Use of Multi-Criteria Decision Analysis (MCDA) for Identification of Hazard Prone Lakes in Chitral River Basin

By

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(MS WRE&M 2020, 00000329848)

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Has been accepted in partial fulfilment of the requirements

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Management

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THESIS ACCEPTANCE CERTIFICATE

It is certified that Ms. Aniqa Murtaza, Registration No. 00000329848, of MS Water Resources Engineering and Management (WRE&M) of batch 2020 has completed her thesis work and submitted the final copy which was evaluated and found to be complete in all aspects as per the policy of NUST/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfilment for the award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have been incorporated in the said thesis.

Signature: ________________________________

Supervisor: __Dr. Hamza Farooq Gabriel__________

Date: ____________________________________

Signature (HOD): __________________________

Date: ____________________________________

Signature (Principal & Dean SCEE): _____________

Date: ____________________________________

DEDICATION

To my dear parents, thank you for your unwavering support and love - this achievement is for you.

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I would like to express my sincere gratitude and appreciation to my supervisor, Dr. Hamza Farooq Gabriel, for his invaluable guidance, support, and belief in me throughout my academic journey. His expertise, feedback, and dedication have been instrumental in shaping my research and helping me to achieve my goals.

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ABSTRACT

Glacial Lake Outburst Floods (GLOFs) are a pressing concern in Pakistan and other parts of the world, posing an immediate threat to downstream communities, infrastructure, and agriculture. Urgent action is required to mitigate the devastating impact of these floods and safeguard the lives and livelihoods of those at risk. The far-reaching and hazardous consequences of Glacial Lake Outburst Floods (GLOFs) are a sobering reminder of the urgent need for effective measures to prevent and mitigate the impact of these catastrophic events. Up till today, no work has been done on Chitral lakes while using Multi-Criteria Decision Analysis (MCDA) to identify hazard-prone lakes. The study was carried out to identify the hazardous lakes in the Chitral basin with the help of MCDA. The study provides valuable insights into all the risk factors related to GLOF and informs the decision-making process while keeping in view the threat linked to a specific lake. Two software ArcMap 10.5 and Stochastic Multi-Criteria Acceptability Analysis-SMAA (a multi-criteria decision-making tool) were used for digitization, criteria assessment, and sensitivity analysis, respectively. Various criteria were chosen from the literature to study the GLOF events Chitral region. Remote sensing data of Sentinel 2 imagery was used to digitize the maps. Seismic data was taken from USGS, and reanalysis data for temperature and precipitation from ERA-5 and GPCC was used. Following lake selection criteria (lake >0.02 km^2, distance <1000m) was taken. All other criteria were defined using ArcMap, Bing Maps, and Google Earth. Around 130 lakes were identified, and 13 were found to be completing our criteria. The study used 10 criteria to study lake behaviour and after determining threshold values, 6 out of 13 lakes were found to be at the highest risk, and one lake was found at medium risk. A sensitivity analysis was performed to predict the future impacts of lakes. Criteria weight sensitivity analysis in SMAA-2 shows the most hazardous criteria in each lake. SMAA-TRI performed a sensitivity analysis to show how previously found lakes changed their risk classes from low/medium to high. The results showed that the developed model is effective in identifying hazard-prone lakes, and the study is relevant to areas (lakes) with no history of GLOF (Glacial Lake Outburst Floods). Further investigation is suggested for high risk posing lakes and continuous monitoring is also required for low-risk lakes along with some other criteria and field investigation.

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List of Abbreviations

ERA-5	European Environment Agency
ECMWF	European Centre for Medium Ranged Weather Forecast
FAO	Food And Agriculture Organization of United Nations
GPCC	Global Precipitation Climatology Centre
GLOF	Glacial Lake Outburst Flood
MCDA	Multi Criteria Decision Analysis
SMAA	Stochastic Multicriteria Acceptability Analysis
USGS	U.S Geological Survey

Chapter 1

INTRODUCTION

1.1 BACKGROUND

Changes in human land use and management result in changes to the World's surface and sub-surface (such as biology, earth, landscape, exterior and groundwater, and human structural characteristics). This phenomenon is known as land use and land cover change. Most land-use practices required for human growth entail the misuse of natural supplies and ecosystem services, which have detrimental local and global effects on the Earth's ecosystem. For instance, during the 1960s through the 1990s, an increase in agriculture and fertilizer uses around the world resulted in environmental harm, such as deterioration of water quality, loss of arable land, and soil erosion.

Throughout response to climate change, glaciers are shrinking and retreating in most of the world. Mountain glaciers are sensitive to climate change indicators, and most of these glaciers are receding globally in response to rising global surface temperatures.(Pohlert, 2014) To comprehend the speeds and magnitudes of environmental change in these locations, a great deal of research has been done on tropical mountain glaciers. The focus of this study is on the glaciers of Chitral. In recent years, these glaciers have undergone widespread and sustained shrinkage.

It is likely to be seen that the sea level will rise in the coming century hence displacing people from their homes due to floods threatening. Therefore, the dynamics of glacier is required to study in detail to overcome this problem. The cryosphere or ice of the earth consists of different and unique depositional and erosional properties depending on the hydrosphere of the earth. There are usually two forms of ice, one is icebergs and the other one is glaciers. Glaciers are large masses of ice that accumulate and flow slowly over time, found on the Earth's surface in areas of high snowfall and low temperatures. These cover around 10% of the global surface and are also a source of powerful erosion. Glaciers usually have high precipitation and cold temperatures. Extremely cold areas also possess glaciers.

Glaciers are gigantic bodies of snow or ice moving slowly form of falling snow. Most glaciers are found in arctic regions. Around 2% of the water on earth is in the form of glaciers which cover around 10% of the earth's total area. Glaciers are the largest form of fresh water. But due to the increase in temperature (global warming) the glaciers are melting which can be a great source of damage to the people living near the glaciers.

Glaciers are a vital source of water because of their ability to store water during the winter season and release it in summer. Hazardous processes like glacier lake outburst floods, rock-slope disasters, and ice landslides can be brought on by permafrost and glacier dynamics. Several kilometres from their source, their occurrences have the potential to mobilize millions of cubic meters of water, ice, and wreckage, affecting populated regions. The harm brought on by these occurrences has been documented for centuries in glaciated regions all over the world. When rivers were blocked by glaciers during the Little Ice Age (LIA), the imprisoned water was unexpectedly released, causing severe flooding throughout Europe. However, due to glacier retreat, permafrost deprivation, and human habitation of high-elevation areas, the number of harmful occurrences associated with glacier and permafrost dynamics has grown since the maximum LIA expansion.

Slope instability in deglaciating valleys has been conditioned by glacier retreat and thinning due to variations in gradient geometry and the reallocation of pressures within rock formations. Due to the acceleration and collapse of rock glaciers as well as the decline in the connection of ice-reinforced rocks, permafrost degradation has also been associated with slope failures. With the entrainment of water, snow, and ice in their routes, slope failures in glacial and periglacial environments often impact sparsely populated valleys, but they can also imperil remote places after developing into complex sediment-laden floods. For instance, in the Peruvian Andes, ice, and snow failures have resulted in wreckage flows that have wreaked havoc on populous regions hundreds of kilometres downstream. These events have been thoroughly investigated from both a human and physical standpoint.

Glaciers are ice bodies that stand for the water of the earth in a significant way. These are stuck together by sheets of ice. The instability of glacier change can cause different hazards, particularly late outbursts. When snow falls in the same India over the years it forms a mountain called glacier mountain. The snow gets firm over the years and forms hard ice sheets. When the ice reaches its sufficient thickness, it causes glacier deformation. Glacier depends on the build-up of snow and its loss. Often ice failed to accumulate on Honda glacier mountain and hence moves downward creating glacial lakes.

When the snow is not properly melted during the summer season and the land faces high snowfall which automatically generates deep layers of snow, glaciers are formed. The snow which remains all year round is called perennial snow. Generally, it takes hundreds and thousands of years to form a glacier.

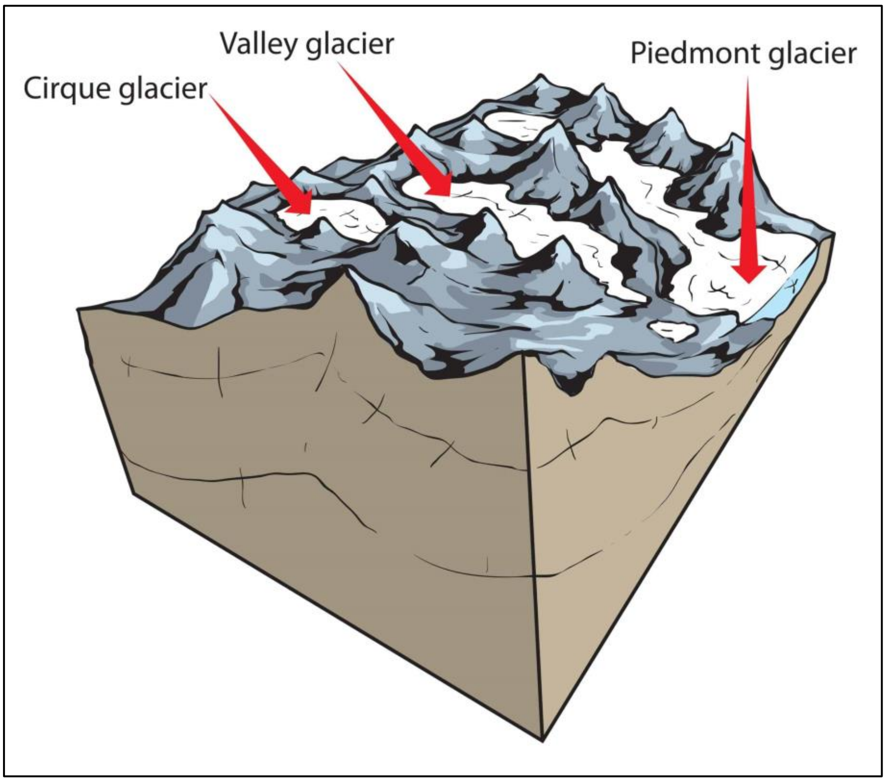

Figure 1-1 Types of Glaciers (Source: https://nayturr.com/types-of-glaciers/)

Three different forms of glaciers are described in Figure 1.1. Cirque glacier forms on the sides of mountains due to avalanches which form a bowl shaped that occurs due to a slope from higher surroundings. If the snow accumulation continues, then the cirque glacier becomes valley glacier, and it continues downward the valley. Ultimately the glaciers forming at the foot of mountains are Piedmont glacier.

