Evolution of mountain lakes in Pskem river basin, Uzbekistan.

In the modern conditions of active use of the foothill and mountainous territories of Uzbekistan, the problem of the threat of outburst of high-mountain lakes of various genesis is becoming increasingly urgent and still remains poorly studied. Research indicates that modern exogenous processes are widespread in mountainous areas, expressed in the formation of mudflows, landslides, rockfalls, avalanches and breakthrough of mountain lakes. Among the above-mentioned catastrophic natural phenomena, mudflows formed as a result of the breakthrough of glacial and dam lakes, as well as intraglacial and intramoraine reservoirs, have a particularly destructive force.

Floods caused by the outburst of high-mountain lakes have enormous destructive power and can cause significant damage: flooding of riverbed areas; destruction of residential buildings, recreation areas, hydraulic structures, industrial facilities; washing away of roads and power lines; flooding or erosion of agricultural lands; death of livestock, human casualties.

Climate change is a driving force affecting mountain lake dynamics globally, with significant impacts observed in Central Asia's mountain ranges. Uzbekistan, a region that has historically lacked a comprehensive assessment of glacial lakes and their temporal evolution, is now the subject of an extensive study focusing on the Pskem River basin.

Utilizing high-resolution satellite imagery from WorldView-2, SPOT5, and IKONOS spanning from 2002 to 2022, along with field study data spanning the last 50 years, this report presents an overview of inventory of the region's mountain lakes, marking a significant enhancement over previous Soviet archival records.

This first detailed inventory incorporates all lakes located at altitudes above 1500 m and with an area exceeding 100 m^2 within the territory of Uzbekistan. The findings indicate an increasing trend in both the number and area of lakes, in line with global observations. Additionally, there is a noted rise in the frequency and number of lake outburst events, prompting an in-depth outburst potential assessment using updated methodologies tailored to local climatic conditions and historical event data.

Introduction.

The impact of global warming is profoundly reshaping the cryosphere, particularly accelerating the retreat of glaciers worldwide, with Central Asia being a region of significant concern. This retreat often results in the fragmentation of larger ice masses into smaller entities and has various downstream effects such as altering river discharge patterns and affecting water resource availability. One of the direct consequences is the formation and expansion of mountain lakes, which brings an increased risk of glacial lake outburst floods (GLOFs)—a threat that Central Asia, with its history of destructive GLOFs in the Northern Tien Shan, Hissar-Alay, and Pamir regions, knows all too well.

Historical records and environmental studies of Central Asia's mountainous regions, dating back to the early 20th century and extending through the Soviet era, have provided a foundation for understanding these dynamic landscapes. However, much of this data has been localized and piecemeal. The region's vulnerability was brought into sharp relief by the catastrophic GLOFs in the latter half of the 20th century, which prompted extensive in-situ observations of over 300 mountain lakes, leading to the creation of the first inventories of Central Asia's mountain lakes and an understanding of their potential hazards.

In the face of such risks, recent efforts have focused on the identification of mountain lakes, the development of detailed inventories, and the determination of their hazard potential through advanced very high-resolution satellite imagery. Despite these advancements, studies in Western Tien Shan and Hissar Alay have remained scarce, and the limited spatial resolution of earlier satellite-based inventories has resulted in significant errors, especially for smaller lakes. The consequences of even small outbursts can be devastating, as evidenced by tragic events in the Shakhimardan river catchment and the Shahdara river catchment, which collectively claimed over a hundred lives.

This report's objective is to enhance the understanding of mountain lake dynamics within the context of the Pskem River basin in Uzbekistan. By providing an updated inventory of mountain lakes in this region, the report aims to refine the assessment of their outburst potential, leveraging the precision of very high-resolution satellite imagery validated against field data. The importance of this work lies not only in its scientific merit but also in its practical applications for risk management and climate adaptation strategies, ensuring the safety of human populations and the conservation of the environment in a changing Central Asian landscape.

