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Susceptibility to Glacial Lake Outburst Flood in the Chajolpaya subbasin, northern Cordillera Real, Bolivia

Suscetibilidade à inundação de lagos glaciais na sub-bacia Chajolpaya, norte da Cordilheira Real, Bolívia

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Abstract: The global trend of glacier area loss, including those located in mountain environments has increased the number of glacial lakes all regions of the world over the 20th and 21st centuries and various mountain communities are at risk of GLOF events. This study aimed to investigate the flood susceptibility associated with glacial lakes fed by tropical glaciers, located in a pilot study area of the Chajolpaya sub-basin, in the north of the Cordillera Real, Bolivia. To assess susceptibility class of GLOFs, factors were selected from glacial characteristics and the AHP methodology - Weighted Hierarchical Analysis method was used. Satellite images were used, referring to the years 1999, 2011, 2015, and 2022, from which 16 glacial lakes in the study area were selected, according to established criteria, to be analyzed and monitored. The number of glacial lakes and the total area of glacial lakes in the area increased since 2015. According to results, two lakes have very high susceptibility to flooding (GLOF - Glacial Lake Outburst Flood), four lakes have high susceptibility to GLOF, six lakes have medium susceptibility, no lake has low susceptibility and four have very low susceptibility to GLOF. These results indicate the existence of cryospheric risks associated with very high and high-risk lakes, which can impact downstream communities.

Keywords: Glacial Lakes; GLOF; Cryospheric Hazards.

Resumo: Grande parte das geleiras em todo o planeta vem sofrendo retração nas últimas décadas como resposta às mudanças climáticas globais. A perda de área das geleiras em todas as regiões do mundo, ao longo dos séculos XX e XXI, resultou em aumento de lagos glaciais. O objetivo deste estudo foi investigar a suscetibilidade de inundação associada aos lagos glaciais alimentados por geleiras tropicais, localizadas em uma área de estudo piloto da sub-bacia Chajolpaya, no norte da Cordilheira Real, Bolívia, utilizando a metodologia AHP - Análise Hierárquica Ponderada, com auxílio de ferramentas de sensoriamento remoto e geoprocessamento. Foram utilizadas imagens de satélite, referentes aos anos de 1999, 2011, 2015 e 2022, a partir das quais foram selecionados 16 lagos glaciais na área de estudo, mediante critérios estabelecidos, para serem analisados e monitorados. Os resultados encontrados indicaram que dois lagos possuem muito alta suscetibilidade à inundação (GLOF - *Glacial Lake Outburst Flood*), quatro lagos possuem alta suscetibilidade a GLOF, seis lagos possuem média suscetibilidade, nenhum lago possui baixa suscetibilidade e quatro possuem muito baixa suscetibilidade a GLOF. Tais resultados indicam a existência de riscos criosféricos associados aos lagos de muito alto e alto risco, e que podem impactar as comunidades a jusante.

Palavras-chave: Lagos Glaciais; GLO; Riscos Criosféricos.

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1. Introdução

The global trend of glacier area loss, including those located in mountain environments throughout the 20th and 21st centuries, has increased the number of glacial lakes (BAJRACHARYA; MOOL, 2009; WILSON et al., 2018). Glacial lakes form behind moraine dams or ice dams, and the breach of these dams can lead to flooding, an event known as GLOF - Glacial Lake Outburst Flood (ITURRIZAGA, 2011). During these events, the accumulated meltwater in the glacial lake is suddenly released (ITURRIZAGA, 2011), potentially causing downstream floods with socio-economic and geomorphic impacts (RICHARDSON; REYNOLDS, 2000; CAREY, 2005).

Lakes at risk of the Glacial Lake Outburst Flood are generally associated with those closest to the glacier, located in areas of high slope and lakes dammed by small moraines (HU et al., 2022; GAIKWAD et al., 2022). Various mountain communities are at risk of GLOF events (WORNI et al., 2012; ANACONA; MACKINTOSH; NORTON, 2015; ZHANG et al., 2023). Therefore, tropical glaciers are connected to glacial lakes and rivers, which are considered relevant for several Bolivian communities. Furthermore, important Bolivian rivers are part of the Madeira River basin, making up the Amazonas hydrographic region (RIBEIRO, 2014). In this sense, the Cordillera Real, located in Bolivia, was chosen to carry out this study.

Glaciers in mountainous regions play a crucial role in the hydrological and socio-economic systems of various countries. They are essential for local communities, providing water for domestic use, energy production in small hydroelectric plants, and irrigation for agriculture, while also holding significant scenic value. Tropical glaciers in Bolivia are linked to glacial lakes and rivers, which are vital for the surrounding communities, particularly those within the Madeira River basin, a part of the larger Amazon River basin. Monitoring tropical mountain glaciers is important for understanding climate change, with studies on glacial lakes and GLOFs (glacial lake outburst floods) being crucial for assessing cryospheric risks. By employing the Analytical Hierarchy Process (AHP) method and remote sensing data, researchers can better understand the temporal evolution of lake areas in response to glacial retreat, ultimately contributing to regional studies.

The primary objective of this research is to investigate GLOFs (glacial lake outburst floods) susceptibility in the Chajolpaya watershed, in the northern portion of the Real Cordillera, Bolivia, using orbital remote sensing data.