Generally, glaciers are classified into two groups that are constrained and unconstrained. but due to the variability of temperature and the landscape the size and shape of the glacier may vary.

Due to increasing temperatures, the glaciers have started to melt which causes the formation of glacial lakes in some areas (Aggarwal et al., 2016). Some lakes are present between the glacier while others are found at the glacier terminus/snout. They provide fresh water to the community living nearby. During the past few decades, glacial lakes have increased by around 50% of their area number and volume (Zhang et al., 2022). Glacier-associated lakes have likely enhanced the glacial refuge via updraft energy communication and contributed to over 15% of the area loss in their connected glaciers (Gilany & Iqbal, 2020).

The water body found due to the melting of glacier activity it's known as a glacial lake. Due to glacier erosion, the snow melts to fill the created depressions, hence forming the lakes. these lakes are usually classified into two groups:

These include distal lakes and ice-contact lakes. The distal lakes are usually distant from the glacier and ice-contact lakes are formed near the glacier. The ice contact lakes generally turn into distal lakes over time.

Figure 1.2 shows the glacial lake phenomena that how the glaciers melt due to excess heat and ultimately goes towards lake formation which also effects the base of glacier.

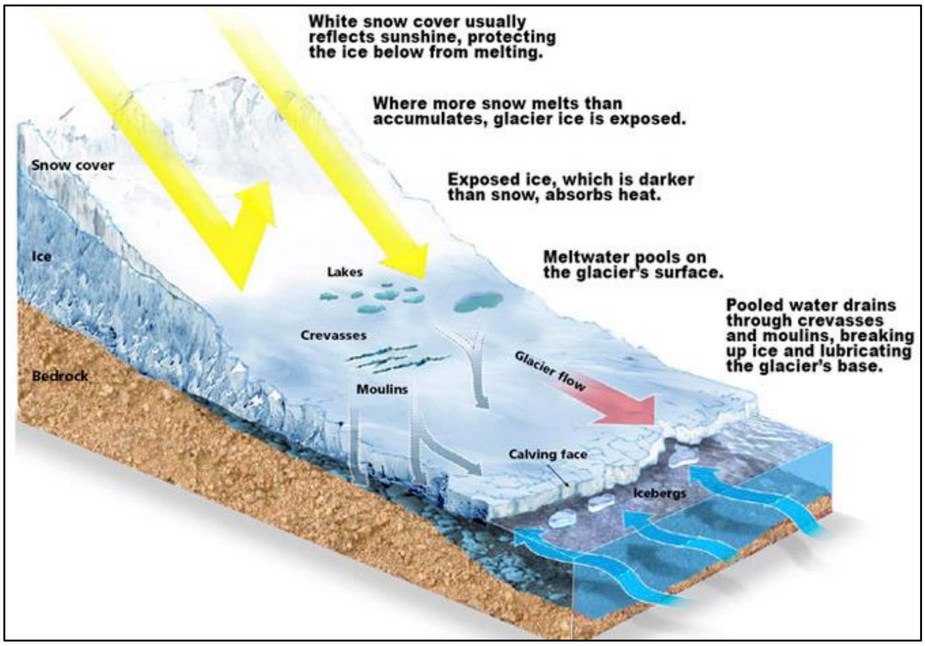

Figure 1. 2 Glacial Lake formation Phenomena (Source: Denever of Natural Science)

1.2 SCOPE OF STUDY

The scope of this study is to identify hazardous glacial lakes in the Chitral basin using Multi-Criteria Decision Analysis (MCDA) and to inform decision-making processes for disaster risk reduction. The study used ten criteria to assess the behavior of glacial lakes and identified thirteen hazardous lakes in the Chitral basin. The study used remote sensing data from Sentinel 2, seismic data from USGS, and reanalysis data for temperature and precipitation from ERA-5 and GPCC.

The limitations of this study are important to consider when interpreting the findings. Firstly, the number of criteria used in the study may not capture all the potential risk factors associated with glacial lake outburst floods. It is possible that additional criteria could have been identified and included in the study that would have improved the accuracy of the results. Furthermore, the study relied on freely available data and did not use any field data, which may have led to some inaccuracies. Field data could have provided additional insight into the behavior of the glacial lakes and the potential risks they pose.

Secondly, the study area was limited to the Chitral basin, which may limit the generalizability of the findings to other regions with different environmental conditions. It is possible that the risk factors and behaviors of glacial lakes in other areas may differ from those in the Chitral basin. This limitation underscores the need for similar studies to be conducted in other regions to provide a more comprehensive understanding of the risks posed by glacial lake outburst floods.

Thirdly, results may vary if we find the same results with different datasets due to their quality and accuracy.

Lastly, the study did not address the socioeconomic factors that may affect the vulnerability of downstream communities to glacial lake outburst floods as we didn't discuss the downstream impacts in this study. These factors, such as population density and infrastructure, could significantly impact the consequences of a GLOF event. Understanding the socioeconomic factors that contribute to vulnerability is critical for developing effective mitigation strategies.

In short, this study can be used for further research with more accuracy i.e., comparison of results with field observations and past events can help us to have better and accurate results.

1.3 RESEARCH SIGNIFICANCE

This study used Multi-Criteria Decision Analysis (MCDA) to identify hazardous lakes in the Chitral basin of Pakistan, shedding new light on the risk factors associated with Glacial Lake Outburst Floods (GLOFs). By pinpointing the most dangerous lakes and determining the criteria that make them so, this research provides a roadmap for disaster risk reduction, land-use planning, and emergency response in the region. With the potential to save lives, protect infrastructure, and preserve the environment, this study's findings have far-reaching implications beyond the Chitral basin and demonstrate the importance of proactive measures to mitigate the impact of GLOFs in vulnerable regions around the world.

1.4 RESEARCH OBJECTIVES

The general goal of this study is to understand the dynamics, occurrence, and magnitude of hazardous processes originating in glacial and permafrost areas in the Chitral region considering the knowledge gaps and the fact that a better considerate of the processes can help reduce damage caused by these events. Understanding and evaluating the GLOF dynamics and risk are given considerable attention because they are one of the most frequent and dangerous events influencing glaciated areas in the extratropical Andes. With the help of different set of criteria, a model was developed in SMAA-TRI as the SMAA model provides a structured approach to decision-making that incorporates both quantitative data and expert judgment, while accounting for uncertainty and randomness The following two goals will be the main emphasis of this study to accomplish the overall goals:

- To evaluate the susceptibility of potential GLOF through MCDA by evaluating a certain set of criteria.
- To carry out a sensitivity analysis to check the precision of results.

1.5 THESIS STRUCTURE

Chapter 1 provides a detailed introduction to Glaciers and the objectives and scope of the study.

Chapter 2 is a review of the papers that are followed up and used in understanding the methodology and basic information.

Chapter 3 describes the geographical detail of the study area along with some salient features and location maps. It is also about data sources and methodology.

Chapter 4 is presenting the integrated results.

Chapter 5 describes conclusions and future recommendations linked to the subject.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

2.1.1 Glaciers in Pakistan

Pakistan possesses a significant number of high mountain peaks and glaciers, making it a vital contributor to the mountainous region of Central Asia. The northern side of Pakistan boasts an abundance of high mountains and great glaciers due to the maximum rainfall during the monsoon season. In fact, around 13 out of the 30 highest peaks in the world are in Pakistan (Craig, 2016). Pakistan has three high mountain ranges, namely Karakorum, Himalaya, and Koh Hindu Kush.

Pakistan also has the largest part of glaciers in Asia and more than 7253 glaciers are present in the country, almost covering 15000 km2 of geographical area. Siachen glacier is the largest glacier in Pakistan, while Chitral has almost 543 glaciers according to different studies. These glaciers are another source of water for about 75% of the rivers in Pakistan, making them of great importance to the country's ecology and economy (Craig, 2016)

The Himalayan Mountain region, spread across most countries of Central Asia, is the highest snow-covered region and supplies water to the highest number of rivers in the area. However, the region is also witnessing increased global warming, causing the temperature to rise, and leading to the melting of snow. As a result, more water is created, which ultimately creates many glacial lakes. This poses a threat of Glacial Lake Outburst Flooding (GLOFs), which can cause considerable damage to the environment, infrastructure, and human lives. In fact, many GLOF events have occurred in the past, with Chitral being considered the most hazardous site for GLOFs (Riaz et al., 2015).

Despite the risks posed by GLOFs, many studies have been conducted on these events and their triggers. Departments like ICIMOD, PMD, and the UN are working to find the main reasons behind GLOFs and to prevent further disasters. Efforts are being made to use satellite imagery data to monitor these areas and take appropriate measures to save them from disasters (Riaz et al., 2015).

In conclusion it is recommended that, all nations need to work together to monitor these areas and prevent the formation of glacial lakes that pose a significant threat. Increased awareness of the risks posed by GLOFs is essential to prevent further damage to the environment, infrastructure, and human lives.

2.1.2 Glacier lake outburst flood (GLOF)

GLOF occurs when the glacial lake faces trouble i.e., seismic activity, temperature rise, intense precipitation events, snow avalanches, rockfall/landslides, glacier retreat, and overtopping of moraine dams. Moraines are the accumulation of debris cover while moraine dams are the dams naturally built due to unconsolidated sediments. As a result, millions of cubic meters of water and debris are released due to sudden events of GLOF, leading to the loss of lives, property, and livelihoods amongst remote and poor mountain communities. A GLOF event often takes along a large amount of debris with it which is a major cause of lake outbursts (Gilany & Iqbal, 2020).

The improvement of glacial deposits and ice-controlled lakes, which have been the cause of disastrous GLOFs, has been aided by glacier retreat as well. New lakes form as glaciers retreat while existing lakes deepen or expand. This increases the hydrostatic pressure above barrages, making them more prone to failure. Additionally, glacier thinning lowers the barriers to the start of disastrous ice-dammed lake drainages. In the Himalayas and the tropical Andes, there has been much research on the traits of unstable dams and the geo-morphologic and socioeconomic effects of GLOFs. GLOF modelling has also been done in these mountain ranges to analyse the dynamics of the GLOF and determine its threat.