The mountainous terrain surrounding Tashkent, the capital city of Uzbekistan, is geographically segmented into the northeastern expanse of the Chirchik river basin and the southeastern Angren area within the Akhangaran river basin. This area encompasses the river systems of Pskem, Chatkal, Oygaing, Maydantal, Angren. Nestled in the northeastern sector of Uzbekistan, the region is framed by the Syr Darya rivers and the fringes of the Western Tien Shan range. Stretching over 280 kilometers from the northeast to the southwest, and spanning 180 kilometers across, the Chirchik-Akhangaran district boasts a varied topography.

The landscape transitions from the towering elevations of the northeast and east down to the comparatively level southwestern territory. The area is known for its active tectonic movements. Mount Beshtor stands as the zenith of the Chirchik-Akhangaran district, soaring to an altitude of 4,299 meters. The climatic conditions are marked by average summer temperatures hovering around 20°C and winter lows plummeting to -30°C.

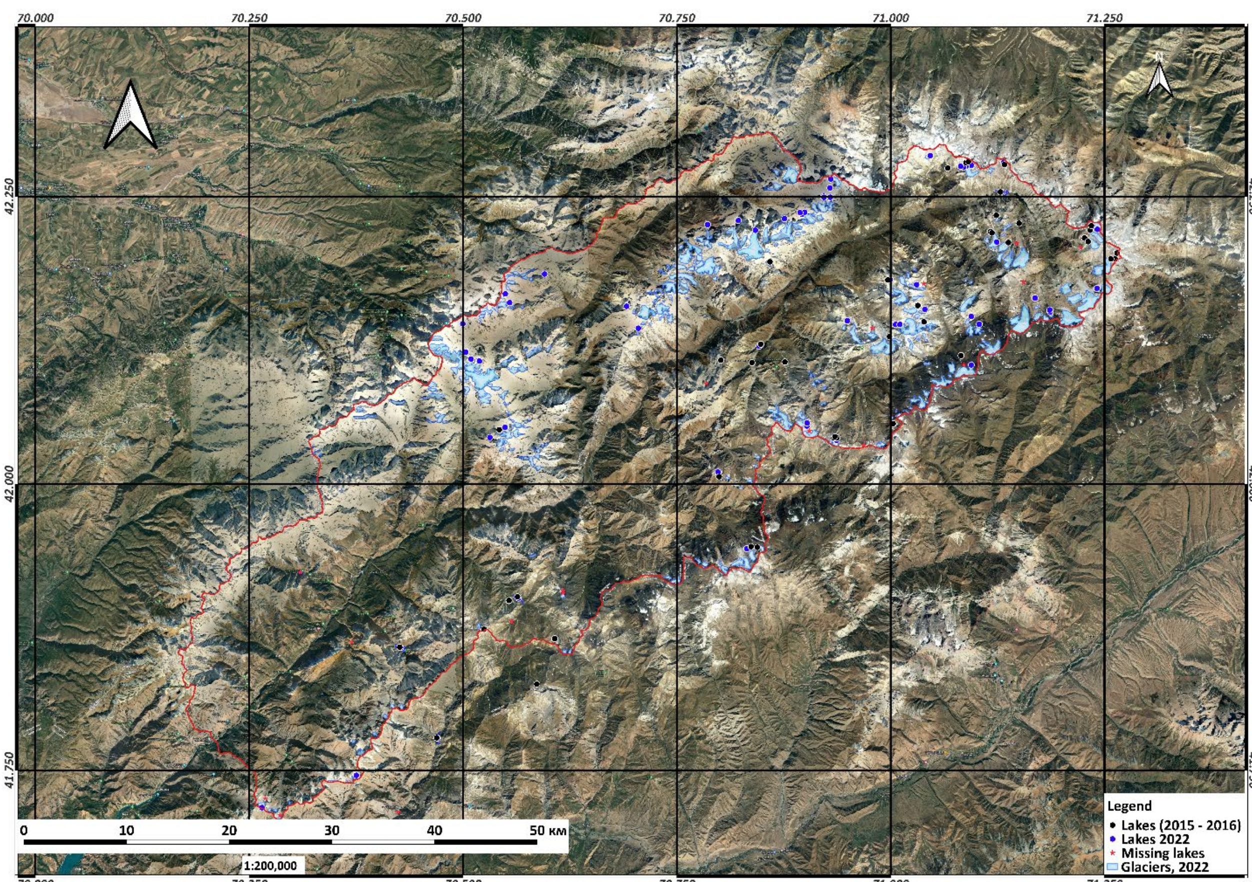


Figure 1. Pskem river basin, the tributary of the Chirchik river, the study site of Tashkent region.

