Investigating GLOF Risk and Hazard in the Cordillera Blanca Region of Peru

GPGN 570 Applications of Remote Sensing
Term Project

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1 Introduction

Within the world's highest mountain ranges, including the Peruvian Andes and its surrounding arid lowlands, glacier and lake-fed streams are critical for human survival. These areas do not experience seasonal snow cover and only experience distinct wet and dry seasons, meaning present glacial stream flow is a valuable buffer against water shortages (Drenkhan et al. [2019]). Downstream communities of these glaciers rely on their water for agricultural purposes and hydropower. As the global climate rises, glaciers are melting and retreating at a growing rate, leading to an increased risk of water scarcity. However, this is not the only risk that rising temperatures and melting glaciers pose to these mountain towns.

In the Peruvian Andes and other high mountain ranges, as glaciers retreat and ice mass decreases through melt, depressions in the ground are uncovered. These depressions can accumulate precipitation and meltwater, leading to the creation of glacial lakes. The current inventory of glacial lakes is rapidly increasing due to the accelerated glacial retreat and melting caused by climate change (Wood et al. [2021]). Glacial lakes pose a unique hazard and risk to the infrastructure of downstream communities due to the potential for a Glacial Lake Outburst Flood (GLOF). These GLOFs typically occur due to one or both of the following mechanisms: structural failure of the dam resulting in fracture or breakage, and overtopping, where water flows over the dam's crest. These mechanisms are often triggered by upstream events such as avalanches or landslides into the lake (Emmer et al. [2022]). The flood peak of a GLOF can far exceed other types of flooding, and in extreme cases, the amount of water released can reach millions of cubic meters (Costa and Schuster). During the 20th century, Peru experienced over thirty thousand deaths due to GLOFs (Carey [2005]). In a study done by Emmer et, al. in 2022, it was found that there have been 160 GLOFs in the Tropical Andes since 1725. Given the frequency and damage that GLOFs cause in the Peruvian Andes and the constant formation of new dammed glacial lakes from climate change, it is necessary for current glacial lakes to undergo a comprehensive risk and hazard assessment.

1.1 Study Area

There have been countless studies on developing risk-assessment frameworks for GLOFs in the Himalayas and specific regions of the Andes. The Cordillera Blanca region of the Peruvian Andes has been extensively studied for historical GLOFs. However, contemporary studies on the potential hazards and risks that current glacial lakes face in this region are limited. Due to the lack of modern studies, this study will focus on current glacial lakes within the Cordillera Blanca region of Peru.

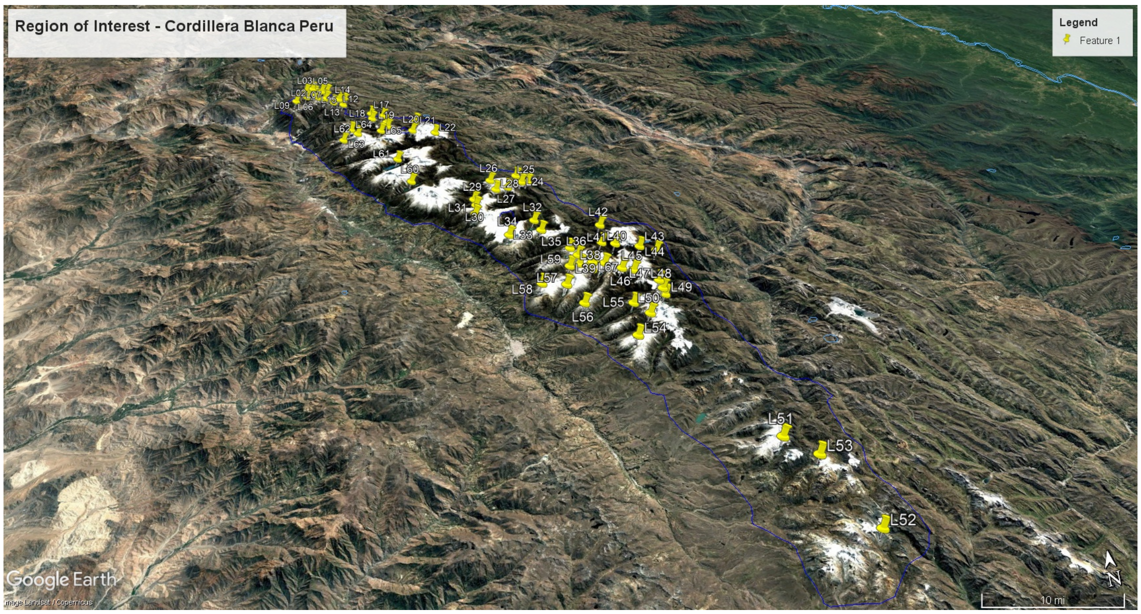


Figure 1: Cordillera Blanca Mountain Range in the Peruvian Andes.

Figure 1 shows the region of interest for this study outlined in blue, with identified lakes. This blue area covers approximately 3500 square kilometers of mountains from latitude $-8.654081°$, longitude $-77.838386°$ to latitude $-10.011881°$, longitude $-77.211834°$.

1.2 Data

This study leverages the use of three different data sources. Sentinel-2 multispectral imagery data was collected via the Copernicus browser for the region of interest. Two multispectral bands were utilized, the green band, $B03$, and the near infrared band, $B08$. Both bands were collected at a spatial resolution of 10 meters and a swath width of 290 kilometers. The Sentinel-2 mission utilizes two satellite platforms, allowing for revisit times of 2 or 3 days (Sentinel-2). The bands used in this study were the product of a 3 day revisit time. Copernicus DEM 30 was collected via the Copernicus browser for the region of interest. The Copernicus Digital Elevation Model 30 (DEM) represents the surface of the Earth at a resolution of 30 meters. It is formed by dividing the Earth into grid cells and assigning each grid cell an altitude value in meters (Copernicus GLO-30). The final data used are images and measurements gathered from the Google Earth Pro desktop application, which is open access.