In the Himalayas, more than 100 GLOF events have been reported since 1900 (Westoby et al., 2014; Zhang et al., 2022). According to previous knowledge, more GLOF events have taken place due to snow avalanches and landslides (Zhang et al., 2022).

Pakistan has faced a 0.76^{o} C rise in temperature during the last 40 decades (Riaz et al., 2015). Amongst 339 calamitous incidents detected along Karakoram Highway (KKH) in Hunza Valley in 1980, the most devastating ones were associated with glacial development that led to outburst floods of ice-blocked lakes. Around 23% of the Karakoram Range is under the gigantic glacial cover. With a total of 2398 glaciers and ice reserves of 2387km (Ashraf et al., 2011). Attabad Lake was formed in January 2010 in Gilgit, Baltistan due to land sliding killing around 60 people. A GLOF event took place in June 2013 in Himalayan Uttarakhand due to ice and snow avalanches killing more than 6000 people (Allen et al., 2016)

At the junction of Hunza and Shimshal, a GLOF event took place and destroyed the Passu village. (Gilany & Iqbal, 2020).

2.2 SYNTHESIS OF PRIOR STUDIES

In the promising volume of a glacial lake outburst flooding (GLOF), different studies were done. For a GLOF event that broke through Lugge Glacial Lake in Lunana region, Bhutan in 1994. Due to less available ground data, three different data from Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and remote sensing digital elevation models (DEM) were used to compare the relatively accurate data. The altitudinal differences of lakes and Root Mean Square Error (RMSEs). ASTER15 proved to be best as it gave the least RMSEs at the highest altitude while ASTER90 and SRTM RMSE changed with the terrain of the area. The areas were topographically categorized. The RMSEs were found low over the ponds/lakes, glacier surfaces, and riverbeds, yet greater over debris ridges and hill rises, associated with non-classified RMSEs. These studies showed that the level of the lake changed after the flood event. The volume of GLOF was estimated along with the future event prediction, and the altitudinal variances, distances, and the main points for outbursts in lakes were predicted with the help of remote sensing data (Fujita et al., 2008).

GLOF has catastrophic effects on both land and human life. A study was conducted (A. Emmer & Vilímek, 2013) about different moraine-dammed lakes of Cordillera Blanca. To know the water discharge along with the debris flow in GLOF hazards, three different methods to assess the flood risks were qualitative, semi-quantitative, and quantitative. A group of five critical stability parameters was necessary for the hazard assessment i.e., Movement of the slope, a water wave from the upstream lake, freeboard size, dam failure due to earth quack, and the difference between natural dams and dams with remedial measures. Every method follows a specific parameter i.e., qualitative gives individual details without any critical values, semi-quantitative has attributed critical values increase in which can cause GLOF while in quantitative analysis with the help of remote sensing data and stability parameters, the data was compared with the previous one to know the GLOF hazards. These results showed Lake Palcacocha had the highest flood hazards. By the mean values we found out that all three methods have different results, so they gave diverse results. Any methods used didn't incorporate all five stability parameters so the results were not satisfactory therefore a new technique is needed to be followed to find better results in the future (A. Emmer & Vilímek, 2013). Using the same technique another study was conducted by (Rounce et al., 2016) in Nepal Himalaya, where eight glacial lakes were found to be prone to GLOF. These studies defined the causes and dangers related to the lakes by defining the same stability parameters.

But these parameters were found to be misleading as the data found was not sufficient to know which lake must be studied more as this study only depended on the remote sensing data i.e., ASTER GDEM models were used. In this study for better risk assessment, GLOF modelling was used along with stability parameters. The numerical models were selected based on the best results they gave for the effect on the downstream area. These numerical models were used to know the features and flow aspects and facets of GLOF. So Modified Single Flow (MSF) and MC-LCP (Monte Carlo Least Cost Path). MSF uses a threshold value for the steep and with that tells us about the flood form while MC-LCP tells us about the flood coverage. MC-LCP was found to be better and more reliable than MSF. According to this model, the downstream effect was found to be of four types very hazardous, hazardous, medium, and low hazards. Hazardous lakes were defined with the help of stability parameters. This approach helped to gather new and reliable results regarding the lakes compared to previous data. Also tell us which type of failure will be caused i.e., self-destructive, or dynamic. The lakes were previously not very much concerned this study made ways to know the traits of those lakes and this will help to know how much impact each lake will have on the downstream in the future along with the hazards for the future (Rounce et al., 2016)

Due to increasing temperature, the glacier melts at their terminus thus forming ice-dammed or moraine-dammed lakes. To avoid disastrous effects hazard monitoring is done to have prior knowledge of GLOF in the future. RS technique is used to have spatial and temporal resolutions. The significance of this research was to investigate the dangers of Passu Lake and its GLOF hazards in the future with the help of hydrological and hydraulic modelling & Geospatial techniques. DEM was used to avoid misleading sinkholes. In hydraulic modelling, HEC-RAS and HEC-GeoRAS were used, and flow was monitored. By comparing areas with previous data through GIS-RS actual present area was found. This study told us about the methodology we can adopt to avoid GOLFs by proper monitoring of glacial lakes and their dams. This risk management cannot stop a flood from happening but can help with a structural or non-structural measure to make its impact lower. (Yasmeen, 2013).

Temperature changes have a great effect on GLOFs it causes changes in precipitation patterns and water stress is created. Melting of ice water is fed to the river so the increase in temperature leaves a greater amount of water in the river. River Chitral is a tributary of River Kabul which is fed by glaciers. In pre-monsoon discharge rate is greater than in the monsoon season. The mean maximum monthly temperature rise shows an increase in maximum discharge monthly. This ultimately takes us to the conclusion that glaciers are melting faster at the rate and losing their capacity to turn back to ice. This study will be useful for the country's future (Khalid et al., 2013).

In the state of Uttarakhand Himalayan range India, Safed Lake is one of the greatest glacial lakes. During the last 50 years, the lake has grown double in size. The growth of Safed Lake was assessed using hydrodynamic models. ASTER data was used for GLOF modelling. Breach formation and failure were calculated by breach hydrograph assessment using HEC-RAS 1D and 2D modelling. Model sensitivity was found for manning's coefficient and breach parameters (i.e., time of moraine failures, flow depth, and flow velocity). Cases were found as 3 scenarios with labels 1,2,3 where in 1 worst case scenario with breach depth 60 m the breach width was greater with less time of failure. With the lessening of breach depth, breach width increased with greater time. Peak flooding increased with a decrease in failure time. Results revealed that flow velocity was more sensitive to manning's coefficient than flow depth. Flow velocity and flow depth decrease with an increase in top width. It showed a sensitivity of flow velocity GLOF is more sensitive than other parameters (Sattar et al., 2020).

GLOFs are a major threat to communities residing near the glaciers. Glacial lakes are formed due to environmental changes i.e., melting of the glacier, dam break, etc. In this research multi-criteria decision analysis (MCDA) is used to identify hazardous lakes. This study can be utilized for any lake type regardless of its type. Different 13 parameters were set with help of Landsat and Bioclimatic variables to know the risk of lakes as high, medium, and low. A sensitivity assessment was performed to check the accuracy of our results by changing Lambda Cutting and threshold values in SMAA-Tri Software and open source. The study was applied to 16 glacial lakes out of 6 that have been already going through GLOF (Kougkoulos, Cook, Jomelli, et al., 2018a).

In this study, research was conducted on a Lower-Barun glacier and its lakes to check the susceptibility of GLOF. It was found that the glacier retreated for four decades, and the lake area increased. With bathymetric survey field data was collected. Using satellite images, the lake and its area, expansion rates and rockfall, etc. were found. With different flow scenarios and increasing breach width, it was found that the lake can be dangerous with the increase in the rate of flow (Gurung et al., 2021).

Due to climate changes, GLOFs have started to occur forming glacial lakes. Several techniques exist to model the GLOF event. Empirical relationships are implemented with several inputs i.e., discharge, lake height, or volume of the lake, we can get a single output. Analytical or parametric models simulate breach development using simplified versions of the physically based equations that describe breach enlargement, whilst complex, physically based codes represent the state-of-the-art in numerical dam-breach modelling. Sources of uncertainty in the GLOF modelling chain have been identified by various workers. However, to date, their significance for the strength of reconstructive and predictive modelling efforts has been largely unexplored and quantified in detail. These sources include the geometric and material characterization of moraine dam complexes, including lake bathymetry and the presence and extent of buried ice, initial conditions (freeboard, precise spillway dimensions), spatial discretization of the down-valley domain, hydrodynamic model dimensionality and the dynamic coupling of successive components in the GLOF model cascade (Westoby et al., 2014).

Dry snow avalanches consist of two layers one is a dense flow layer that is small, powdered snow particles present in the air. Its density is of one smaller order than dense flow. A simulation model for two separate layers has been created for separate sub-models. These models explain the transition of mass and momentum between layers. Two-dimensional granular flow model for the dense flow and the three-dimensional turbulent mixture model for the powder flow was made. The result with SAMOS showed good agreement with the observations. The model was found to be superior due to its path showing and the impact of pressure. Boundary conditions can also be calculated. This model can be used for detailed analysis but lack physical effects (Sampl & Zwinger, 2004).

In this study lakes of area < 0.1 km^2 were studied. 57 factors were selected of which were divided into six categories. Some of them were avalanches, lake perimeter, rock falls and landslides, temperature, dam instability, precipitation, etc. a glacier inventory RGI v^0 was used in this study. A method of the fuzzy consistent matrix (FCM) was cast off to determine the weight of the groups made. Five groups were made for the lake's distribution i.e., very low, low, medium, high, and very high. GLOF susceptibility was sensitive to event threshold values. An analytical hierarchy process was used to comply weighting factor to each category and by applying sensitivity analysis it was found which lake was potentially dangerous. All the result was compared to previous data to know their validity. So, with the help of these assessment factors lakes were characterized (Zhang et al., 2022).