Precipitation patterns vary across the district, with the plains accumulating 250 to 300 mm annually, the foothill zones receiving slightly more at 350–400 mm, and the western mountainous parts, subject to the brunt of cold air masses, registering between 800–900 mm. Notably, the bulk of the annual rainfall occurs during the colder seasons.

The Chirchik river basin, with a notable area of 14,900 km², serves as a channel for the glacial meltwaters of the Chatkal and Pskem rivers. Originating from the Talas Alatau's southwestern slopes, the Chatkal river meanders westward, flanked by the Sandalash and Koksu-Chatkal mountain ranges. The Pskem's sources trace back to the glaciers straddling Kazakhstan and Uzbekistan. Another significant river, the Akhangaran, with a basin area of 7,710 km², springs from the Chatkal range and is entirely contained within Uzbekistan, eventually joining the Syr-Darya river with peak flows in the springtime.

Observations of outbursts of dammed, moraine-glacial lakes and intra-moraine-glacial reservoirs show that this phenomenon is multifactorial. Detailed observations of outbursts of various types of lakes are absent due to objective reasons, primarily due to the inaccessibility of territories, therefore it is impossible to model the processes of outburst of high-mountain lakes correctly. Which determines the need to develop criteria based on which it would be possible to draw sufficiently justified conclusions about the outburst hazard of a particular lake.

Factors causing or contributing to the outburst of high-mountain lakes can be divided into: morphological, engineering-geological and hydrometeorological.

Morphological factors:

• type of basin by morphogenesis;

• volume of lake bowls and intra-glacial reservoirs;

• greatest depth;

• indicators of elongation, compactness, relative depth;

• excess of the lowest point of the dam above the water level in the lake;

• buffer volume, i.e. the difference in volumes at spontaneous outflow and high water level;

• dynamics of moraines.

Engineering and geological factors:

• tectonics of the area where the lakes are located;

• geological structure and lithological composition of rocks;

• porosity and voidage of water-retaining dams and the lake bed;

• the nature of the conjugation of blockages and moraine deposits with the bedrock sides and the valley bed;

• the nature of the processes of water runoff from the lake and the interaction of the flow with the body of the blockage or moraine, determining the process of filtration and suffusion;

• dynamics of seasonal and permafrost zones.

If there are modern or ancient tectonic faults in the area of the lake, there is a possibility of movement of huge masses of rocks, which can contribute to the collapse of part of them into the lake basin, its overflow and destruction of the dam. As a result of mechanical and chemical suffusion, which occurs when water is filtered through the body of a blockage or moraine, weakened zones are formed, leading to the destruction and erosion of rocks. Springs, hollows, erosion niches and a gully network are formed on the surface of the downstream slope of dams. The most dangerous processes are the cutting of ravines into the body of blockages, leading to a violation of its integrity, the connection between individual blocks, the possibility of movements, the formation of cracks and catastrophic destruction.

Hydrometeorological factors:

• abnormally high accumulation of precipitation in the winter-spring period and abnormally high air temperatures during the period of greatest filling of lakes, contributing to an intensive increase in the level and their overflow;

• the size of modern and ancient glaciation, determining the stadial moraine complexes and contributing to the formation of sporadic moraine-glacial lakes;

• pulsation of glaciers;

• ablation processes of glaciers and snowfields;

• the position of the zero isotherm;

• intensity of filling and emptying of reservoirs;

• amplitude of level fluctuations.

These factors allow us to indirectly determine changes occurring in the lake-dam complex and various deviations from ordinary situations. For example, a temporary cessation of runoff in periglacial zones during a period of intensive melting indicates disturbances in the drainage system of the glacier tongue and moraine, their blockage and accumulation of water masses in intra-moraine and intraglacial reservoirs. Significant values of the specific water catchment indicators (the ratio of the water catchment area to the lake area), conditional water exchange (the ratio of the inflow volume to the lake volume) in combination with the morphological features of the basin, the conditions of outflow from the lake (filtration, overflow) and their changes also indicate the state of water-retaining dams and the possibility of critical situations.