2. Methodology

Figure 1 identifies the study area of this work, the Chajolpaya hydrographic sub-basin, located in the Cordillera Real, a vast mountain range north of the capital of Bolivia. Table 1 presents the data used to carry out the present study. The selection of satellite images considered the dry seasons, i.e., with the lower cloud cover, therefore, between the months of May to October. The satellite images selected to carry out this research were co-registered and the mean squared error (RMSE - Root Mean Squared Error) obtained was between 0.34 and 5.97 m. The vectorization of the lakes was based on images from the years 1999, 2011, 2015 and 2022. The processing and organization of the database were carried out in ArcGIS.

Table 1 – Data and respective sources used in the research.

Data	***Source***
Precipitation data	http://senamhi.gob.bo/index.php/inicio
Global Land Ice Measurements from Space - GLIMS	https://www.glims.org/
Shapefiles of rivers and canals in the study region	http://geo.gob.bo/portal/
DEM (Alos Palsar)	https://search.asf.alaska.edu/#/
Image *Planet Scope*	https://www.planet.com/explorer/
Image *WorldView-2*	-
Images Landsat 5	https://earthexplorer.usgs.gov/

Source: Authors (2023).

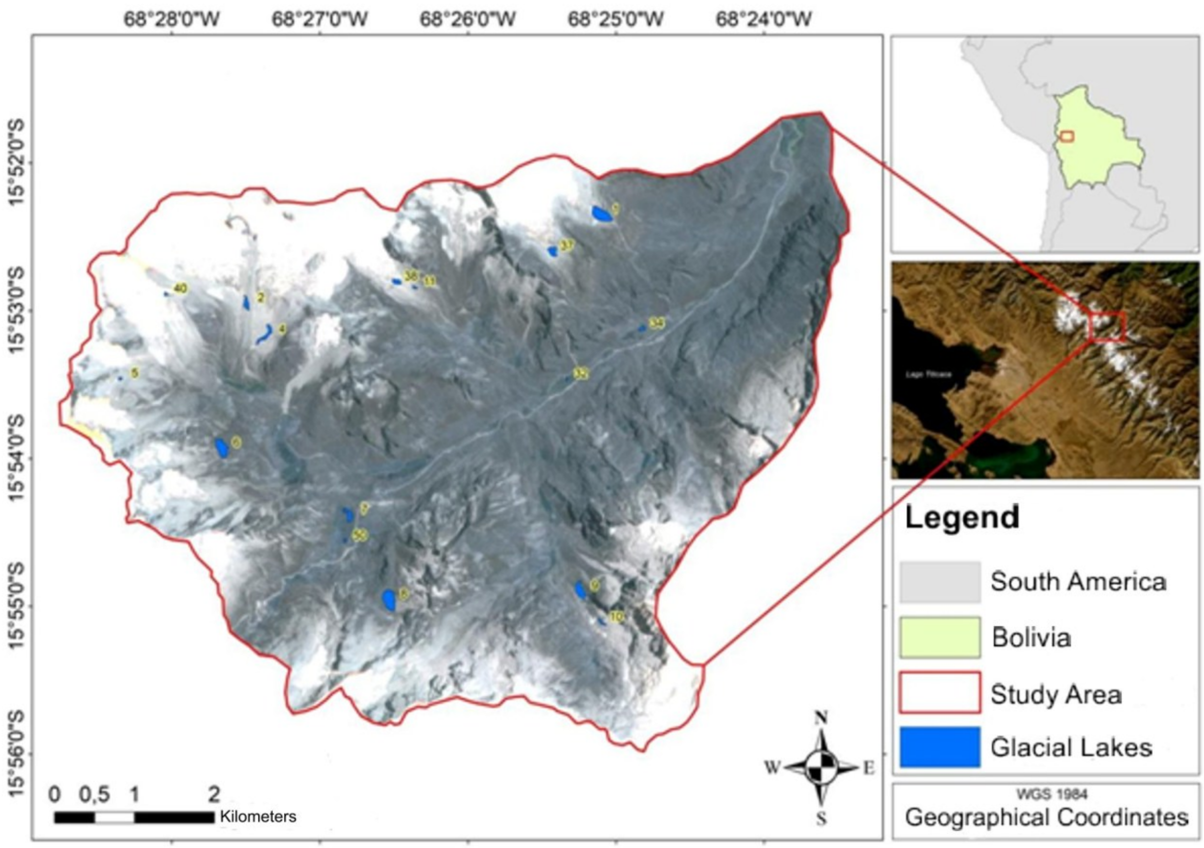

Figure 1 – Location of the study área and ID of the analyzed glacial lakes.
Source: Authors (2023).

The Planet Scope image from 2022 was used to delimit the sub-basin concerning the study area. The image was imported into the ArcGIS program. The hydrographic sub-basin of the study area was vectorized, based on the drainage basins polygons mapped and made available by the Global Land Ice Measurements from Space (GLIMS), in addition to using shapefiles of rivers in the region. Also, in this step, the Digital Elevation Model (DEM) from the ALOS satellite with the PALSAR sensor, which provides altimetry information, was downloaded and used to vectorize the sub-basin. After delimiting the study sub-basin, the sub-basin area was calculated, resulting in a value of 49.63 km².