In this study (Ashraf et al., 2011), downstream impacts of GLOF were studied. The remote sensing data of ETM+ was used to study glacial lakes in the Karakorum area. Around 887 lakes were identified outro if which 16 were found to be potentially dangerous lakes for GLOF. A specific criterion was defined for the lake to be hazardous i.e., glacier snout meeting the lake, moraine-dammed lake, seismic activity, and rock fall, etc. with the survey it was found that glacial lakes had devastating effects on people, and proper flood mitigation techniques and remedial measures should be adopted for saving the community from the vulnerability of lakes.

A study was done on the Testa River basin in Sikkim state of India. Glacier mapping was done to identify the glaciers and snow cover. Supervised classification and NDWI were used to classify glacial lakes 143 lakes were found. 18 PDGL were found by setting different parameters I.e., area slope, distance from the glacier, and yearly growth. Lake 140 was found to be the most vulnerable. Different DAMBRK parameters were generated, and hydrodynamic modelling was done by MIKE-11 (Aggarwal et al., 2016).

This study shows different parameters required to analyse GLOF in an area by using different remote sensing techniques and GIS modelling. Landsat TM, aerial photogrammetry was used to observe land and potential lakes. A lake outburst in the Swiss Alps was studied. Lake growth rate & change detection was studied with the help of geo data and field investigations. Also, temperature events were used. Empirical relations were developed to find parameters i.e., a volume area, etc (Huggel, Kääb, Haeberli, Teysseire, et al., 2002).

The area of the upper Indus Basin is a very prone area for GLOF events. As the area was so large so it was difficult to monitor that area physically. Two potentially hazardous lakes were identified using HEC-RAS. Shyok River basin was a threatened zone according to study carried out by (Gilany & Iqbal, 2020). It was found that no matter how much lower or higher the discharge was the Barah village was affected by GLOF events. This study helped to generate future flood prediction and mitigation.

Iturrizaga, (2014) provides a conceptual framework for the spatiotemporal distribution pattern of the main lake types within the context of the Cordillera Blanca's glacier history. One of the largest concentrations of proglacial lakes in high-mountain settings can be found in the tropical mountain range; these lakes were created because of the present trend of glacier retreat. Large settlement areas in the Rio Santa Basin have been badly impacted by glacial lake outbursts in the 20th century. Along with the remarkable newly formed lakes, the middle, and lower valley parts have geomorphological traces of ancient lakes. The study offers a genetic classification of the main types of lakes and provides information on their genetic makeup, based on empirical data from field research in more than 20 valleys and the analysis of air and satellite pictures. The distinct stages of the Pleistocene to present glaciation and their concomitant geomorphological landforms are linked to the creation of the lakes and their repeated distribution pattern. (Iturrizaga, 2014) presented a comprehensive landscape evaluation used to focus attention on the spatial arrangement of the lakes concerning one another in addition to the individual lakes. The hazard potential is interpreted in terms of implications, particularly for outburst cascades involving two or more lakes. According to their unique topographical and glaciological contexts, specific lake types of clusters in different Andean Mountain ranges on a superregional scale. Even while all the glaciated regions have had significant ice losses, only a few mountainous places, like those in the Cordillera, are prone to the formation of moraine-dammed lakes. The fundamental governing variables for their genesis are addressed from a glacial-geomorphological point of view. An Andes N-S profile depicts the distribution of the main types of glacier lakes.

Mountains & Haemmig, (2015) has shown that glacial lake outburst floods (GLOFs), also known locally as allusions, which are brought on by enormous outbursts of water from glacial lakes in the Cordillera Blanca Mountains, repeatedly occur and have exceptionally high destructive potential. To explain the history of GLOFs in the Cordillera Blanca Mountains, archive materials as well as interpretation of SPOT and LANDSAT satellite photos have been employed. Considering ongoing climate change, the formation and evolution of glacial lakes as well as recent factors impacting the GLOF hazard of a few lakes have been assessed. Ground measurements and satellite photos were used to detect a significant increase in lake surface areas. The current risk that natural disasters linked to glacial lakes pose to the regional capital city of Huarás has been assessed. Research has shown that the changing natural hazard conditions in high mountains are significantly influenced by global warming and deglaciation.

(Huggel, 2004) shows that climate change has a significant impact on the dynamics of periglacial and glacial regions. Permafrost degradation and the abrupt retreat of alpine glaciers might result in scenarios that have never happened before, changing the risky situation correspondingly. Conflict over natural dangers is also made more likely by the concurrent increase of human activity in mountainous locations. Such rapid changes necessitate methods for ongoing observation of the impacted areas and models to evaluate the effects of the hazard processes. This study examines the risks associated with periglacial debris flows, glacial lake outbursts, and ice avalanches. The rationale for establishing concepts for glacier risks and analysing them based on estimates of the Event size and chance of occurrence was the dearth of uniform ways for doing so. The methods primarily rely on practical knowledge, empirical correlations, and physical principles (Huggel, 2004). Remote sensing data and associated image processing techniques are used to collect information on the surface features of the glacier and periglacial environments. Methods are described for identifying dangerously steep glaciers, documenting and evaluating glacial lakes, and identifying unstable debris reservoirs. The analysis is supported by terrain modelling methods based on openly accessible digital elevation models (DEM) or models created from remote sensing data. One can do a preliminary evaluation of the effects of glacier risks using GIS-based models that employ flow-routing algorithms. The techniques were initially developed in the European Alps, but applications in sizable, isolated high-mountain regions, such as the Andes, demonstrate the tremendous potential of these techniques in these places. The models were developed with ease of use in mind and come in a variety of forms. This makes it simpler to utilize in practice, which has already been accomplished in several situations. The research prospects are encouraging because of trends toward increasingly very high-resolution satellite sensors and the growing accessibility of data from remote sensing derived DEMs. The related data flow necessitates the use of effective data management and processing methods. The study's parameters the established approaches and models are intended to provide current and future image availability as well as the ability to use topographical data financially and intelligently.

(S. Wang & Zhou, 2017) showed that in China, the Nyenchen Tanglha Mountains and the middle eastern Himalayas are the main high-risk sites for glacial lake outburst flood (GLOF) disasters. As a result of the local climate warming over the past 20 years, glaciers in these areas have rapidly retreated and thinned, resulting in the formation of new glacial lakes and the extension of existing glacial lakes. These regions are situated in the tectonic seismically active and often active band that separates the Indian and Eurasian plates. During earthquakes, glaciers, mountain slopes, and moraine dams have frequently lost some of their stability, which has led to unbalanced glacial lake conditions and an increase in loose debris in valleys. The likelihood of GLOFs and disasters occurring will likely be high given the frequency of earthquakes and ongoing global warming (S. Wang & Zhou, 2017). Discusses the conditions and mechanisms that lead to GLOF disaster development, as well as the temporal and spatial aspects of GLOF disasters. It also suggests an integrated risk management plan to deal with GLOF disasters. It intends to improve disaster risk analysis, as well as the capability of risk management and disaster prevention and reduction and make it easier to lessen the effects of GLOF disasters on mountain economic and social systems.

(Kougkoulos, Cook, Jomelli, et al., 2018a) present a Multi-Criteria Decision Analysis (MCDA) method that can be used to quickly identify potentially hazardous lakes in areas with a variety of glacial lake types, little to no field data, and no personalized GLOF risk assessments. Our MCDA model allows the relative risk posed by a variety of glacial lake types to be analysed simultaneously within any region. It is desk-based and employs freely and generally available data inputs and software. They have identified 13 exhaustive, non-redundant, and consistent GLOF risk criteria through an examination of the GLOF risk influencing elements and the stringent criteria selection constraints intrinsic to MCDA. They evaluated the risk associated with 16 existing glacial lakes and 6 lakes that have already produced GLOFs using our MCDA model and found that their findings are consistent with those of earlier research. To identify lakes that are sensitive to the criteria and risk thresholds used, as well as to validate the validity of our model results and assumptions, he conducted sensitivity analyses for the first time in GLOF risk assessment. The MCDA method has the important advantage of making sensitivity analyses simple to perform. Although they indicated that more research is needed to establish the relative weighting of evaluation criteria and the thresholds that establish the amount of risk for each criterion, these sensitivity studies validate their model overall (Kougkoulos, Cook, Jomelli, et al., 2018a), then used the tried approach, used as a case study on 25 potentially hazardous lakes in the Bolivian Andes, where GLOF risk is poorly studied. Three lakes were found to pose "mid" or "high" risk, and further in-depth research is needed.

(Clague & Evans, 2000) In British Columbia's high mountains, lakes that have been dammed by moraines are abundant. Most of these lakes were created when Little Ice Age-era valley and cirque glaciers began to retreat from their elevated elevations. Because they have steep sides, low width-to-height ratios, are made of loose, improperly sorted silt, and may include ice cores or interstitial ice, many moraine dams in British Columbia are prone to failure. Additionally, the lakes frequently have steep slopes along their edges that are vulnerable to rock falls and avalanches of snow and ice. In most cases, overtopping and incision cause moraine dams to fail. Heavy rainstorms, avalanches, or rock falls that cause waves to breach the dam are examples of triggering events (Clague & Evans, 2000), described abrupt drainage of an ice-dammed lake upstream can potentially cause the dam to overtop itself. Other potential failure modes include piping and the melting of ice cores from moraines. British Columbia experiences devastating floods that are orders of magnitude bigger than typical stream flows when moraine dams fail. Most outburst floods exhibit an exponential rise in discharge, which is then abruptly followed by a fall to background levels when the water source is depleted. Peak discharges are influenced by downstream terrain and sediment availability, failure causes, reservoir water volume, and dam features. Floods from moraine-dammed lakes have higher peak discharges than floods from glacier-dammed lakes for the same potential energy on the dam site. As the floodwaters run down rocky valleys, substantial amounts of sediment may be mobilized, resulting in highly mobile debris flows. These flows are more devastating than the floods from which they originate and have larger discharges. In British Columbia and elsewhere, huge lateral and end moraines are created after protracted cool climate periods, which is when moraine dam collapses are most common.