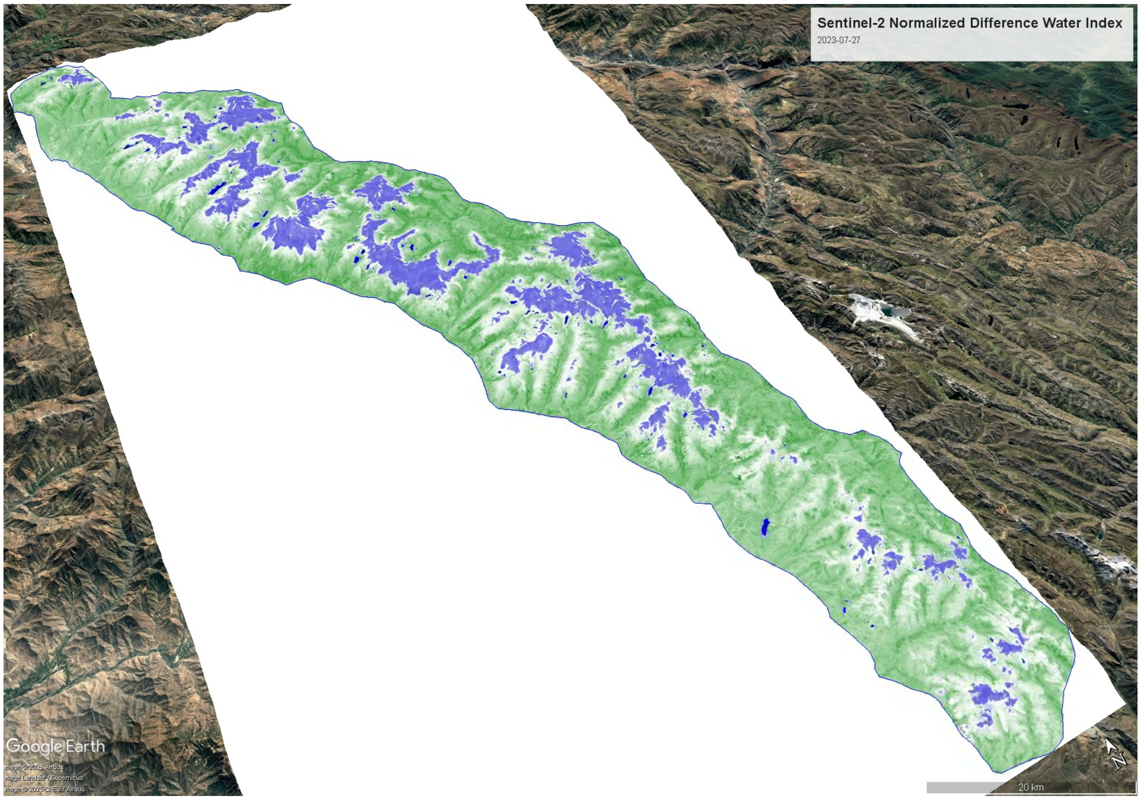


Figure 2: Sentinel-2 (with NDWI calculation).

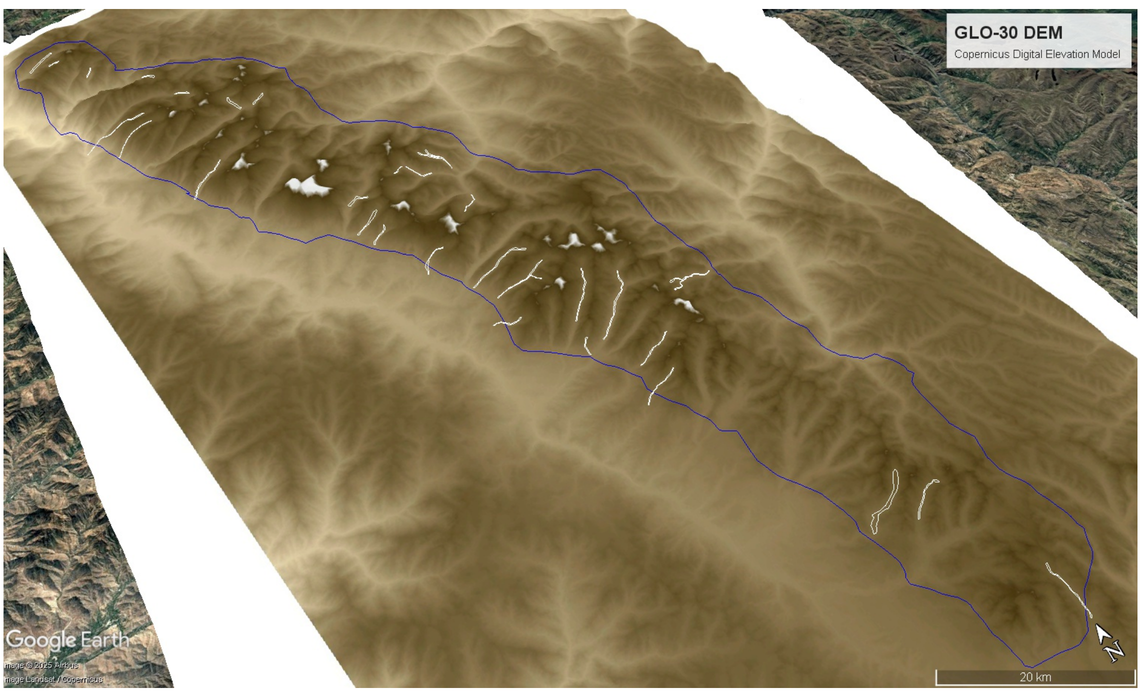


Figure 3: Copernicus Digital Elevation Model.

2 Methods

There are four steps to determining the hazard and risk of a glacial lake outburst flood.