Regarding the parameters and weights used for the AHP methodology application, the methodology of Gaikwad et al. (2022) was modified and applied in this study. In the present study, the following parameters were used: glacial lake area (AL), adjacent glacier area (AG), distance from lakes to adjacent glaciers (DG), slope (D), lake elevation (EL), lake dam type (TB), distance between lakes and nearest community (DC), and distance between lakes and the river (DR). The classes and scores were elaborated according to the specific characteristics of the present study. Therefore, eight parameters with different classes and weights were applied (Table 2). Regarding the classes of each parameter, class 1 indicates low risk, class 2 is medium risk, and class 3 is high risk. Regarding the weights of each parameter, the same weights applied by Gaikwad et al. (2022) were used.

After obtaining and processing the eight parameters described above and including their respective classes/scores in the attribute table of the lakes shapefile in 2022, these polygons were converted to raster (3 m spatial resolution). Following of this step, it was possible to apply the Analytic Hierarchy Process (AHP) in the present study, adapting the methodology proposed by Gaikwad et al. (2022) (Figure 2).

Table 2 – Parameters and their respective classes and weights.

Parameter	***Parameter Classes***	***Parameter Weight (AHP)***
Lake Area (AL)	1 - up to 0.00025 km² 2 - between 0.00025 and 0.01 km² 3 - above 0.01 km²	0.294
Adjacent Glacier Area (AG) or Glacial Cover	1 - up to 1.18 km² 2 - between 1.18 and 5.27 km² 3 - above 5.27 km²	0.247
Distance from Lake to Adjacent Glacier (DG)	1- greater than 2 km 2 - between 0.5 and 2 km 3 - less than 0.5 km	0.161
Slope between Glacier and Lake (D)	1 - less than 30° 2 - between 30 and 45º 3 - greater than 45º	0.098
Lake Elevation (EL)	1 - less than 4,390 m 2 - between 4,390 and 5,075 m 3 - above 5,075 m	0.094
Lake Dam Type (TB)	1 - without dam 2 - with rock dam 3 - with moraine dam	0.049
Distance from Sub-basin to Community (DC)	1 - greater than 50 km 2 - between 30 and 50 km 3 - less than 30 km	0.036
Distance from Lake to River (DE)	1 - greater than 2,400 m 2 - between 1,200 and 2,400 m 3 - less than 1,200 m	0.020

Source: Authors (2023) – parameters and weights adapted from Gaikwad et al. (2022).

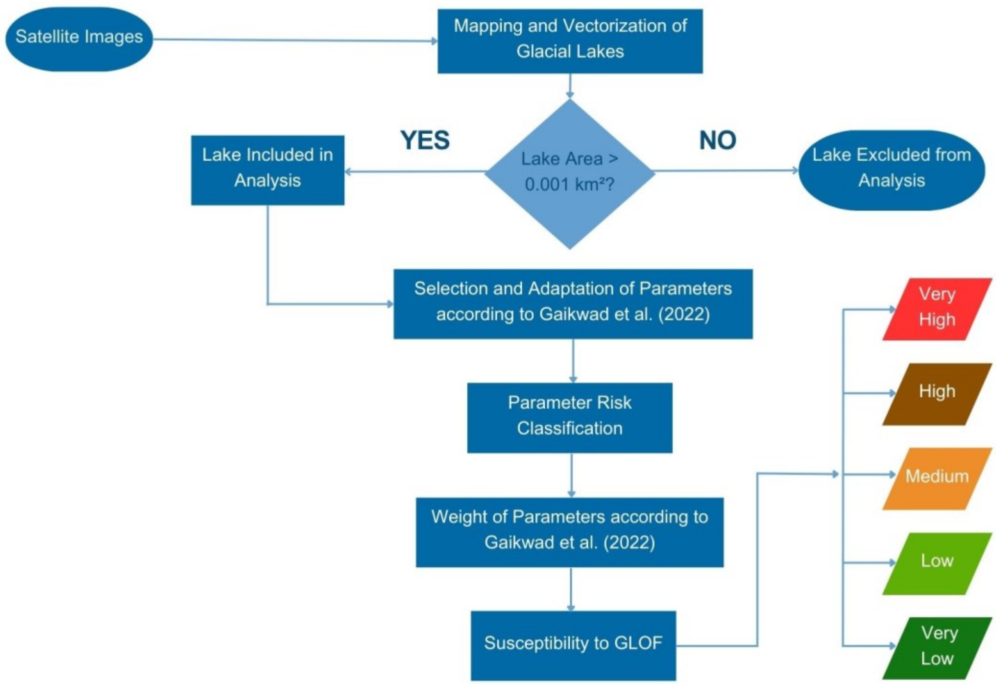

Figure 2 – Schematic representation of the AHP method.
Source: Authors (2023).

To extract the weighted hierarchical analysis methodology, susceptibility to Glacial Lake Outburst Floods (GLOFs) was calculated using the raster files generated for each parameter (which contain the classes of each lake) and their respective weights:

$$\text{Susceptibility to GLOF} = ((AL*0.294) + (AG*0.247) + (DG*0.161) + (D*0.098) + (EL*0.094) + (TB*0.049) + (DC*0.036) + (DR*0.020))$$

On what,
AL = Lakes Area Raster
AG = Adjacent Glacier Area Raster (glacial cover)
DG = Distance Raster from Lakes to Adjacent Glacier
D = Slope Raster between the Lakes and the Adjacent Glacier
EL = Lakes Elevation Raster
TB = Lagos Dam Type Raster
DC = Distance Raster from Lagos to the nearest Community
DR = Distance Raster from Lakes to River

3. Results and Discussion

3.1 Variation in Glacial Lake Area

The sub-watershed showed 50 different lakes when observing satellite images, but had 32 lakes in the year 2022, representing a total area of 0.1558 km² on that date. Only lakes with an area greater than 0.001 km² in 2022 were considered for this study, in accordance with the proposal by Kougkoulos (2019) (Figure 3). As a result, 16 lakes, representing an area of 0.1483 km², were included in the analysis. The number and area of the lakes varied over time.