(Huang et al., 2011) shows that competing interests of diverse stakeholders frequently make decision-making in environmental projects difficult and involve the evaluation of trade-offs between socio-political, environmental, and economic repercussions. To support decisions in many different sectors, multi-criteria decision analysis (MCDA) arose as a formal approach. It can be particularly helpful in environmental decision-making. This study examines MCDA's uses in the environment. Through a series of queries in the Web of Science database, more than 300 publications published between 2000 and 2009 reporting MCDA applications in the environmental sector were found. The papers were categorized according to the decision or intervention type, as well as the environmental application area. Additionally, the publications were categorized using the MCDA analysis methodologies (analytic hierarchy process, multi-attribute utility theory, and outranking). The findings point to a significant increase in MCDA environmental applications during the previous ten years in all environmental application categories. Environmental applications have had success with a variety of MCDA techniques. A review of a few papers where several methods were used in parallel with the same problem shows that the recommended course of action does not differ significantly with the method applied, even though the use of the specific methods and tools varies in different application areas and geographical regions.

(Huggel, Kääb, Haeberli, Teysseire, et al., 2002) shows that in high mountain regions, glacier lakes are a frequent occurrence. Outbursts from glacier lakes have frequently resulted in fatalities as well as significant harm to the nearby infrastructure. There is still significant uncertainty regarding the hazard potential of glacial lakes in several high mountains ranges around the world, particularly about the impacts of rapid glacier retreats because of climatic warming. Therefore, a significant barrier is presented in the area-wide detection and modelling of glacier lake hazard potentials. The study's methodology, which integrates three scale levels, enables a gradual focus on crucial glacier lakes. Channel indexing, data fusion, and change detection are some of the remote sensing techniques that are provided for use in assessing the hazards associated with glacial lakes (Huggel, Kääb, Haeberli, Teysseire, et al., 2002), tells that it is necessary to calculate the maximum discharge and runout distance of outburst floods and debris flows to estimate the potential disaster amplitudes. Existing empirical relationships are assessed, and supplementary ones that can be inferred from the data at hand are suggested. Tests using data from a recent lake outburst event in the Swiss Alps demonstrate the basic applicability of the suggested methodologies and the value of empirical relations for preliminary hazard evaluations. In particular, the measured runout distance of the debris flow caused by the eruption does not go beyond the maximum runout distance that has been empirically estimated. The discussion concludes with a list of decision criteria and associated remote sensing methods. A list like this is crucial for assessing a lake's risk potential.

In this study (Ashraf et al., 2011) focussed outburst of floods resulting from glacial lake dam failures, which is a major risk. The likelihood of outburst floods depends on several variables, including the size and volume of the lake, glacier change, the glacier's morphometry about the valley and surrounding moraines, and glacier velocity. Useful for distant mountainous places, remote sensing provides an effective tool for displacement calculations and risk assessment of the detection of potentially problematic glacier lakes. This paper focussed that not all crucial factors can be found via space borne imaging. A further interpretation by a professional is necessary. The accuracy of ASTER data is sufficient to determine surface velocity. Ikonos data provides more detail, but correction requires more work. Areas with nil or very slow movement rates can be seen on every analysed glacier tongue with debris covering it.

Here, (Huggel et al., 2004) showed that the populated mountainous areas like the Swiss Alps, glacial dangers like ice avalanches, glacial lake outburst floods, and debris flows have severely damaged infrastructure. Basic glaciological, geomorphological, and hydraulic principles as well as knowledge obtained from past events must be considered when assessing such threats. A method for estimating glacial hazards' potential severity and the likelihood of occurrence was described. Based on empirical relationships collected from published case histories from the Swiss Alps and other alpine regions, an analysis of magnitude was conducted. Due to the quick changes like glacial systems, the rarity of the occurrences, and the high complexity of the underlying processes, it was challenging to predict the probability of occurrence (Huggel et al., 2004), described chances qualitatively and methodically using indicators such as dam type, geometry, and freeboard height (for glacial lakes) as well as avalanche recurrence propensity, precursor events, and enhanced water supply to the glacier bottom (for ice avalanche events). The assessment methodologies were applied to an ice avalanche in the Swiss Alps and a recent lake outburst with debris flow. The findings provide plausible event maxima that weren't surpassed by actual occurrences. The techniques offer first-order assessments and can be used in dynamic alpine environments where the expansion of infrastructure and population necessitates a constant assessment of dangers.

(Simon J. Cook et al., 2016) discussed that even though the Bolivian Andes' glaciers are a significant supply of water for the region's cities and mountain villages, relatively little research has been done to determine how much they have changed in size over the past few decades. Proglacial lakes have grown alongside glacier retreats in many mountainous areas, and they can present a risk for glacial lake outburst floods (GLOF). Despite previous GLOF incidences here, no research has examined the growth of such lakes in Bolivia. The Bolivian Cordillera Oriental saw an overall areal reduction of 228.1 22.8 km2 (43.1%) between 1986 and 2014, according to the mapping using satellite photos. The Tres Cruces region saw the most shrinkage (47.3%), which was followed by the Cordillera Apolobamba (43.1%) and the Cordillera Real (41.9%). In line with tendencies in the majority of other deglaciating mountain ranges, proglacial lakes have increased in number as glaciers have retreated while the quantity of ice-contact lakes has declined. Uncertainty about the causes has led to a pattern of lake change that has changed dramatically throughout the study, which suggests that as the ice continues to recede, monitoring of lake development will be necessary. In the end, GLOF risk over the Bolivian Andes using the 2014 database of proglacial lakes. They identified 25 lakes that could be a threat to downstream infrastructure and communities from GLOF and argue that it is necessary to conduct additional research on potential GLOF effects (Simon J. Cook et al., 2016).

2.3 GAP ANALYSIS

MCDA, operations research, and management science subfield, aims to develop decision support tools and strategies for tackling complex decision problems. It has been applied to environmental and disaster-related issues such as floods, landslides, avalanches, and water management (Huang et al., 2011; Merad et al., 2004). MCDA has not yet been used for evaluating GLOF risk in Chitral, but it can be a useful tool for deciding which lakes need further analysis, monitoring, or remediation in regions with various glacial lake types. MCDA used different criteria from different backgrounds which could be used universally to identify the lakes geographical and physical characteristics. Individual lake study in Chitral can help to evaluate the different risk associated with these lakes as each lake can have a different triggering factor due to change in geographical features and elevation as compared to to previous studies done in Chitral. It is different from previous studies as it used previous data of 25 years to evaluate the temperature/precipitation seasonality and seismic activity over the Chitral region to identify the present risk level of a particular lake. Also, no such study was done in Chitral previously on any lake especially with help of MCDA.

Chapter 3

STUDY AREA AND METHODOLOGY

3.1 STUDY AREA

3.1.1 General

The Chitral is situated on River Chitral (35°51′N, 71°50′E) in the province of Khyber Pakhtunkhwa, Pakistan with a total area of 14755 m^2 and an elevation of 4921 ft. It shares the border with Afghanistan. Kunar River, a tributary of the Indus River, also known as Mastuj, Chitral, or Kama River, is present in Chitral, fed mostly by glacier meltwater. Chitral has a population of more than 300,000. The valley is flanked by glaciated mountain ranges with altitudes of 5500 to 7000 m. Chitral consists of 543 glaciers, of which few have a history of GLOF and have formed glacial lakes. Chitral is famous for its landslides, mass movements, and GLOFs. These flash floods seriously threaten the people, lands, and irrigation channels.

The average increase rate of population was found to be 2.3% for the three decades from 1951 (Nu, 2001) Chitral is in the mountain range of Koh Hindu Kush, undulating mountainous areas and valleys. There is an excessive amount of vegetation in this area because of the high precipitation index. Summers are normal but winters are too hard. Mountain peaks are covered with snow throughout the year. Tirich Mir is one of the highest mountains in Pakistan. Figure 3.1 shows the map of Chitral in Pakistan.

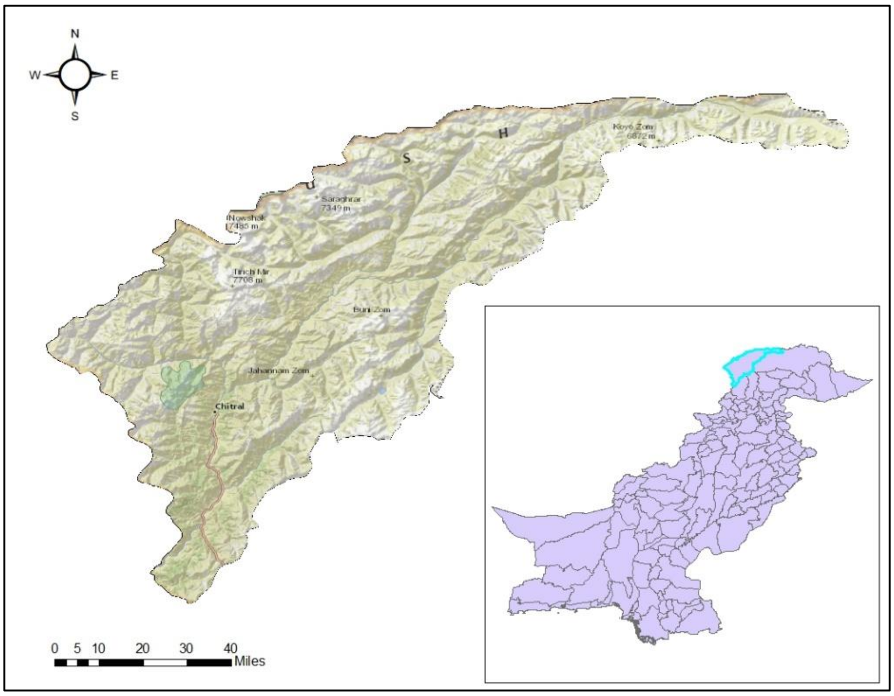

Figure 3. 1 Map of Chitral Basin

3.1.2 Climate

Chitral has a predominantly alpine climate, characterized by cold winters and cool summers. The average temperature in the district ranges from -10 to 20 degrees Celsius, with the highest temperatures occurring in the summer months and the lowest temperatures in the winter. The area receives relatively low levels of precipitation, with most of the precipitation falling as snow in the winter months.

The climate of Chitral is semi-arid. Where the prediction of temperature can be unpredictable. The drainage area of the Chitral River is 11.396 km^2. Chitral River, also known as Yarkhum or Mastuj River is a tributary of River Sindh. The river has recorded an average annual runoff of 8670 mm^3 over the past 34 years, from 1964 to 1998. On July 16, 1973, the discharge was measured at 1586 m^3/s, and on March 10, 1964, it was measured at 46 m^3/s. The river is fed by melting glaciers and snow, so it flows continuously throughout the year. During the monsoon season, which runs from July to September, some additional runoff can be observed (Aslam et al., 2021).