1. Identify Lakes
2. Collect Hazard Features
3. Collect Risk Features
4. Final GLOF Risk and Hazard Assessment

2.1 Lake Identification

The lakes were identified using the Normalized Difference Water Index (NDWI). NDWI is a remote sensing technique used to monitor and identify changes in water bodies and water content in vegetation. NDWI utilizes green and near-infrared bands to enhance the color of water bodies in an image. Using the green and near-infrared bands from Sentinel-2 and Equation (1), we can form a composite map representing the NDWI for the region of interest (see Figure 2).

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

After finding the NDWI, the water bodies will appear to be dark blue. Clear dark blue bodies (lakes) are seen in Figure 2. However, there are also lighter blue or purple spots, which represent surface snow or glaciers. The glacier NDWI behavior, coupled with the fact that some lakes are small, makes the automatic identification of lakes in this region difficult. Thus, the process of identifying and marking lakes becomes a manual process. Using the Sentinel-2 NDWI product as a highlighted guide, and the Google Earth Pro imagery to confirm, 66 individual lakes were found and 3 localized collections of lakes were identified (see Figure 1). Some lakes were identified but not marked due to one or more challenges: indistinguishable features, small size, excessive distance from downstream infrastructure, or connection to previously identified and marked lakes. Additionally, because the resolution is poor and automatic identification was difficult, it was not possible to identify the features from later sections automatically, meaning that for each feature, we had to find/calculate the value manually. Thus, the number of lakes was further decreased to 33 using the challenges previously described as disqualifiers (see Figure 4).

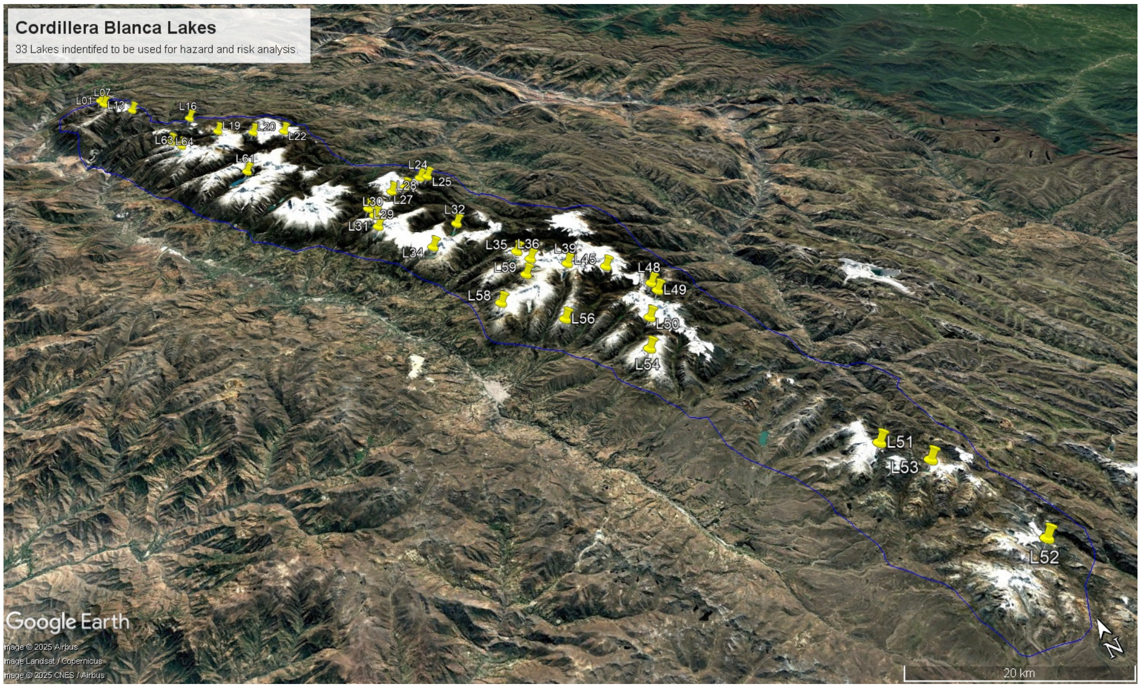


Figure 4: Lakes used in Risk and Hazard Assessment.

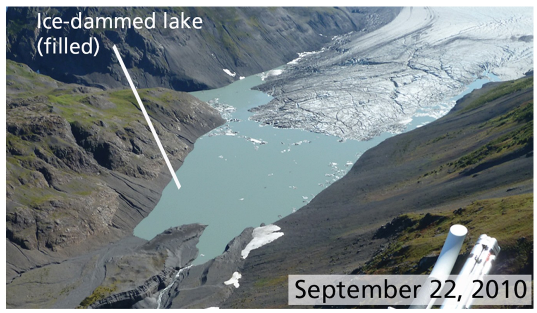
2.2 Hazard Features

The hazard features describe the probability that a GLOF will occur. They are lake and surrounding area features that will impact dam stability and the risk of overtopping. The most influential feature determining dam stability is dam type. There are three different dam types: bedrock, moraine, and ice. Bedrock dammed lakes are lakes where their downstream boundary (what is preventing them from draining) is composed of bedrock. These lakes have the smallest probability of dam breakage and fracture (Hambrey [1994]). Moraine dammed glacial lakes are the most interesting type. They form during glacial advance, followed by retreat. As the glacier advances, it pushes debris and other sediment forward, forming a mound (moraine). As the glacier starts to retreat the moraine remains, and a depression can form between the glacier and moraine. As this depression fills with melt and rain water a moraine-dammed glacial lake is formed (Hambrey [1994]). Moraine-dammed lakes have an elevated risk of fracture because the moraine ridges can become extremely unstable. The final dam type is ice-dammed lakes. Ice-dammed lakes form when a surging glacier with terminus advance blocks valleys, restricting flow, or when any glacial ice blocks a river and restricts drainage, causing accumulation (Emmer [2017]). Figure 5 shows the three different dam types. The moraine dammed glacial lake (Figure 5b) is very interesting because we can see how it was formed. The glacier would have advanced toward the bottom left section of the image on a curved path, but once it started retreating, it left depressions, one of which accumulated water, becoming a glacial lake. There are no ice-dammed glacial lakes located within the ROI, however it is possible for them to form in the Cordillera Blanca region, thus they still needed to be included within the analysis. The 2022 study by Emmer et, al. found that for 160 historic GLOFs, 99 (61.9%) were from moraine-dammed lakes and 26 (16.3%)

