) could be missed. Additionally, while the NDWI thresholding method generally mapped the lake outlines well, it can be imperfect. Classification uncertainties may arise from shadows, seasonal

snow/ice cover on the lake, or turbidity differences, potentially causing slight under or overestimation of lake area in some years. We mitigated this by manually verifying polygons, but subtle errors remain possible. Regarding bathymetric data, our surveys provide a one-time measurement of depth distribution for each lake. We assumed that lake bottom morphology has not changed dramatically in recent years; however, processes like sediment infilling or further ice melt within moraines could alter depths over time. Without repeated surveys, we cannot quantify those changes. Moreover, the empirical area–volume (and area–depth) relationships used to estimate volumes from satellite observations carry significant uncertainties for individual lakes [56]. We found that, while the formula performed within $\sim\pm 25\%$ for several lakes, it misestimated Lake No. 6's volume (under-predicting by $\sim 59\%$). Such large errors arise because real lake shapes can deviate from the average scaling assumptions, especially very shallow lakes or those altered by human intervention, which do not deepen proportionally with areas. This highlights a limitation in applying generalised models to every lake: our volume estimates for past years (when only area was available) should be treated as first-order approximations rather than exact values. Finally, we inferred hazard potential qualitatively (e.g., by volume and growth rate), but did not formally model flood inundation extents or downstream vulnerability. These limitations suggest caution in over-interpreting any single aspect of our results, and they point to clear avenues for further research.

Building on this study, several opportunities for future work emerge. A comprehensive inventory of moraine-dammed lakes in the Ile-Alatau (and the wider Zailiyskiy Alatau) using high-resolution satellite data would allow us to place these four lakes in context, identifying other candidates for detailed study or urgent mitigation. This could be complemented by repeat field surveys: conducting bathymetric measurements at multi-year intervals on the same lakes would reveal how volumes are changing. Such information would refine our understanding of lake evolution and improve volume predictions. Furthermore, adopting emerging technologies could greatly enhance data collection. Unmanned aerial vehicles (UAVs) and drone-based LiDAR or photogrammetry could map lake surface elevations and even shallow bathymetry, while satellite altimetry missions (like ICESat-2) might be leveraged to detect changes in lake surface height, offering a way to estimate volume change remotely if coupled with area measurements [40,45]. Another important research direction is to integrate our findings with process-based GLOF modelling. Using the bathymetric profiles and lake volumes we obtained, one could run breach models (such as HEC-RAS with an embankment breach module, or specialised GLOF simulators) to simulate flood hydrographs and downstream inundation for the worst-case scenario at each lake [67]. This would move from hazard identification to quantitative risk analysis, highlighting which settlements or infrastructure would be affected and how severely. One study has emphasised that there remains a need to translate scientific assessments into community resilience [60]. Future studies could thus explore the social dimension of GLOF risk in the Ile-Alatau, e.g., assessing community awareness of glacial lakes, evaluating early warning system requirements, and identifying any barriers to emergency response. Overall, by pursuing these future directions, we can build on the foundation laid by this study, moving from diagnosing the current state of moraine-dammed lakes toward a proactive framework that anticipates changes, reduces disaster risk, and safeguards the various stakeholders who are connected by the rivers of the Ile-Alatau. In the face of accelerating climate change and its high-altitude impacts, such forward-looking research and action are essential to prevent the worst outcomes of glacial lake outburst floods.

6. Conclusions

Our integrated remote sensing and field-survey analysis provides the first volume-resolved, 8-year chronicle of moraine-dammed lake evolution in the Ile-Alatau, revealing both the pace and heterogeneity of change now underway. PlanetScope-derived shorelines showed that proglacial Lakes 5 and 2 are expanding steadily at 4.8% and 15% in area, respectively, and now storing $>1.8 \times 10^6 \text{ m}^3$ of water combined. The shallow thermokarst Lake 13 bis grew by 37% in just 5 years. In contrast, Lake 6 has been curtailed by engineering draw-down, shrinking 44% and demonstrating the efficacy of sustained intervention. Echo-sounder bathymetry confirms that our regionally calibrated area–volume model reproduces storage within $\pm 25\%$ at three of the four sites, offering a rapid screening tool where ground access is limited.

These findings underscore that the lake response to climate forcing is strongly modulated by basin morphology and human management, so uniform hazard assumptions are inappropriate. Secondly, the confluence of sub-daily, 3-metre imagery and targeted bathymetry can now deliver near-real-time updates of both area and volume, enabling dynamic rather than static risk assessments. Moreover, Lakes 5 and 2 have crossed the empirical volume ($>10^6 \text{ m}^3$) and setting (ice-cored moraine dams) thresholds associated with catastrophic GLOFs in Central Asia, making them prime candidates for early warning systems, contingency routing, and periodic draw-down.

Policy makers should prioritise investment in automated satellite monitoring pipelines, formalise GLOF-specific evacuation maps for downstream settlements, and incorporate adaptive engineering—such as siphon outlets—into regional climate-risk strategies. Future research should extend the bathymetric network, refine area–volume scaling for low-relief basins, and couple lake-storage trajectories with glacier mass-balance and extreme-precipitation projections to anticipate compound hazards. By demonstrating an end-to-end methodology that is both transferable and operational, this study offers a blueprint for safeguarding mountain communities facing accelerating cryospheric change.

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