3.1.3 Elevation

The digital elevation model in Figure 3.2 shows the elevation of the terrain, allowing us to visualize the height of mountains, valleys, and other topographic features. It gives information about the slope and aspect of the area for direction and steepness of the terrain. Hydrological features like water and stream networks along with the LU/LC of this area can be found.

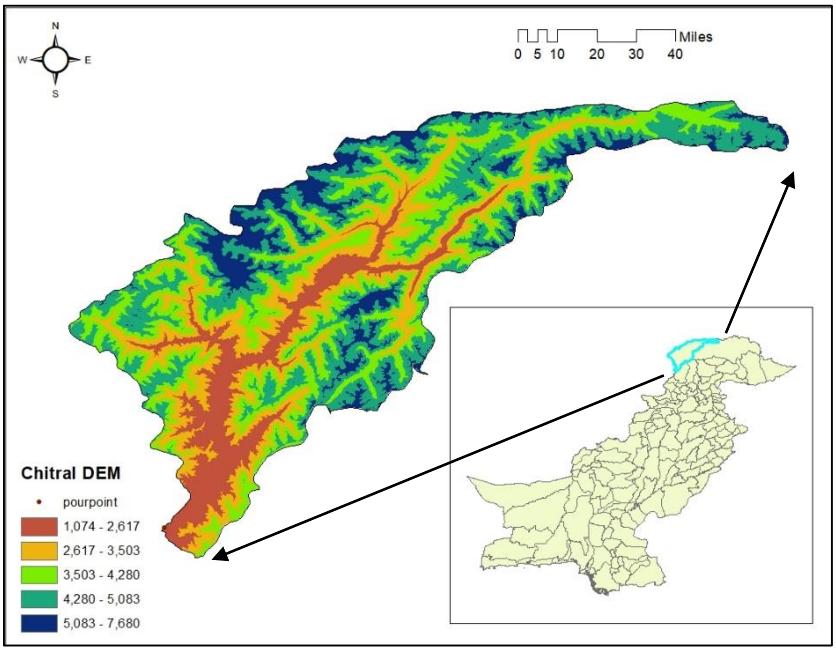

Figure 3. 2 Digital Elevation Map of Chitral Basin

3.1.4 Slope

Chitral is in the Hindu Kush Mountain range in north-western Pakistan, and the slopes in the district are characterized by steep inclines and rugged terrain. The topography of Chitral is shaped by the complex geology of the Hindu Kush Mountain range and the processes of uplift, erosion, and glacial activity that have shaped the area over millions of years.

The steep slopes in Chitral are a result of the district's mountainous terrain, with elevations ranging from 600 meters in the low-lying valleys to over 7,700 meters at the highest peaks. The slopes in the district can vary in angle, with some areas featuring near-vertical cliffs and others featuring gentler inclines.

The steep slopes of Chitral can create challenges for human activities, including transportation, agriculture, and forestry. The slopes can also increase the risk of natural hazards, such as landslides, rock fall, and debris flows, which can be particularly dangerous in areas that are densely populated or that are used for critical infrastructure, such as roads and bridges.

To mitigate the risks associated with steep slopes, some techniques and approaches have been developed, including slope stabilization measures, such as retaining walls, slope drains, and vegetation planting, as well as risk assessments, monitoring, and early warning systems.

Overall, the slopes in Chitral are an important aspect of the district's geography, and they play a critical role in shaping the district's climate, ecology, and human history. The rugged and challenging slopes of Chitral provide a unique and beautiful landscape, but they also pose significant challenges and risks that must be carefully managed to promote sustainable development and protect human safety and well-being.

3.1.5 Land use / Land cover

The region of Chitral has diverse land uses and covers such as vegetation, settlements, water bodies, and snow. Categorizing the land into these groups is significant for various purposes, such as hazard assessment, environmental management, and sustainable development. For example, understanding the distribution of snow cover and its impact on the landscape can help assess the risk of avalanches and other hazards.

3.1.6 Normalized Difference Vegetative Index (NDVI)

Figure 3.3 NDVI tends to show the vegetation of the area. Where negative values show barren lands and rocky area, while 0-0.2 shows low vegetation, shrubs, or grassland while 0.2-0.5 shows moderate vegetation and 0.5< values show dense vegetation and forests.

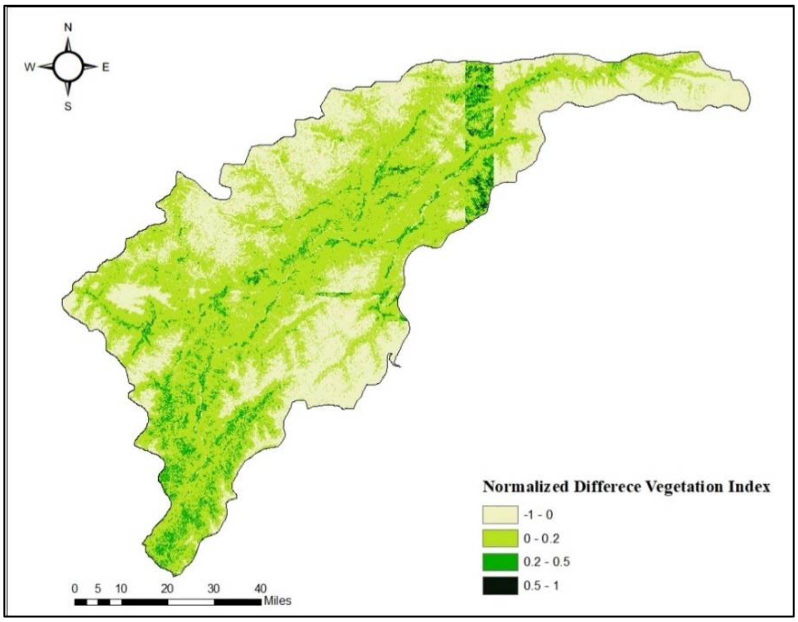

Figure 3. 3 Normalized Difference Vegetative Index of Chitral Basin

3.1.7 Soil classification

In Chitral, the soil is classified into three categories Glaciers, Lithosols, and Heplic Xerosols as shown in Figure 3.4. the data was extracted from FAO. The FAO soil databases are a comprehensive collection of soil data from around the world. The data is collected through various methods such as field observations, laboratory analyses, and remote sensing technologies and is stored in different databases.

These databases provide information on soil properties such as texture, pH, depth, and organic matter content, used for various purposes such as land use planning, soil conservation, and climate change adaptation.

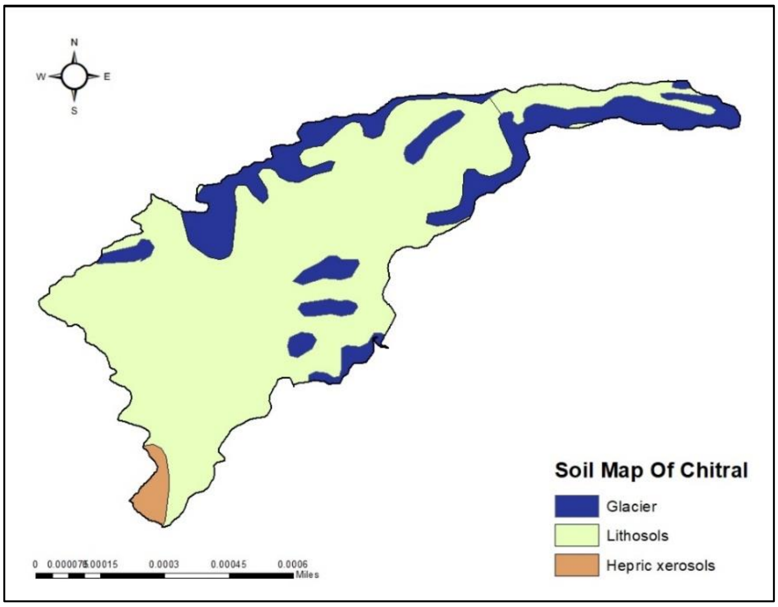

Figure 3. 4 Soil Classification Map of Chitral

(Source: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/)

The data is collected by different organizations and is regularly updated. The FAO soil databases are available for free on their website, providing a consistent platform for soil data access to researchers, policymakers, and land managers worldwide.

3.1.7.1 Glaciers

Glaciers are large bodies of ice and snow that accumulate and move under their weight.

3.1.7.2 Lithosols

Lithosols are characterized by their shallow depth, rocky substrate, and low fertility. Lithosols are typically found in areas with steep slopes, high elevation, and low rainfall, and they are typically not suitable for agriculture.

3.1.7.3 Heplic xerosols

Hepalic Xerosols are a type of soil found in some parts of the world, including Chitral, Pakistan. Xerosols are a subgroup of soil types that are characterized by their low water-holding capacity and high susceptibility to drought.

3.2 METHODOLOGY

3.2.1 Stepwise Procedure

Figure 3.5 shows the methodology for the steps that are going to be taken in our study. First data will be collected. Secondly lakes would be identified. By applying all the selected criteria over the lakes, the risk of GLOF would be identified. At the last sensitivity analysis would be performed to check the future impacts of changes on the lakes.