were from bedrock-dammed lakes (Emmer et al. [2022]). Furthermore, Emmer found that for lakes where the cause could be determined, the most prevalent cause of GLOFs was calving, ice avalanches, and ice dam failures, with over 40 GLOFs (Emmer et al. [2022]).

(a) Bedrock

(b) Moraine



(c) Ice (Not in ROI)

Figure 5: Three Different Glacial Lake Dam Types.

The impact that glacial calving or ice avalanches can have on a lake relies on how close the glacier is to the lake. The closer the glacier, the more impact velocity an ice-event will have on the lake, which increases the risk of dam overtopping or dam fracture (Drenkhan et al. [2019], Taloor et al. [2024], Kougkoulos et al. [2018]). To calculate the distance between a lake and its nearest glacier, we rotate the Google Earth Pro view to be completely top-down, such that the lake appears to be the nadir point. Then we can use the measuring tool to find the horizontal distance (without elevation) between the lake and the glacier. Some lakes do not have a glacier near them; these lakes have less than a low probability of GLOF occurrence, thus for the *distance from glacier* feature, they will have a unique value.

Another feature that will determine the impact velocity of an ice event is the slope between the lake and its nearest glacier. The smaller the angle, the less impact velocity ice will have with the lake, decreasing the risk of dam overtopping or fracture (Drenkhan et al. [2019], Taloor et al. [2024], Kougkoulos et al. [2018]). To calculate the slope, we utilized the Google Earth Pro path tool. We created a path between the glacier and lake, which provided the average negative slope percent, for which we can apply Equation (2) to transform the values to degrees.

$$\text{Slope}^\circ = \arctan\left(\text{Slope}(\%)\,/100\right) \tag{2}$$

The final two crucial hazard features are the local seismic activity and the dam freeboard.

Seismic activity will determine the chance of a rock avalanche causing a GLOF (Kougkoulos et al. [2018]). The greater the peak ground acceleration, the more likely and more severe a rock avalanche occurrence is. Additionally, greater peak ground accelerations increase the risk of dam fracture. The dam freeboard refers to the height difference between the top of the dam and the water level. The shorter the dam freeboard, the increased risk of dam overtopping (Emmer [2017], Taloor et al. [2024], Kougkoulos et al. [2018]). Unfortunately, due to the resolution of current data and the lack of data in some areas, both seismic activity and dam freeboard cannot be found for the region of interest, and thus won't be included in the hazard and risk assessment.

2.3 Risk Features

The risk features describe how much damage the ensuing water and debris from the GLOF can cause. The risk features we will prioritize are lake area and volume, downstream slope steepness, and the connection between the lake and other lakes or rivers.

The area and volume of the lake will determine how much water is released during a GLOF, and by extension, how much water will reach downstream infrastructure. The larger the glacial lake, the greater the risk of more damage occurring (Drenkhan et al. [2019], Taloor et al. [2024], Kougkoulos et al. [2018]). To find the area of the lake, we used the Google Earth Pro polygon tool to trace the lake boundary while the lake was centered and magnified in the field of view. Google Earth Pro then provides the approximate area of the polygon in square meters. Figure 6, as well as Figure 5a and 5b, show manually generated lake outlines in red.

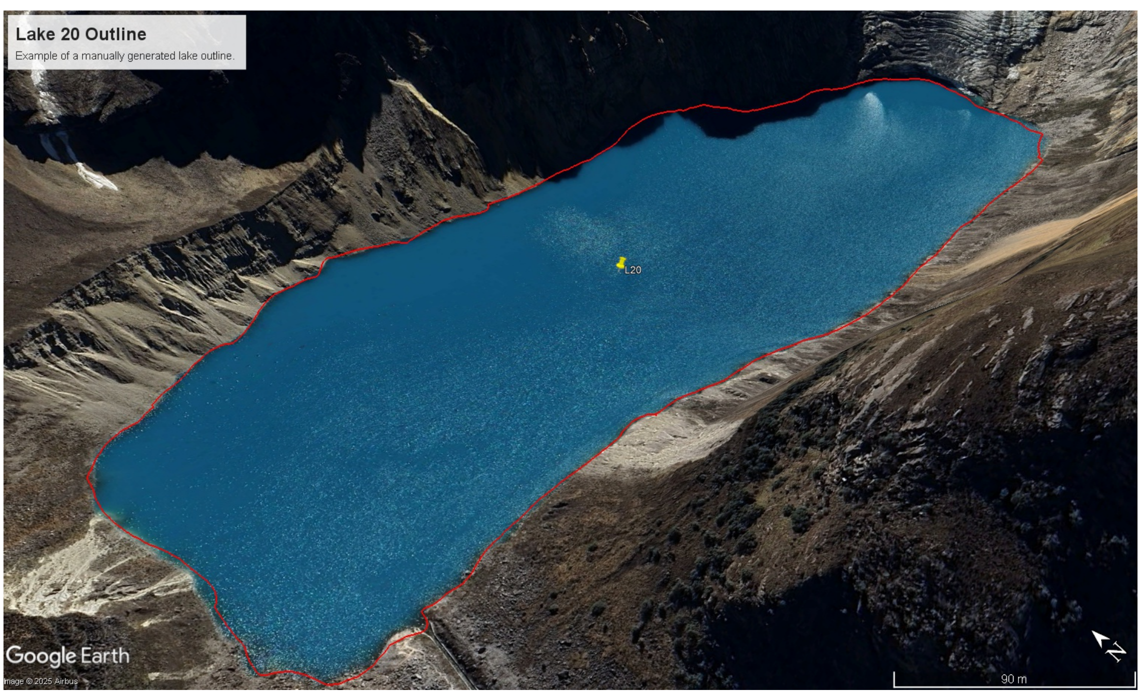


Figure 6: Lake 20 Manually Generated Lake Outline.