Methods.

For the purpose of identifying lakes within the Pskem river basin region, a diverse array of satellite imagery was utilized, including WorldView-2, IKONOS, and SPOT 5, as delineated in Table 3. These images were sourced from a variety of fee-free public web portals, such as Google Earth, Bing, Yandex, Here.com, and Arc Imagery, offering resolutions from as sharp as 0.5 m for WorldView-2 (panchromatic at Nadir) to 2.5 m for SPOT 5 imagery. Predominantly, these images were captured in the warmer season, specifically from June to October, and span the years 2010 to 2022, with a bias towards August to minimize snow cover interference. For precision in area calculations, we reprojected the original imagery from the World Mercator projection to the UTM projection, zone 42, on the WGS84 ellipsoid, utilizing ArcMap software for topographic alignment.

Advanced topographic data, including lake elevations and dam specifics, were extracted from the integrated datasets of Japanese L-band Synthetic Aperture Radars (PALSAR and PALSAR-2) from the Advanced Land Observing Satellite (ALOS) and the Shuttle Radar Topography Mission (SRTM). The PALSAR system delivers high-resolution all-weather, day-and-night surveillance, along with interferometric capabilities.

Image analysis

The process of lake identification in the high-resolution imagery was conducted manually across the mountainous territories of Uzbekistan, with special attention to the Pskem river basin. This involved discerning the lakes by their shapes, hues, and proximities to glacial and rock glacial features. We conducted a thorough visual sweep from the highest altitudes downstream, labeling the lakes in a clockwise direction and then digitizing their contours into ArcGIS shapefiles.

Our inclusion criteria encompassed lakes situated above 1500 m asl to encapsulate the periglacial zones, with a minimum area of 100 m², a practical threshold for visual detection. Below, we delve into the classification of these lakes based on their relation to glacier positions.

Lakes were categorized based on established classifications and defined as follows:

- **Supraglacial lakes** are perched atop glacier surfaces, confined by ice, typically forming in stagnant, flat areas due to thermokarst activity.

- **Proglacial lakes** are found at the fore or flanks of glaciers or adjacent to nunataks, usually moraine-dammed but can also be ice-dammed or rock-dammed.

- **Periglacial lakes**, named after the zone influenced by past glaciation, are considered here to be within 2 km of glacier termini, based on field observations, indicative of their genesis being intimately linked to glacial activity.

- **Extraglacial lakes** are situated beyond 2 km from current glacier termini, often dammed by landslides or rock, with some resulting from past glaciations.

Dams were identified as barriers withstanding the hydraulic pressure of the lake's water body, discernible in satellite images. These included:

- **Ice dams**, primarily composed of glacial ice, subject to local topography and hydraulic pressures.

- **Ice-debris dams**, comprising ice with moraine or rock glacier material.

- **Moraine dams**, remnants of past glaciations that now act as barriers to meltwater.

- **Landslide dams**, formed by landslides and often linked to seismic activity or rapid meltwater flow.

- **Bedrock dams**, created in the wake of glacier retreat leaving deepened bedrock topography.