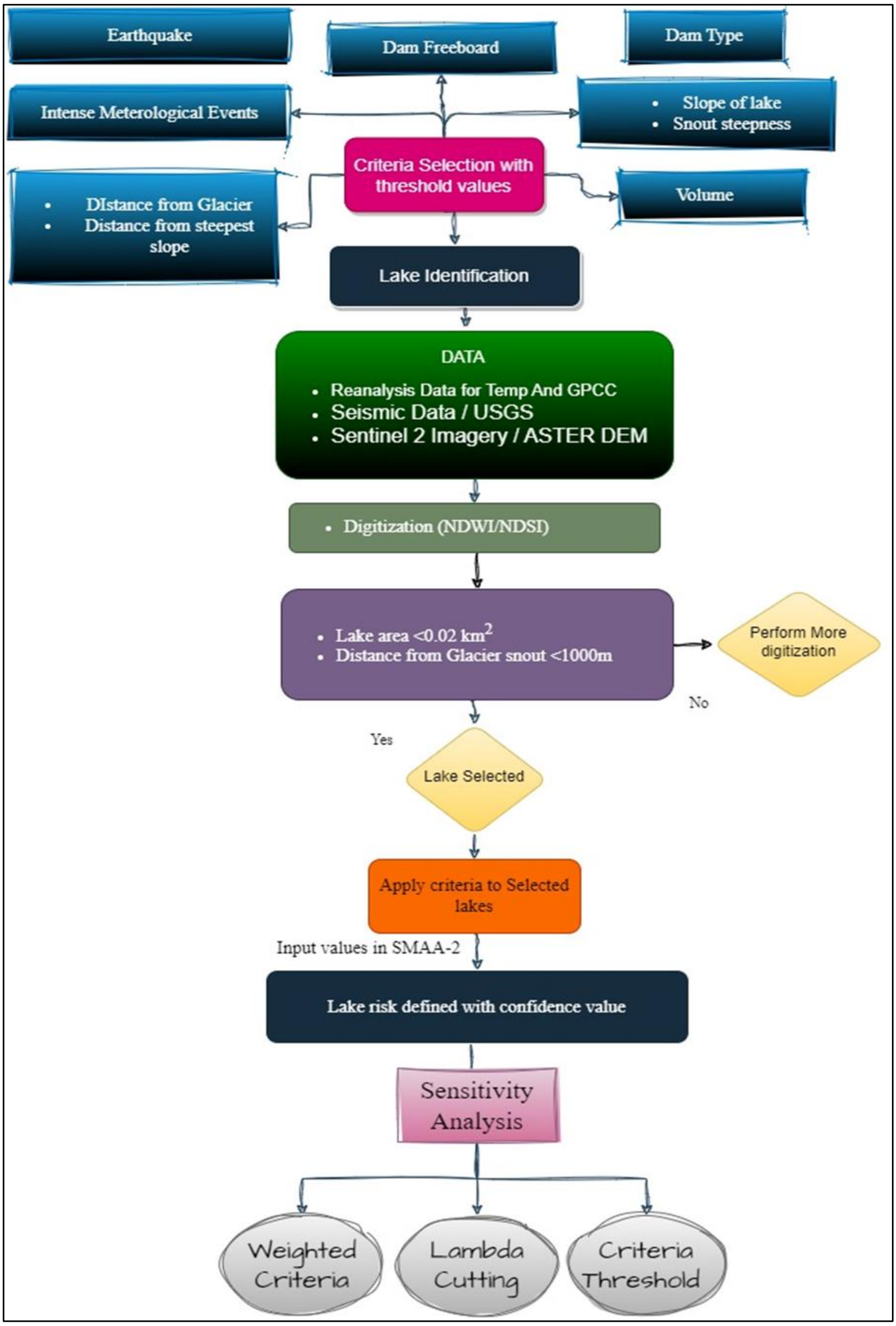

Figure 3. 5 Methodology flow chart

3.2.2 Data sets

Multiple satellite imagery sources were utilized to locate lakes and identify potential risks in the Chitral area. Sentinel 2, Google Earth, and Bing maps were used, with the data collected organized in Table 3.1 indicating period, resolution, and source. The Chitral region was divided into 144 grid points using ArcMap, and precipitation and temperature data were obtained from GPCC and ERA-5 through Python coding and R-language. The combination of these data sources and analytical tools allowed for a comprehensive assessment of the lakes and their associated risks in the area.

Table 3-1 Details of data collection with source

No.	Data	Period	Resolution	Source
1	Sentinel 2/ Landsat 4-5/8	2022	20m	USGS Earth Explorer
2	Seismic data	1998-2022		USGS-Global Seismic Hazard map (units: richer or magnitude scale)
3	Precipitation	1993-2017	0.1^{o}	GPCC
4	Min/Max Temperature	1993-2017	0.1^{o}	ERA-5

Google Earth and Bing maps were also used in the identification of lakes and selected criteria.

3.2.2.1 GLOBAL PRECIPITATION CLIMATOLOGY CENTRE

The Global Precipitation Climatology Centre (GPCC) is a climatological research institute within the German Meteorological Service (Deutscher Wetterdienst, DWD). It was founded in 1991 based on the experiences gained in the DWD's World Climate Programme. The GPCC's research focuses on the development and application of high-quality global precipitation data sets. The GPCC uses the best available ground-based precipitation data from the Global Climate Observing System (GCOS) Global terrestrial Network-Hydrology (GTN-H) to produce these data sets. The GPCC is currently the only institute in the world to produce a complete set of monthly precipitation estimates for the entire globe. The GPCC products are used by a wide variety of national and international institutes and organizations. The GPCC is one of the DWD's six main research centres. It is in Potsdam, Germany, and is part of the DWD's Earth Observation Centre.

Figure 3.6 shows the GPCC data-based product for 25 years. GPCC is renowned for its near-real-time "Monitoring Product" and "First Guess Product," which indicate the extent of station data coverage. In addition, GPCC's centennial "Full Data Reanalysis with the most recent Version 7" from June 2015 is available in the five most recent versions. These products provide comprehensive information on precipitation patterns across the globe. (Schneider et al., 2016)

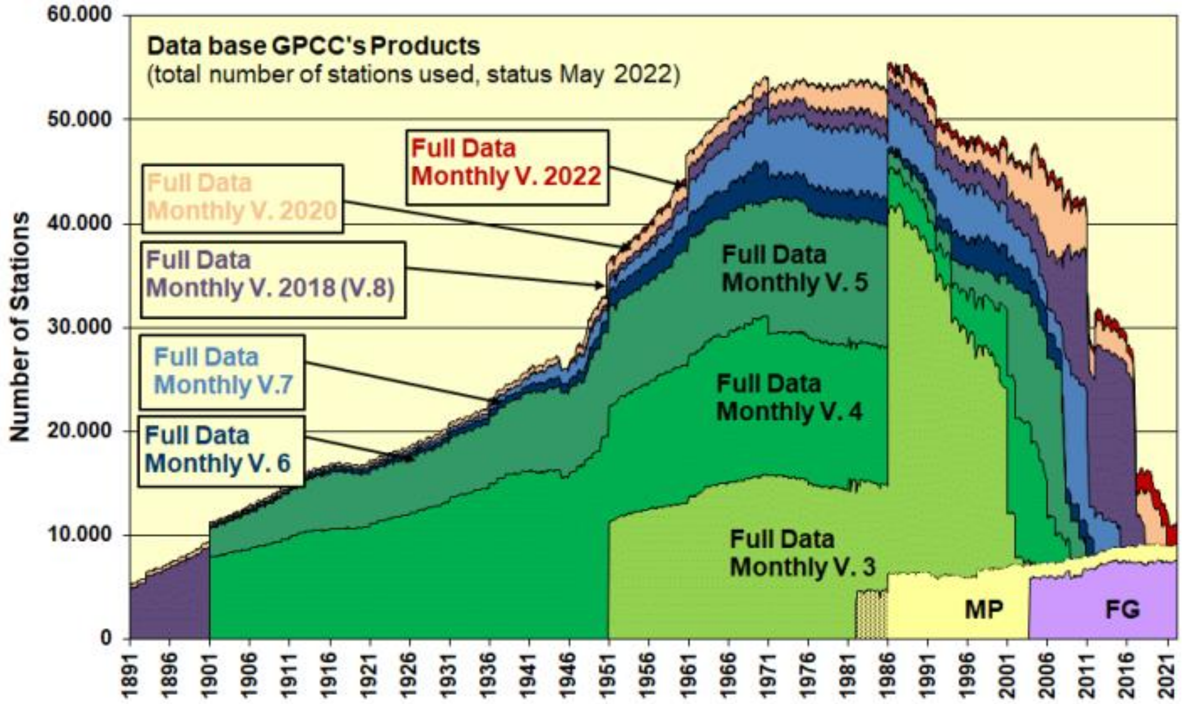

Figure 3. 6 GPCC's Product Data Base (Source: (Schneider et al., 2016)

The GPCC is the world's largest archive of monthly precipitation data. The GPCC collects, quality controls, archives, and distributes precipitation data from all over the world. The GPCC's main task is to generate monthly global precipitation products. The GPCC is a member of the World Climate Research Programme (WCRP) and the Global Climate Observing System (GCOS). The GPCC products are based on data from more than 8,000 stations worldwide. The GPCC data set is the largest data set of its kind in the world. It is continuously updated with new data as they become available. The GPCC is the only institute in the world that uses a consistent and homogeneous methodology to generate monthly global precipitation products. The GPCC products are therefore the most consistent and homogeneous data set of their kind in the world. The GPCC products are used by scientists all over the world for research on the global water cycle, climate change, and climate variability. The GPCC products are also used by national and international organizations for applications in weather.

3.2.2.2 ERA5 REANALYSIS DATA

The ERA5 reanalysis data is a global atmospheric reanalysis effect given by the European Centre for Medium-range Weather Forecasts (ECMWF). It combines a wide range of observations with the model's dynamical understanding of atmospheric processes and provides a consistent, homogeneous, and high-resolution record of atmospheric conditions from 1879 to the present. The ERA5 reanalysis data includes a range of atmospheric variables such as temperature, moisture, geopotential, wind, and precipitation. It is provided on a global latitude/longitude grid with a 0.25-degree horizontal resolution and 137 vertical levels. The data are available in two formats: a compressed netCDF format and a GRIB edition 1 format. The ERA5 reanalysis data is updated regularly and is available for download from the ECMWF website. The ERA5 reanalysis data is a valuable resource for weather and climate research. It has been used in a wide range of studies, from global climate change research to weather forecasting.

The ERA5 project is a global reanalysis product that uses a modern observation-based atmospheric data assimilation system to provide a consistent record of atmospheric variables such as air temperature and humidity, precipitation, cloud cover, and surface pressure. ERA5 started in 1978, with the latest version covering the period from 1979 to the present. ERA5 is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides a high-resolution global atmospheric reanalysis dataset that is freely available to the public. The data is updated every 3 hours for the most recent 10 years, and every 6 hours for the most recent 5 years. The ERA5 dataset is available in both a native (i.e., gridded) and a pressure-level format. The native format is in 0.25 x 0.25-degree latitude x longitude resolution, while the pressure-level format is in 1-degree x 1-degree latitude x longitude resolution. The ERA5 dataset is also available in a monthly mean format, which is a useful product for climate studies. The fifth generation of the global reanalysis by the ECMWF, known as ERA5, is now available. It covers the period from 11950 to the present. ERA5 provides estimates of various atmospheric, oceanic, and land-based climate variables. It is based on the data collected from a 30-kilometer grid and resolved the atmosphere using surface levels up to 80 km. the data are used to calculate uncertainties for each variable.