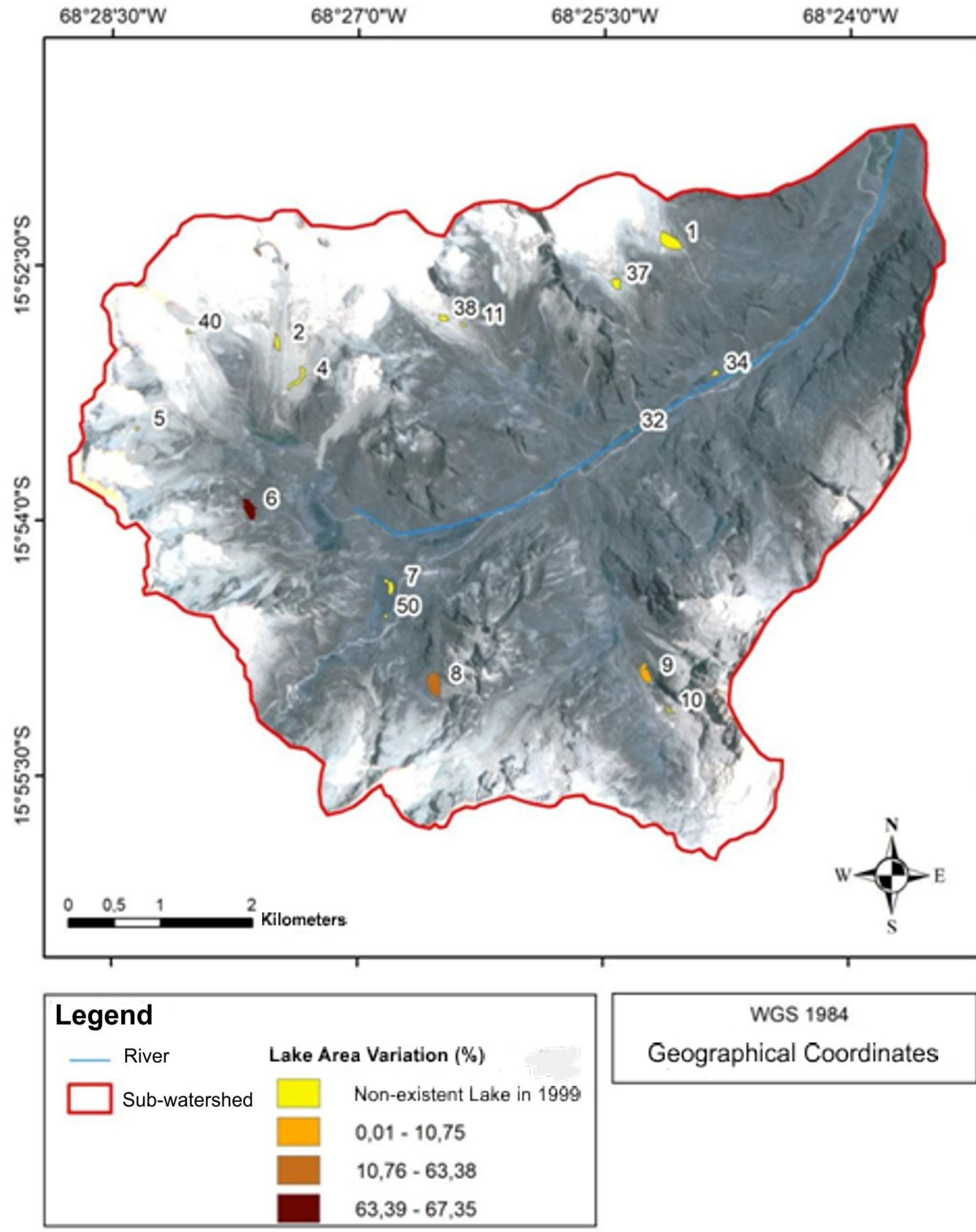

Figure 3 – Lake area variation between 1999 and 2022.
Source: Authors (2023).

Similar findings of an increase in the number and size of lakes are also reported in other regions (SHUKLA; GARG; SRIVASTAVA, 2018; ANACONA; MACKINTOSH; NORTON, 2015; CARRIVICK; TWEED, 2013), including Bolivia (COOK et al., 2016). Cook et al. (2016) demonstrated an increase in the number and size (area) of proglacial lakes in the Bolivian Eastern Cordillera from 1986 to 2014. The total number of lakes within 500 m of the glacier margins increased from 145 to 225 lakes (55%), while the lake area increased from 6.33 ± 0.63 to 8.73 ± 0.87 km² (38%). Likewise, the behavior of lakes in the present study suggests that climate change may be contributing to an increase in glacial area loss in recent decades, resulting in the expansion of existing lakes and the formation of new lakes. This scenario indicates a potential rise in GLOF events in study area in the future.

Over 32 years (1986-2018), in the Cordillera Real, Kougkoulos (2019) demonstrated that glaciers below 5,000 m of the altitude retreated from 28 km² to 5 km², glaciers between 5,000 and 5,500 m in altitude retreated from 208 km² to 106 km² (49%), and glaciers above 5,500 m in altitude retreated from 79 km² to 59 km² (25%).