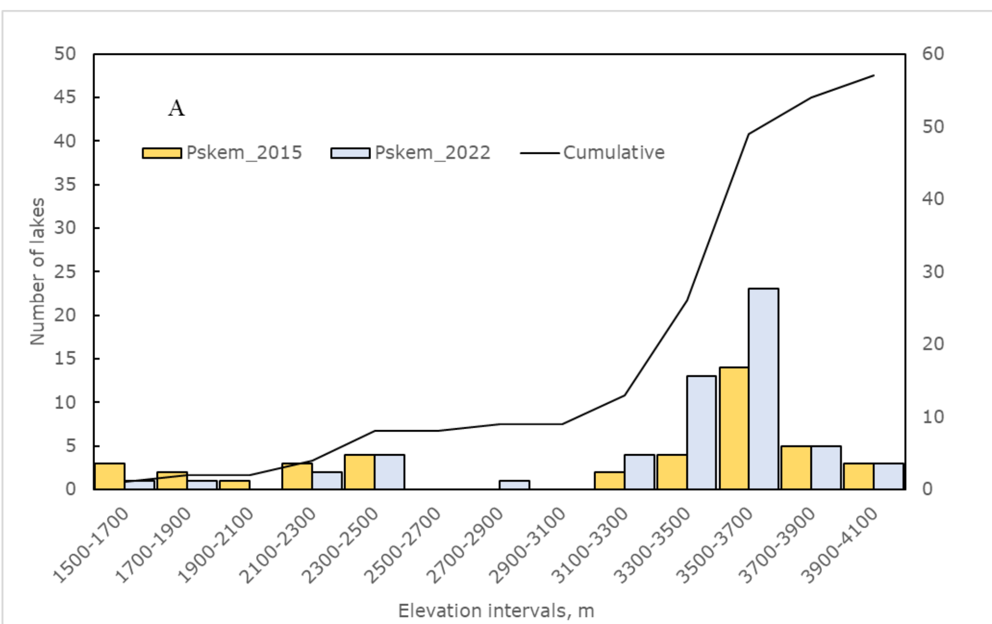
Connections and triggers for lake outbursts, freeboard height, and dam geometry were also analyzed for their role in potential outburst events. Each lake was examined for its outburst probability based on several parameters, which were subsequently recorded in the inventory database for the Pskem river basin. This database features 16 parameters, including the lake ID, coordinates, altitude, area, catchment name, region name, dam type, lake type, drainage type, connections, estimated freeboard, dam height, crest width, potential impact triggers, hazard index value, and hazard rank.

In assessing lake area uncertainties, errors were estimated to be half the pixel's dimension, leading to a mean error calculation for each satellite image's resolution. This provided a comprehensive uncertainty analysis for lake area estimations, with total uncertainty for all lakes averaging at 0.8%. Georeferencing errors were deemed negligible due to the lakes' typically flat terrain locations. It's important to note that lake areas can fluctuate considerably during the melt season and year over year, necessitating the use of the most dynamic and contrast-rich images for accurate representation.

Results.

During analysis, focusing on the Pskem River basin, we have catalogued an array of lakes, with a significant number identified as new bodies of water in 2022. These lakes present a wide range of areas, elevations, and hazard potential classifications.

The results of the Pskem River basin reveals that from 2015 to 2022, lake areas have undergone considerable changes, with some expanding and others shrinking in size.



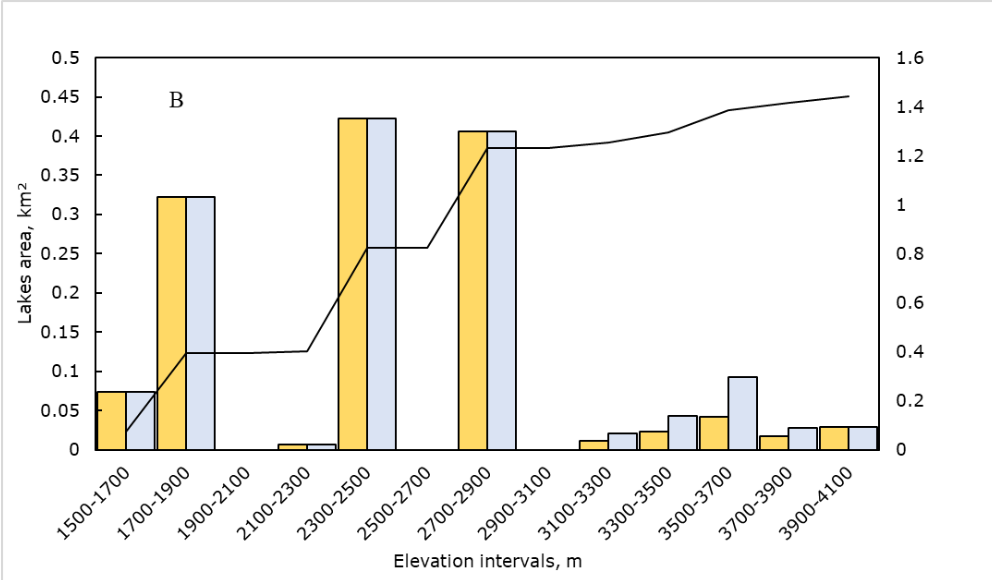


Figure 2. Distribution of lakes in the study region by area and elevation in 2015 and 2022.