To accurately find lake volume, we would need to know the exact bathymetry of the lake bed and the water column height. While it is possible to gain approximate lake depth values via satellite-derived bathymetry or airborne lidar, this region of interest does not have those data products available. Instead, it was necessary to employ a volume estimation function (Equation (3)) that was derived from known lake volumes and areas within the Chenab basin in the Northwestern Himalayas (Taloor et al. [2024]).

$$V = 0.104A^{1.42} \tag{3}$$

Equation (3) estimates the volume (m^3) of the lake given the surface area A (m^2) of the lake.

Similar to how the slope determines the impact velocity of ice on a lake, increasing the hazard of a GLOF, the downstream slope of a lake determines the impact velocity of water and debris released from a GLOF on downstream infrastructure. The steeper the slope, the harder and faster ensuing flood waters will reach downstream infrastructure, resulting in more damage (Emmer [2017], Taloor et al. [2024], Kougkoulos et al. [2018]). The downstream paths were developed using the same Google Earth Pro path tool as the upstream slopes and utilized Equation (2) to transform the slope measurement into degrees. Downstream paths were determined to be the path from the terminus of the lake to the nearest downstream infrastructure, which was noticeable on Google Earth Pro (see Figure 7). For some lakes, it was difficult to determine the expected flow path of a GLOF due to the lack of a clear elevation change in the Google Earth Pro imagery. For these lakes, the Copernicus DEM was used to visualize the elevation changes better and predict a more accurate flow path (see Figure 8).

As mentioned earlier, the more water and debris within the GLOF, the more damage that can be done. Suppose a glacial lake of interest is located upstream from other lakes, and these connected lakes lie in the GLOF flow path of the upstream lake. In that case, the bursting of the upstream lake can cause the bursting of the downstream lake(s), leading to an increase in the amount of water and debris within the GLOF (Taloor et al. [2024]). It was determined that low risk lakes were connected to no downstream lakes or rivers, medium risk lakes were connected to either few or small lakes, and large risk lakes were connected to many or large lakes. A manual inspection was done using Google Earth Pro scenes to determine the connection status of the glacial lakes of interest.

Figure 7: Manually Generated Lake Downstream Paths.

(a) Lake 01

(b) Lake 01 Overlayed by DEM

Figure 8: Lake 01

2.4 GLOF Risk and Hazard Assessment

To provide a final risk and hazard assessment for each glacial lake of interest, the found features were given a score of one to three, where one suggests a low hazard/risk GLOF and three represents a high hazard/risk GLOF. For the hazard features *distance to glacier* and *upstream slope*, a special value of zero was assigned to lakes that did not have a glacier near them, as the lakes not only had a low risk GLOF but a decreased risk overall because of the glacier's absence. The boundaries for each feature determining GLOF hazard/risk were determined by analyzing previous literature on GLOF hazard and risk assessments and choosing the most appropriate boundaries for the region of interest. Tables 1 and 2 show the boundaries used in this study. Applying these boundary conditions to the derived feature values and summing all hazard/risk scores allows for the calculation of total hazard and risk per lake. Which, when averaged, determines the overall GLOF risk assessment for the lake.

Hazard Features			
Feature Name	Low (1)	Medium (2)	High (3)
Dam Type	Bedrock (b)	Moraine (m)	Ice (i)
Distance to Glacier*(m)	> 800	$400 - 800$	< 400
Upstream Slope*(deg)	< 30	$30 - 38$	> 38
*If no glacier is present, these values are 0			

Table 1: Boundaries for the found Hazard Features.

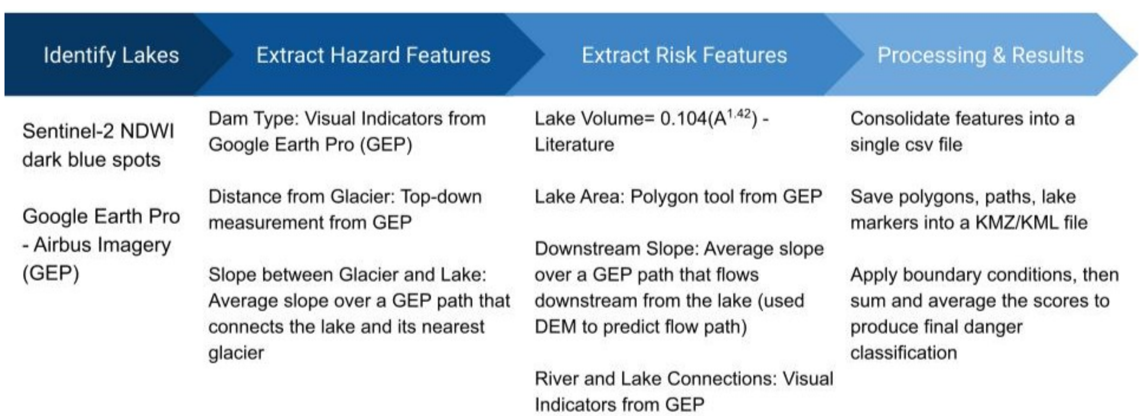


Figure 9: Method and Data Framework Snapshot.