Some lakes may experience a reduction in their areas and disappearance in the coming years as glaciers contribute to river flow during the dry season in regions with solid precipitation seasonality (MARK; MCKENZIE, 2007; SORUCO et al., 2015). This discharge will likely intensify as glacier mass loss accelerates (LAFRENIERE; MARK, 2014), however, this is a temporary effect, which will decrease as the glacier reduces in size (POUYAUD et al., 2005).

In the future, the complete disappearance of the glaciers in the Cordillera Real will lead to a reduction in runoff of 12% per year, and 24% during the dry season (SORUCO et al., 2015). Making a parallel with the variation in lake areas, it can be understood that glacial lakes will tend to increase rapidly in size and quantity in the coming years, due to the retreat of glaciers. This fact could provide a greater temporary supply of water for the population, considering that Andean countries are very dependent on fresh water from glacial basins, which are used for domestic, agricultural or industrial use (RIBEIRO, 2014), and, at the same time, it may leave it more exposed to GLOF events. On the other hand, as the ice disappears from these locations, these events will no longer happen (HAEBERLI; WHITEMAN, 2021).

The understanding of the spatio-temporal variation and their formation pattern and rate of increase of glacial lakes is necessary to assess the probability of occurrence of GLOFs. An updated lake inventory, area change detection, classification and GLOF susceptibility assessment of glacial lakes are critical factors that pose major obstacles to mitigation strategies and better preparedness against glacial hazards (GAIKWAD et al., 2022; GAIKWAD; GUHA; TIWARI, 2022).

Many lakes may cease to be directly fed by glaciers with the continued glacial retreat in the region. Lake 11 evidenced a decrease in área of these lakes are related to glacier retreat, as verified by satellite images used to identify the lakes. In this sense, the study by Rounce et al. (2023) projected that global temperature increase between 1.5°C to 4°C will result in losses of one-quarter to nearly half of the world's glacier mass by the year 2100, considering that mass loss is directly related to temperature increase.

Discussions at the 2021 Conference of the Parties (COP26) indicated that the average global temperature is projected to increase by 2.7°C this century. Glacier mass loss affects sea level rise, water resources, and natural hazards. According to Fischer et al. (2016), accelerated glacier melt in mountain glaciers strongly signals global climate change and affects local geomorphological and hydrological processes.

3.2 Characteristics of Glacial Lakes

Concerning the area of the lakes in 2022, it was found that none have an area below 0.00025 km², 11 lakes have an area between 0.00025 and 0.01, and 5 lakes have an area above 0.01 km². According to Wang, Qin, and Xiao (2015), in the last 20 GLOF disasters with any record, 95% of lake areas exceeded 0.02 km². Three (IDs 1, 6, and 8) glacial lakes had an area above 0.02 km².

Kougkoulos (2019) excluded lakes smaller than 0.01 km² from his analysis due to low risk for lakes in this context. Adapting Kougkoulos' (2019) methodology, lakes with an area of less than 0.001 km² were excluded from the present study. For future work, it is suggested to consider the volume of the lakes as an analysis parameter, as done by Qi et al. (2022), rather than only the area of the lakes.

A stable glacial lake exists continuously in the temporal series of the research, whereas an unstable glacial lake refers to new lakes and those that are disappearing (ZHANG et al., 2023). In the present work, only three lakes do not have variations in period. The remaining lakes are unstable, with four identified only in 2022. Monitoring these lakes is important because rapid changes in lake area can disrupt the water balance, resulting in GLOFs from moraine-dammed lakes (WANG, QIN, XIAO, 2015).