On average, lakes have increased in area by approximately 1,710 square meters, although this change is highly variable, as indicated by a standard deviation of 10,127 square meters. The maximum increase in a single lake's area was about 57,458 square meters, while the largest decrease was around 17,380 square meters. In 2023, the study identified 21 new lakes, with an average area of 3,180 square meters and significant size variability.

The mean elevation of the lakes stands at approximately 3,268 meters, displaying variability in lake altitudes, with the lowest at 1,525 meters and the highest at 4,088 meters. A correlation has been observed between the hazard criteria and the physical characteristics of the lakes; those with "Low" hazard criteria are generally larger in area and situated at lower elevations, whereas lakes with "High" or "Medium" criteria are found at higher elevations with varied areas.The comprehensive area analysis from 2022 compared to 2015 underscores the dynamic nature of the Pskem River basin's glacial lakes, reflecting broader regional climate trends. This report underscores the critical need for ongoing monitoring and assessment to inform risk management and climate adaptation strategies in Uzbekistan's mountainous regions.

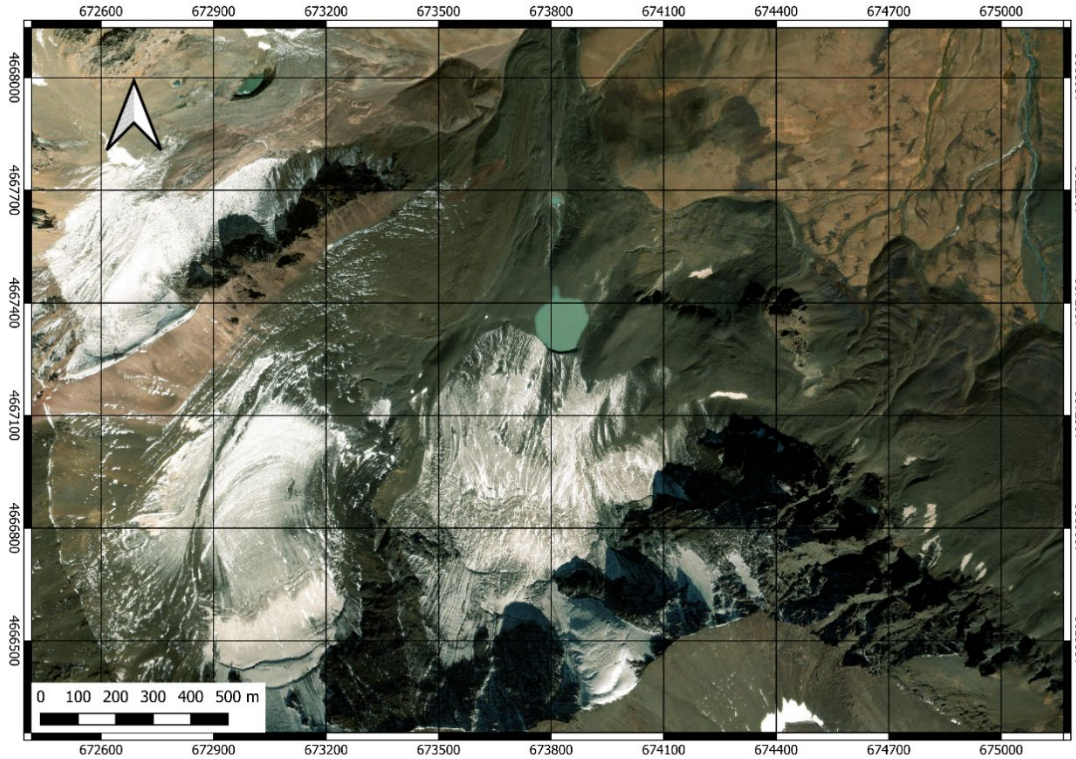


Fig. 3. Newly identified lake – Pskem river basin, at the altitude of 3623 m.a.s.l., average area of 17 000 m^2 and medium outburst hazard.