Risk Features			
Feature Name	Low (1)	Medium (2)	High (3)
Lake Area(m^2)	$< 10^5$	$10^5 - 5(10^5)$	$> 5(10^5)$
Lake Volume(m^3)	$< 10^6$	$10^6 - 10^7$	$> 10^7$
Downstream Slope (deg)	< 13	$13 - 18$	> 18
River & Lake Connections	None	Some lakes / small	Many lakes / large

Table 2: Boundaries for the found Risk Features.

3 Results

3.1 Hazard and Risk Features

A total of 33 lakes were identified, and their features were collected. Of these lakes 45.5% ($n = 15$) were identified as bedrock-dammed, 54.5% ($n = 18$) were identified as moraine-dammed, and 0% were identified as ice-dammed glacial lakes (see Figure 10). The number of lakes with small downstream connections was approximately equal to that of lakes with larger connections. 54.5% of lakes had no downstream connections to other water sources, 24.2% had large connections, and 21.2% had small connections. The largest lake was lake 61, with an estimated volume of $7.708 \times 10^7\, m^3$, and the smallest lake was lake 54, with an estimated volume of $2.926 \times 10^5\, m^3$. Figure 11 shows dam type plotted against other features. There does not seem to be a relationship between dam type and volume. However, there is a slight relationship between dam type and distance from glacier, where more moraine dams are located closer to the glacier than bedrock dams. From Figure 10 and 11, it is important to remember that 5 lakes are not near a glacier, of which 2 are moraine dammed and 3 are bedrock dammed. Furthermore, all of the 4 lakes in contact with glaciers are moraine dammed. For the 18 moraine dammed lakes, 61.1%($n = 11$) are not connected to downstream water sources. Whereas for the 15 bedrock dammed lakes, 46.7% ($n = 7$) are not connected to downstream water sources. Despite the moraine dam type having a larger range for downstream slope values, its first quartile, median, and third quartile are very similar to the values for the bedrock dammed lakes (see Figure 11).

Name	Area (m^2)	Volume (m^3)	Dam Type	Connection	Distance From Glacier	Up Slope (MAXpct)	Upstream Slope (MAXdeg)	Down Slope (MAXpct)	Downstream Slope (MAXdeg)	Down Slope (AVGpct)	Downstream Slope (AVGdeg)
L01	1.99E+05	3.483E+06	b	Y2	-1	0	0.00	56.5	29.466	14.23	8.099
L07	5.42E+04	5.487E+05	b	Y2	576	71.5	35.56	55.9	29.205	14.9	8.475
L13	2.11E+05	3.792E+06	b	Y1	-1	0	0.00	87	41.023	21.4	12.079
L16	1.37E+05	2.039E+06	b	Y1	500	59.5	30.75	70.4	35.146	22.1	12.462
L19	3.12E+05	6.583E+06	m	N	457.79	82.6	39.56	48	25.641	7.3	4.175
L20	3.93E+05	9.153E+06	m	Y2	0	69.3	34.72	46.9	25.127	14.5	8.250
L22	1.35E+05	1.998E+06	m	Y2	447.85	72.4	35.90	54.9	28.767	10.9	6.221
L24	8.86E+04	1.103E+06	b	N	313.08	82.5	39.52	36.2	19.900	10	5.711
L25	7.54E+04	8.768E+05	b	N	426.62	67.9	34.18	69.3	34.722	15.3	8.699
L27	2.35E+05	4.412E+06	b	N	864.01	63.6	32.46	38.5	21.057	8.2	4.688
L28	1.01E+05	1.334E+06	m	Y1	1009.84	70.2	35.07	51.3	27.158	21.7	12.243
L29	1.75E+05	2.905E+06	m	N	609.8	74.7	36.76	61.8	31.716	17.8	10.093
L30	3.45E+05	7.589E+06	m	Y2	401.03	77.2	37.67	84.6	40.231	18.9	10.703
L31	2.08E+05	3.693E+06	b	Y1	327.9	74.5	36.69	63.1	32.252	22.2	12.517
L32	3.52E+05	7.816E+06	m	N	126.04	72.7	36.02	65.5	33.225	17.3	9.815
L34	1.77E+05	2.943E+06	m	N	408.54	67.9	34.18	63.6	32.456	23	12.953
L35	3.94E+05	9.179E+06	m	N	179.85	65.7	33.30	42.7	23.122	12	6.843
L36	1.84E+05	3.114E+06	m	N	0	77.2	37.67	43.1	23.316	10.2	5.824
L39	4.69E+05	1.174E+07	m	N	286.41	71	35.37	36.3	19.951	6.2	3.548
L45	4.54E+05	1.122E+07	b	N	421.92	78.1	37.99	26.6	14.896	5	2.862
L48	2.47E+05	4.725E+06	b	Y1	493.49	69.6	34.84	58.5	30.328	10.7	6.107
L49	2.32E+05	4.332E+06	b	Y1	250.67	57.5	29.90	52	27.474	10.7	6.107
L50	6.00E+05	1.666E+07	b	N	385.29	69.7	34.88	30.2	16.804	5.2	2.977
L51	9.79E+04	1.271E+06	m	Y2	0	53.8	28.28	40.7	22.146	8.3	4.745
L52	7.48E+04	8.676E+05	b	Y2	726.99	51.9	27.43	31.4	17.432	6	3.434
L53	6.62E+04	7.283E+05	m	N	94.76	57.8	30.03	19.2	10.869	5.7	3.262
L54	3.48E+04	2.926E+05	m	Y1	289.79	78.9	38.27	33.1	18.315	8.2	4.688
L56	2.68E+05	5.310E+06	b	N	-1	0	0.00	53	27.924	22.4	12.626
L58	1.13E+05	1.559E+06	b	N	504.43	56	29.25	63.7	32.497	17.6	9.982
L59	3.83E+04	3.350E+05	m	N	-1	0	0.00	67.5	34.019	13	7.407
L61	1.76E+06	7.708E+07	m	N	-1	0	0.00	92.6	42.800	13.7	7.801
L63	2.85E+05	5.807E+06	m	N	415.65	66.4	33.58	65.8	33.345	23.6	13.279
L64	5.41E+05	1.439E+07	m	Y2	0	65.9	33.38	83.9	39.997	26.1	14.628

Figure 10: Glacial Lake Hazard and Risk Features.