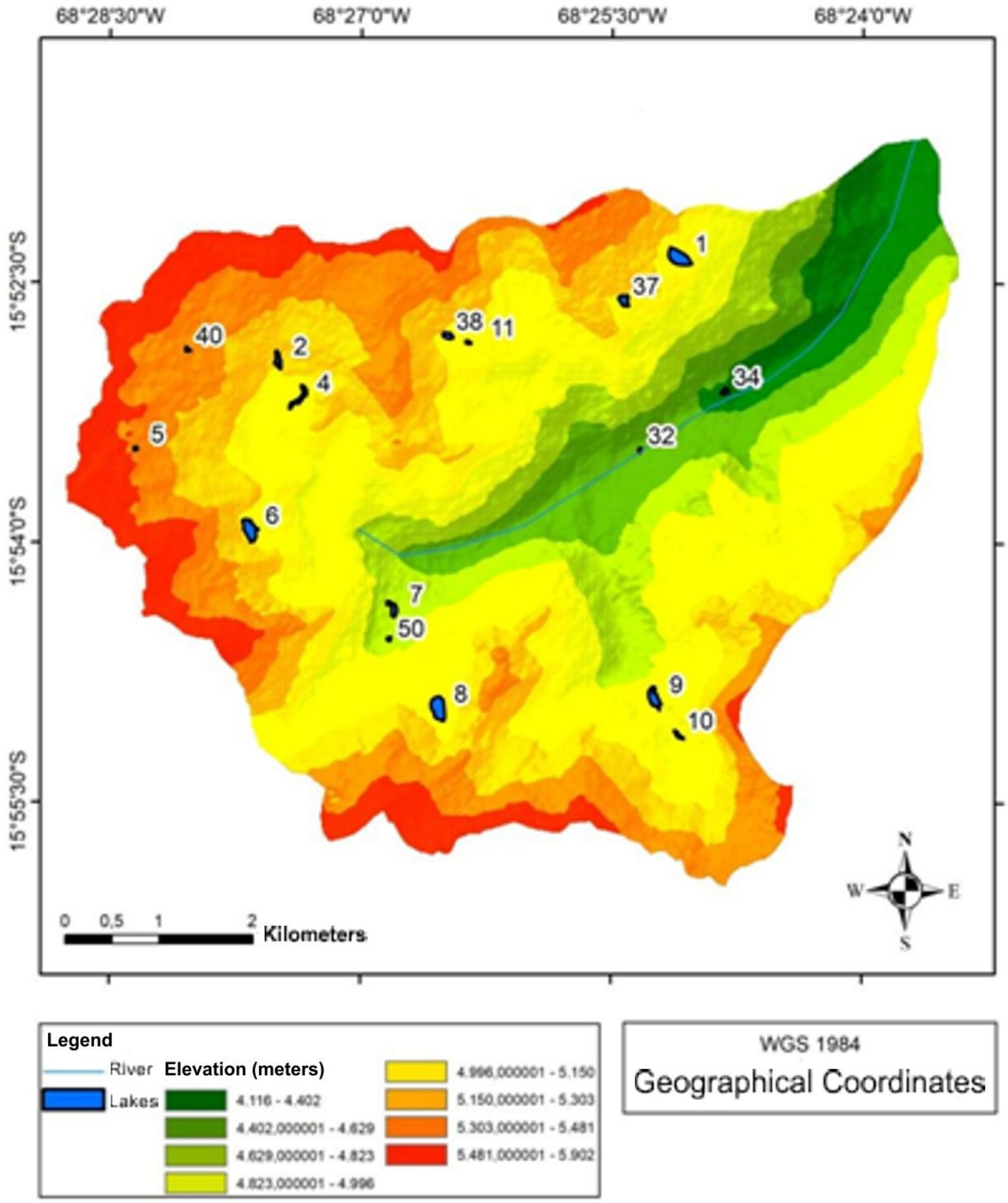

Figure 4 – Elevation map of the study área.
Source: Authors (2023).

The distance of each lake to the adjacent glacier ranged from 0 to 2 km. It was observed that one lake is more than 2 km away from its adjacent glacier, seven lakes are between 0.5 and 2 km, and eight lakes are at a lakes are within 500 m of a glacier. The occurrence of GLOFs is likely when proglacial lakes are 500 m from a glacier (WANG et al., 2011; WANG; QIN; XIAO, 2015; COOK et al., 2016), as lakes in contact with the ice or at a distance of less than 500 m from the glacier they can be affected by mass movements, generating considerable waves. (WANG et al., 2011; WANG; QIN; XIAO, 2015; COOK et al., 2016), as lakes in contact with ice or less than 500 m from the glacier can be affected by mass movements, generating considerable waves. In 1941, a GLOF occurred in Lake Palcacocha, where a glacier-calving iceberg caused a flood that destroyed the city of Huaraz and resulted in about 6,000 deaths (CAREY et al., 2012).

Kougkoulos (2019) considered the following risk classes for the parameter of distance between the glacial lake and the adjacent glacier: 500 to 250 m (low risk), 250 to 10 m (medium risk), 10 m to glacier contact (high risk). The author emphasized that the selection of these values was somewhat subjective. Similarly, in the present study, it was necessary to adapt the classes and consider those lakes located less than 500 m (0.5 km) from the glacier as high risk, because the average distance between the lakes and their adjacent glacier is greater than 500 m. For example, lake 32 is located 2.28 km from its adjacent glacier.

The maximum elevation context of the study sub-watershed is 5,902 m and the minimum elevation is 4,116 m, resulting in an average elevation of 5,042 m. The highest lake (ID 5) is at an altitude of 5,447 m, while the lowest (ID 34) is at 4,390 m (Figure 4). Notabily, the northern sector of the sub- watershed has a higher elevation, which may also explain the more significant presence of glacial coverage in this region. The lack of lakes supplied by the North sector in 1999 highlights the elevation of the glacial front during the period.

Four lakes were identified with the type of rocky dam, two of which (IDs 1 and 37) are situated in a cirque valley. These were assigned a risk classification of 2 because, in a way, they are not "dammed" lakes but lakes occupying depressions, also called confined lakes (MERGILI; SCHNEIDER, 2011; KOUGKOULOS, 2019). Therefore, they are considered relatively stable lakes considering the type of dam (HUGGEL et al., 2004). Nine lakes with moraine dams were identified as a value to the risk of 3, as this type of lake is considered more dangerous, as an initial event can form a breach in the moraine, draining the lake (WESTOBY et al., 2015). Additionally, three lakes with no dam type were identified and assigned a risk of 1, considering there is no risk of sudden breach.

Concerning downstream communities, the nearest one is at a distance of 30.71 km in a straight line, considered a medium-risk distance in this study.

Regarding the distance between the lakes and the river, the following results were found: five lakes are located 1,200 m from the river or less, classified as high risk. Eight lakes are located between 1,200 and 2,400 m from the river, classified as medium risk. Three lakes are at a greater distance of more than 2,400 m, classified as low risk. The proximity of glacial lakes to the river course can have a significant impact in the event of a GLOF.