Area and Elevation Distribution: In 2022, the dataset includes 21 newly identified lakes, broadening the scope of our hydrological understanding of the region. These lakes demonstrate a considerable range in size, with the mean area being approximately 3,180 square meters, and a notable variability in dimensions as indicated by the standard deviation of around 4,007 square meters.

The lakes are categorized by hazard criteria, with 'High' hazard lakes averaging an area of 3,789 square meters and 'Low' hazard lakes averaging significantly more at about 34,653 square meters, suggesting that lakes with lower hazard potential are generally larger and possibly more stable.The elevation-based categorization aligns with the hazard criteria, where 'High' hazard lakes are situated at an average elevation of 3,563 meters, while 'Low' hazard lakes tend to be at a lower mean elevation of approximately 2,311 meters.

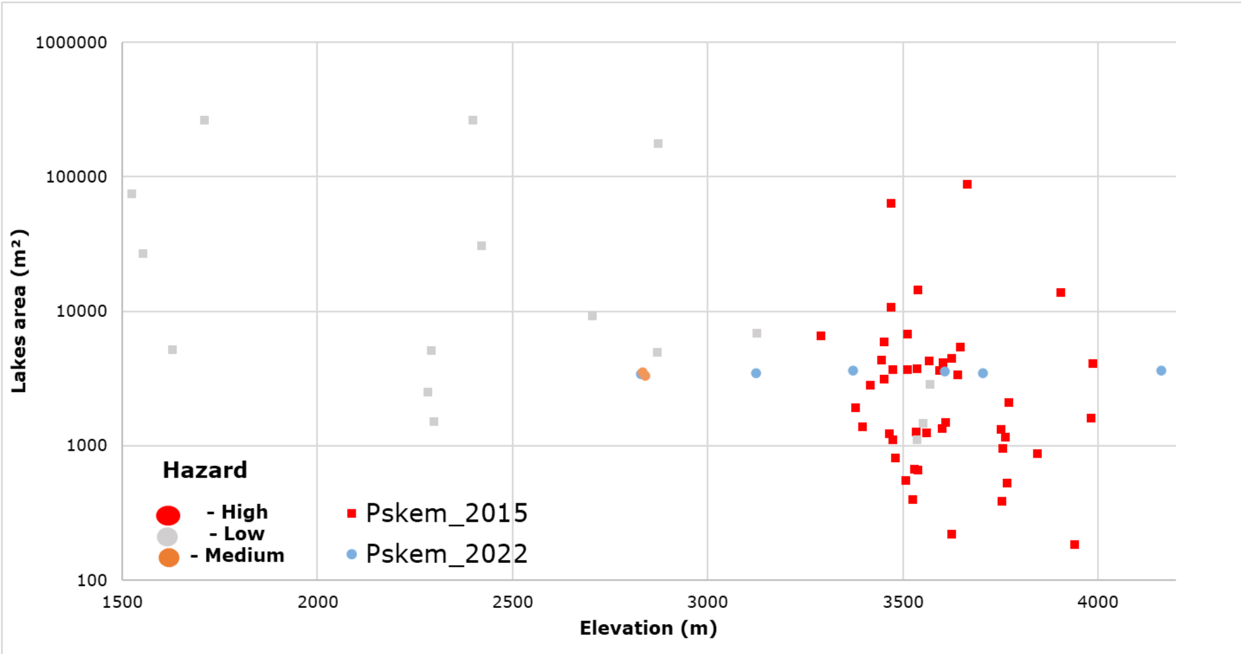


Fig. 4. Distribution of lakes according to lake area and elevation.
Different colors indicate differences in outburst potential and observed year.

A discernible correlation between hazard criteria and lake characteristics suggests that lakes with 'Low' hazard criteria are generally larger and at lower elevations, compared to those with 'High' or 'Medium' criteria, which are smaller and situated at higher elevations.

This comprehensive study reinforces the understanding that glacial lakes within the Pskem River basin are undergoing significant alterations in response to climatic and environmental changes. These alterations are not uniform across the region, with some lakes expanding and others contracting. The findings underscore the importance of continued monitoring and assessment to inform risk management strategies for the local communities and ecosystems dependent on these hydrological resources.