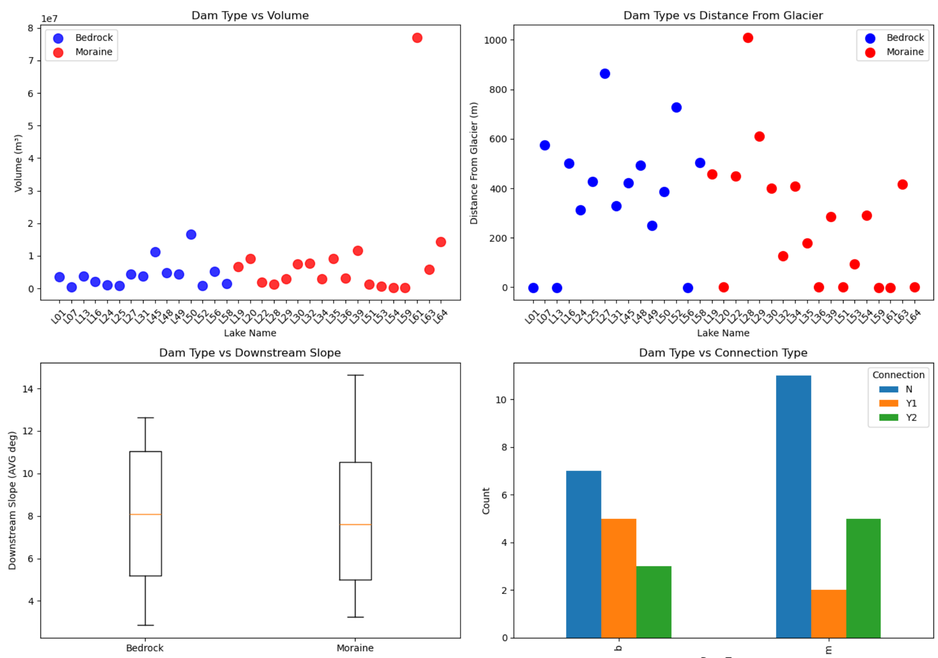


Figure 11: Examination of Dam Type Versus Other Features.

3.2 Hazard Assessment

The boundaries were applied to the derived features using a Python script and producing the results seen in Figure 12. Among the 33 lakes of interest, 24.2% ($n = 8$) have low risk, 72.7% ($n = 24$) have medium risk, and 3% ($n = 1$) have a high risk of a GLOF occurring and causing significant damage. While most lakes were classified as medium risk, there were only 6 lakes with an average score above 2, and the remaining 18 medium risk lakes' average scores rounded up to 2. Lake 64 poses the greatest risk and hazard with a total hazard score of 18, while Lake 56 poses the least risk with a total hazard score of 7. The volume, area, and distance to glacier features have variable scores, while dam type and downstream slope have more uniform scores. Furthermore, only lakes 63 and 64 have semi-steep downstream flow paths. Interestingly, there are 5 lakes with high risk volume levels, but only 3 lakes with high risk areas. Figure 13 shows the average hazard scores in histogram format with 10 bins. The distribution of average scores seems unimodal and normal, with the most scores falling in the range 1.5 and 1.75.

Lake Name	Volume	Area	Dam Type	Distance to Glacier	Upstream Slope	Downstream Slope	Connection	Total Hazard	Avg Hazard	Classification
L01	2	2	1	0	0	1	3	9	1.285714286	L
L07	1	1	1	2	2	1	3	11	1.571428571	M
L13	2	2	1	0	0	1	2	8	1.142857143	L
L16	2	2	1	2	2	1	2	12	1.714285714	M
L19	2	2	2	2	3	1	1	13	1.857142857	M
L20	2	2	2	3	2	1	3	15	2.142857143	M
L22	2	2	2	2	2	1	3	14	2	M
L24	2	1	1	3	3	1	1	12	1.714285714	M
L25	1	1	1	2	2	1	1	9	1.285714286	L
L27	2	2	1	1	2	1	1	10	1.428571429	L
L28	2	2	2	1	2	1	2	12	1.714285714	M
L29	2	2	2	2	2	1	1	12	1.714285714	M
L30	2	2	2	2	2	1	3	14	2	M
L31	2	2	1	3	2	1	2	13	1.857142857	M
L32	2	2	2	3	2	1	1	13	1.857142857	M
L34	2	2	2	2	2	1	1	12	1.714285714	M
L35	2	2	2	3	2	1	1	13	1.857142857	M
L36	2	2	2	3	2	1	1	13	1.857142857	M
L39	3	2	2	3	2	1	1	14	2	M
L45	3	2	1	2	2	1	1	12	1.714285714	M
L48	2	2	1	2	2	1	2	12	1.714285714	M
L49	2	2	1	3	1	1	2	12	1.714285714	M
L50	3	3	1	3	2	1	1	14	2	M
L51	2	1	2	3	1	1	3	13	1.857142857	M
L52	1	1	1	2	1	1	3	10	1.428571429	L
L53	1	1	2	3	2	1	1	11	1.571428571	M
L54	1	1	2	3	3	1	2	13	1.857142857	M
L56	2	2	1	0	0	1	1	7	1	M
L58	2	2	1	2	1	1	1	10	1.428571429	L
L59	1	1	2	0	0	1	1	6	0.857142857	L
L61	3	3	2	0	0	1	1	10	1.428571429	L
L63	2	2	2	2	2	2	1	13	1.857142857	M
L64	3	3	2	3	2	2	3	18	2.571428571	H

Figure 12: Glacial Lake GLOF Hazard and Risk Assessment.