The maximum slope found in the study sub- watershed was 77.63°, and the minimum was 0°, resulting in an average slope of 27.24°. Concerning the slope between lakes and their respective glaciers, four lakes had slopes between 30° and 45°, and 12 lakes had slopes above 45°. None of the lakes had a slope lower than 30° concerning their adjacent glacier, indicating that all lakes are classified as medium or high risk about the slope parameter.

According to Wang et al. (2011), the distance from the lake to the adjacent glacier, as well as the slope between them, are factors that significantly influence the possibility of ice reaching the glacial lake after detachment. Only Lake ID 2 is in an area of lower slope; however, it still fell into the risk class 2, as areas with slopes between 30° and 45° are within less than 250 m of proximity to this lake. In other words, steep slopes are farther away from this lake than from others but still within less than 250 m. According to Carrivick and Tweed (2013), increases in slope angle and relief, along with the loss of internal friction and cohesion of slope materials, prepare slopes for failure. These conditions increase susceptibility to mass movements.

3.3 Glacier Lake Outburst Flood (GLOF) Susceptibility

Two lakes exhibit very high susceptibility to GLOF, four have high susceptibility, six have medium susceptibility, none have low susceptibility, and four have very low susceptibility (Figure 5). The AHP method presents itself as a plausible alternative for monitoring remote regions, capable of being adapted according to the specific characteristics of the study area. The result could be even more precise if applied in union with field research. Zhang et al. (2023) also employed the AHP method and the resulting assessment was validated when the lake with the highest risk score experienced a GLOF event in 2020.

Lakes 1 and 4, identified as lakes with very high susceptibility to GLOF, are located in the northern portion of the sub-watershed, which maintains the largest glacial coverage area in the study area. These lakes were also classified as high risk concerning the following parameters: lake area, distance to the adjacent glacier, and slope. These are the four parameters with the highest weight in the AHP methodology, influencing the results for lakes 1 and 4 (very high susceptibility).

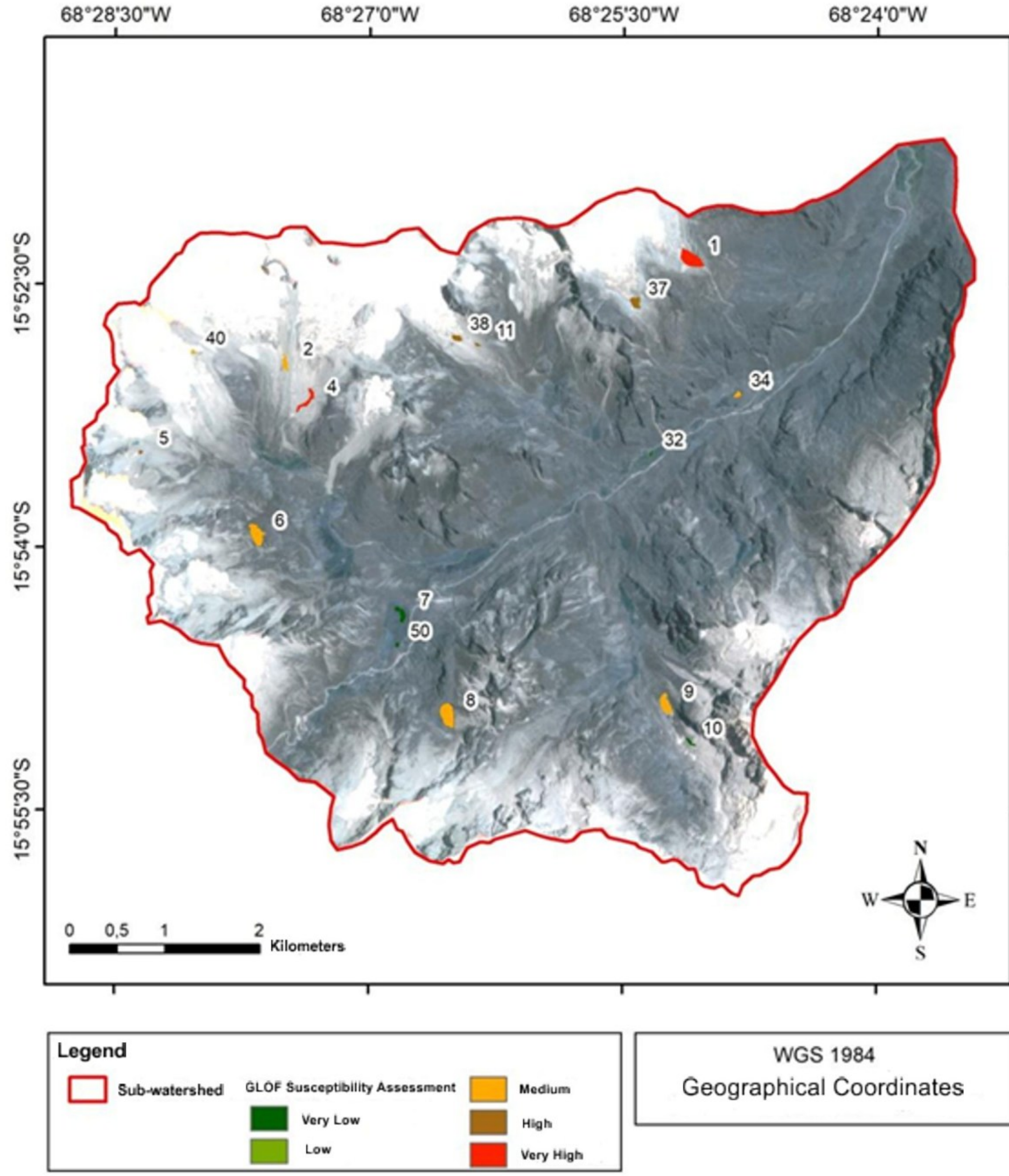

Figura 5 – Mapa de suscetibilidade a GLOF.
Source: Authors (2023).

Regarding lakes 5, 11, 37, and 38, classified as having high susceptibility to GLOF, it was observed that they also received a score of 3, indicating high risk, concerning the parameters of glacial coverage area, distance to the glacier, and slope. However, in terms of lake area, they all received a score of 2, hence medium risk, which led to their classification as lakes with high susceptibility to GLOF instead of very high susceptibility.

Lakes 2, 6, 8, 9, 34, and 40, classified as having medium susceptibility to GLOF, presented varied scores across each parameter. None of the lakes were classified as having low susceptibility to GLOF; however, all lakes exhibit susceptibility. Lakes 7, 10, 32, and 50 were classified with very low susceptibility to GLOF because few parameters of these lakes were classified with a grade of 3 (high risk). For instance, lake 32, despite receiving a score of 3 for glacial coverage area, slope, and distance to the river, received a score of 1 for distance to the glacier and type of dam. Lake 10 scored 3 for slope and type of dam, and lakes 7 and 50 received three only for the parameter distance to the river.

It is important to note that lakes 1 and 4 were not identified in images from 1999, suggesting that they did not exist then. However 2011, lake 1 emerged, initially comprising two smaller lakes that merged, as observed in the 2015 image. From 2011 to 2022, lake 1 experienced an increase in area of 0.0251 km², representing a growth of 836.67%. Similarly, lake 4 appeared in images only in 2011 and by 2015 was already unified (initially consisting of two lakes in 2011). From 2011 to 2022, lake 4 increased its area by 0.0070 km², representing a growth of 194.44%.

The behaviour of lakes 1 and 4 during the study period may be a response to glacier mass loss, as observed by other authors (COOK et al., 2016; KOUGKOULOS, 2019), indicating that the current scenario of GLOF susceptibility could become even more concerning. Monitoring lakes and glaciers in the studied sub- watershed, especially lakes 1 and 4, would be one of the primary measures to mitigate cryospheric risks associated with them, such as flood risks.

Simultaneously, glacier lakes serve as a water source for downstream populations and various economic activities. Managing and monitoring glacier lakes can yield co-benefits concerning disaster risk reduction, water resource management, and energy production. However, legal, social, cultural, and policy constraints persist in their implementation (HAEBERLI et al., 2016; VUILLE et al., 2018). Downstream communities can be negatively impacted, as exemplified by the 1941 GLOF at Palcacocha in Peru. In other words, the deglaciation of glaciers and proglacial lakes is a challenge for future monitoring. More areas need to be monitored to obtain reliable data and develop local adaptation measures and process models for other regions worldwide (FISCHER et al., 2016).

Kougkoulos (2019) studied three large lakes in Bolivia and, while analyzing potential flood scenarios in downstream communities, found that 1,140 people would be affected. The author also emphasizes that lakes should be monitored in light of glacier retreat to assess the consequences for their volume. This same consideration can be applied to lakes fed by glaciers in the Chajolpaya sub- watershed. For better adaptation to glacier-related risks, planning and implementation of preventive measures are necessary, such as hazard identification, building codes, zoning and land use planning, establishment of evacuation routes, alerts and alarm systems, emergency protocols, education, and outreach programs, among others (SCHNEIDER et al., 2014; MUÑOZ et al., 2016). This effort must be based on comprehensive strategies that promote integration among science, culture, policy, and practice, involving local populations (PAYNE; SHEPARDON, 2015).

4. Conclusions

A comprehensive temporal analysis using high-resolution spatial imagery is crucial for gaining insight into the changes in lake size over the past few decades. The size of these lakes can fluctuate from year to year due to the impact of precipitation and the melting of snow and ice in the surrounding sub- watershed. It is important to take into account the variability of these factors when evaluating changes in lake area. This study analyzed cryospheric risks associated with glacier lakes in the northern portion of the Cordillera Real, Bolivia. A detailed temporal analysis with high-resolution spatial images is relevant for understanding lake variation over recent decades. Lakes may experience interannual variation influenced by precipitation and snow and ice melt in the sub- watershed, and the behaviour of these variables should be considered in lake area assessments.

In 2022, a total of 32 glacier lakes were identified, with 16 being chosen for analysis and monitoring in this study using specific criteria. By employing the AHP methodology, the study identified two lakes with a very high susceptibility to GLOF, as well as four lakes with high susceptibility, indicating the presence of cryospheric risks. This information is crucial for the downstream communities in the sub- watershed and local authorities, as it allows for clearer planning and implementation of monitoring policies in the region.

For future discussions, it would be beneficial to provide a more comprehensive description of the study area. In terms of the study's parameters, it is advisable to utilize lake volume instead of area, and to conduct individual vectorization for each glacier. Furthermore, it is recommended to conduct studies on the downstream population in order to comprehend the effects of GLOF-associated risks.

Due to climate and socio-environmental changes, the tropical Andes face numerous challenges related to freshwater supply, sustainable use, and high mountain hazards. Addressing these challenges requires holistic strategies that foster integration among science, culture, policy, and practice, actively engaging local populations.

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