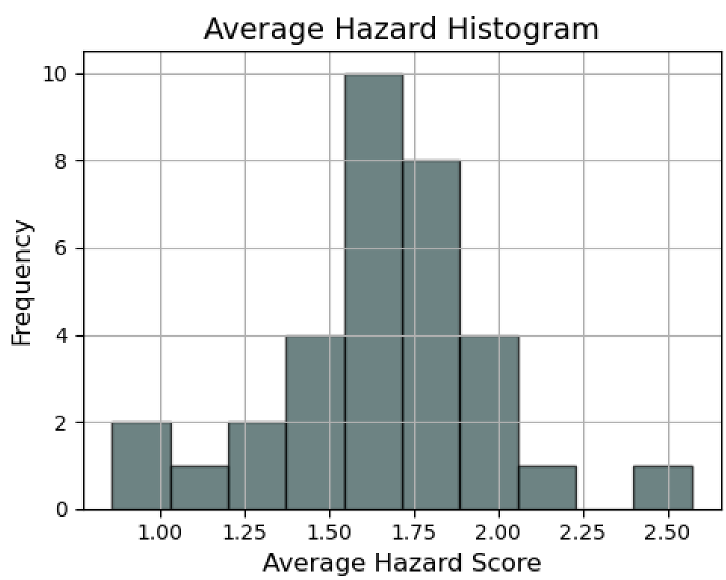


Figure 13: Histogram of Average Hazard of Glacial Lakes.

4 Discussion

4.1 Implications for GLOF Hazard and Risk Assessment

This study's GLOF hazard and risk assessment framework is effective because it uses open-sourced remote sensing data and other publicly available data products. However, the data scarcity and lack of high-resolution products within the Cordillera Blanca region prevent the framework from being an easily usable and widely accessible tool. It requires hours of manual data collection, which would be inadequate to monitor risk and hazard over dynamic seasonal and annual variations. To produce a more applicable framework, more remote sensing data at better resolutions is needed to employ an automatic feature finder that would be able to input an image and output the desired features. Additionally, dam freeboard and seismic activity would provide more information on the likelihood of a GLOF. Past studies have tested their frameworks on historical GLOF occurrences to produce an accuracy measurement, however the limits of this project did not allow for historical GLOF analysis, but future work in this area would be invaluable (Emmer et al. [2022], Wood et al. [2021]).

The weak correlation between moraine-dammed lakes and proximity to glaciers is surprising, as it contradicts the expected relationship where these lakes typically form from advancing and receding glaciers. The correlation between dam type and downstream connections is less surprising because we expect moraine-dammed lakes to form in isolated areas. After all, it is unlikely a glacier would advance and recede, forming a glacial lake and then repeat that process at a higher elevation near the first lake. The seemingly normal distribution of average hazard scores produced by this framework suggests that most lakes in the region have similar moderate risk profiles rather than extremely low or high risks. This provides an interesting advantage for future monitoring, as we can compare future distributions to determine how GLOF risk changes over time and how GLOF risk in the Cordillera Blanca region compares to risk in other high mountain regions.

4.2 Uncertainty

The google earth pro measurements are not accurate, there is no guarantee the point of view while measuring was at the nadir point, meaning some measurements could be skewed. Furthermore, all images used to measure the features for each lake were taken in July or other summer months, which increases the likelihood of a GLOF occurring due to increased melting and unstable glaciers (Drenkhan et al. [2019]). The behavior of glaciers and glacial lakes differs during the wet season, which can also increase the likelihood of a GLOF. Thus, this framework would only be useful for glacial lakes during the summer months, and an expanded framework would be needed to handle glacial lakes in the wet season. The flow path measurements were manually created at the author's discretion; thus, they do not provide the most accurate flow path. Utilizing an Arc-GIS package to map the predicted flow paths based on the digital elevation model would provide more accurate downstream slope measurements. These new paths could also help better determine the amount of damage possible by examining what infrastructure the flow path intersects (Emmer et al. [2022]).

4.3 Climate Change Paradox

Given the history of GLOFs in the Cordillera Blanca region, to have only one high risk lake is surprising. However, it introduces an interesting possibility. While climate change is melting the glaciers in high mountain regions, forming more glacial lakes, is this melting or loss of glacier mass also preventing the GLOFs from occurring? It would be interesting to examine GLOF hazards and risks over time, simultaneously with the evolution of nearby glaciers. As previously mentioned, seasonal conditions will impact how a GLOF framework is designed, thus it would also be vital to examine how climate change impacts glaciers and glacial lakes during the wet season as well as the dry.

5 Conclusion

This study presents a basis for assessing GLOF hazards and risks in the Cordillera Blanca region of the Peruvian Andes using remote sensing techniques and open-source data. The identification and analysis of 33 glacial lakes determined that 72.7% present medium risk, 24.2% present low risk, and only 3% present a high risk of a GLOF. Lake 64 emerged as the highest risk lake, while Lake 56 showed the lowest risk. We found that dam type will play a significant role in determining GLOF risk because 54.5% of the lakes were moraine dammed while 45.5% were bedrock dammed. This supports previous research that found moraine dammed lakes accounted for 61.9% of historical GLOFs in the Cordillera Blanca region. The high presence of medium risk lakes in this study emphasizes the need for continued monitoring and analysis of this rapidly changing region.

The framework used in this study demonstrated both strengths and limitations. The utilization of open source data makes this approach accessible, however the manual nature of feature collection makes its applicability for large scale and rapid monitoring difficult. Further research must focus on automated lake identification and feature extraction, incorporating higher resolution data and introducing additional features such as dam freeboard and seismic activity. In conclusion, this assessment provides a strong foundation for GLOF risk assessment in the Cordillera Blanca region, and as climate change continues to shape mountain landscapes and water resources, developing robust monitoring and risk frameworks is necessary to protect downstream communities.

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