Some Points should be remembered for ERA 5:

The ERA5 reanalysis data are provided by the Copernicus Climate Data Store (CDS). The ERA5 reanalysis data are accessible through the CDS API. The ERA5 reanalysis data are presented in netCDF format. The ERA5 reanalysis data are presented in a regular grid. The ERA5 reanalysis data are offered in a global grid. The ERA5 reanalysis data are supplied every 6 hours. The ERA5 reanalysis data are offered in a compressed format. The ERA5 reanalysis data are presented at a 0.25° x 0.25° spatial resolution. The ERA5 reanalysis data are provided for the years 1979-present.

3.2.3 Lake selection criteria

3.2.3.1 Problem Description

The MCDA approach is simple, user-friendly, and efficient, making it ideal for the fields with limited information and field data. MCDA has mainly been utilized for environmental and disaster-related issues such as floods and avalanches (Huang et al., 2011)

The problem of evaluating GLOF risk can be approached in several ways using MCDA: (Roy & Vanderpooten, 1996)

Description Problem: This involves presenting multiple alternatives (e.g., dangerous glacial lakes) and a set of criteria without making any final decision recommendation.

Sorting Problem: The alternatives are sorted into predetermined categories based on the level of risk (e.g., high, medium, low risk). This method can also be used to screen and reduce the number of alternatives considered.

Ranking Problem: The alternatives are ranked from highest to lowest risk, with equal ranks possible. Each lake is assigned a numerical value based on its GLOF risk, but some may share the same rank.

Choice Problem: The goal is to select one alternative or to narrow down the group of alternatives to a subset with equivalent or incomparable risks.

3.2.3.2 Rules to select a criteria

A basic problem description for natural hazards and their risk management was given by (Roy & Vanderpooten, 1996) they consist of four factors in which firstly the problem was described and then evaluated based on its present alternatives then they were ranked from low to high-risk factors. This way the one chose where the study was to be conducted further.

For the selection of a hazard or there are a few points that we should be keeping in mind.

Exhaustiveness: All the criteria must be used which are interlinked with each other. No important criteria must be missed. This will help to split up a composite criterion, and issues will be avoided in the results.

Non-redundant: unnecessary criteria must not be selected as most criteria select the same features and results. (W. Wang et al., 2011)

Uniformity: the criteria selected must be consistent with its results, whether high or no risk.

3.2.3.3 MCDA for selection of hazard prone lakes

Previously many criteria were selected by (A. Emmer & Vilímek, 2013; Huggel et al., 2004; Mergili & Schneider, 2011). In risk assessment studies, the criteria used for evaluation are often chosen without clear reasoning or are based on past studies. This can lead to bias in the selection process. To avoid this bias, Multi-Criteria Decision Analysis (MCDA) guidelines should be followed. These guidelines help to ensure that all available options are considered and that there are no issues with incompleteness, repetition, or inconsistency. MCDA is particularly helpful in areas where data or knowledge is limited. (Kougkoulos, Cook, Jomelli, et al., 2018a). Only 10 criteria were selected to find PDGLs with the help of available data and without the help of field measurements.

Earthquake:

Regional seismic activity is a well-known trigger for natural hazards such as dam collapses, rockfalls, landslides, snow avalanches, and icefalls (Mergili & Schneider, 2011). The established thresholds classify seismic hazard levels as low (<0.5 m/s2) and high (>0.5 m/s2). To account for global seismic hazards, (Shi et al., 2015) proposed an upper threshold of 3.9 m/s2 and introduced a medium-risk category. Therefore, it is critical to consider the potential impact of regional seismic activity when evaluating the safety of dams and other natural hazards. (A. Emmer & Vilímek, 2013; Mergili & Schneider, 2011; Rounce et al., 2016; Shi et al., 2015)

BIO-4a/BIO-15

Intense precipitation and high-temperature events have been classified as "hydrometeorological" situations, which have the potential to trigger mass movements into a lake, leading to devastating flooding and loss of life (Huggel, 2004; W. Wang et al., 2011). Therefore, understanding the mechanisms behind these events is crucial to prevent their damaging effects. If we split them into two categories, then with the help of Reanalysis data from GPCC/ERA-5 for precipitation and temperature respectively. With help of Bioclimatic variables BIO-4 and BIO-15 for the calculation of precipitation and temperature values over different grid points. (O'Donnell & Ignizio, 2012).

Precipitation and temperature seasonality were classified into three risk categories each. For precipitation, the low-risk category was (<50%,) the medium-risk category was (50-100%), and the high-risk category was (>100%). Temperature seasonality was classified as low risk (<50%), medium risk (50-100%), and high risk (>100%) based on the standard deviation of monthly temperature averages.

Dam type

The dam freeboard is important in preventing waves from overtopping a dam. However, measuring the freeboard height using satellite data can be difficult. To establish risk levels, previous studies have used open-source, high-resolution satellite imagery to determine the freeboard height and established thresholds for low, medium, and high risks. These thresholds represent freeboard heights >15 meters (low risk), freeboard heights ranging from 15-5 meters (medium risk), and freeboard heights <5 meters (high risk). (X. Wang et al., 2013; Worni et al., 2014)

Dam freeboard

The type of dam is a crucial factor in assessing the likelihood of an outburst. Research indicates that ice-dammed lakes are responsible for 70% of the historical and modern glacier floods, with moraine-dammed lakes accounting for 9%. In contrast, the dam type/trigger for 16% of the floods is unknown, while volcanic activity accounts for 3% of occurrences. While moraine-dammed lakes have a higher mortality rate than ice-dammed lakes, we only consider the stability of the dam in this study. Therefore, previous research has established three classes of dam types: ice dam (high risk), moraine dam (medium risk), and bedrock dam (low risk). These classifications are consistent with previous studies. (Huggel et al., 2004; X. Wang et al., 2013; Worni et al., 2014)

Slope

GLOFs are mainly caused by mass movements entering a glacial lake due to steep slopes. Areas with a slope greater than 30° are susceptible to landslides. We considered 25° as the minimum threshold slope that can generate mass movements into a lake. Lakes that are further than 500m from a slope, or closer than 500m from a < 25° slope are not considered. We defined three classes: <30° slope (low risk), 30-45° slope (medium risk), and >45° slope (high risk). (Rounce et al., 2016; Worni et al., 2014)

Distance from glacier

The distance of the lake from its mother glacier determines its threat to avalanches in case of calving. Different studies used glacial lakes with 500m (W. Wang, 2015; W. Wang et al., 2011) but here in this study due to the lesser number of lakes and the limited area we used lakes up to 1000m distance from glacier snout. So, lakes with a distance ≥250m are taken to be of low risk. 250-10m (medium risk) and <10 is off (high risk) category.

Distance between lake and steepest slope

It gives the distance between the lake and the distance of the vertical slope from that lake. The greater the distance, the lesser would be its risk factor. This criterion has the same divisions as the distance from the glacier. (Simon J. Cook et al., 2016)

Snout steepness

A steep glacier snout can cause an increased level of ice calving into a lake and can raise the risk of a GLOF. Wang et al. (2011) and Emmer et al. (2015) classified the parent glacier snout steepness into three classes: <15° (low risk), 15°-25° (medium risk), and >25° (high risk). This classification is used to determine the risk level of a GLOF from a parent glacier situated in proximity to a lake. (Adam Emmer, 2017; W. Wang et al., 2011)

Lake Volume

Lake volume determines how much water is present there in a lake approximately. Different equations were used to determine the volume for Moraine/Bedrock dammed or Ice Dammed lakes. (S. J. Cook & Quincey, 2015; Westoby et al., 2014)

The first mean depth of Ice Dammed lakes was found by. $\mathbf{Dm = 1 \times 10^{-5} A + 7.3051}$

And for moraine/bedrock dammed lakes **Dm = 3 × 10−5 A + 12.64**

Then with the help of mean depth Volume was calculated. **(V= Dm*Area)**

Based on the analysis, three classes of risk were defined: low risk (<1 x 106 m3), medium risk (1 x 106 m3 - 10 x 106 m3), and high risk (10 x 106 m3 - 100 x 106 m3).

Where the dam type is not known, then volume was calculated by the (Huggel, Kääb, Haeberli, Teysseire, et al., 2002) Equation ($\mathbf{V= 0.104\ A^{1.42}}$)

Lake discharge

The (Walder & Costa, 1996) equation was used to calculate the peak discharge (Q_{max}) of lakes with ice dams. The equation is.

$$Q_{max} = 1100 \times (V/10^6)^{0.44}.$$

For potentially dangerous moraine-dammed lakes and bedrock-dammed lakes, the (Evans, 1987) equation was used. The equation for these lakes is.

$$Q_{max} = 0.72V^{0.53}.$$

3.2.4 Identification of lakes

The following selection criteria were applied to select lakes for further study.

- Area of the lake should be **>0.02** $km^{2.}$ (W. Wang et al., 2012; Zhang et al., 2022)
- The distance of the lake from the glacier should be 1000m.

3.2.5 Thershold value

The criteria threshold value defines the categories that are defined with the help of different values. Here almost all threshold values Table 3.2 were taken from the previous literature review to identify three classes for lake identification. i.e., low, medium, and high. (Chen et al., 2001; Figueira & Roy, 2002; Huggel, 2004; Ives et al., 2010; Kougkoulos, Cook, Jomelli, et al., 2018a; Sattar et al., 2020)

Table 3-2 Threshold Values for all Selected Criteria

Sr. #	Criteria Name	Units of criteria	Low risk	Medium risk	High risk	Criteria evaluation
1	Earthquake	Magnitude/ Rector scale	<0.5	0.5-3.9	>3.9	ArcMap
2	Precipitation	Precipitation in percentage	<50%	50-100	>100	ArcMap
3	Temperature	Temperature in percentage	<50%	50%-100%	>100%	ArcMap
4	Dam Type	N/A	Bedrock dammed	Moraine dammed	Ice dammed	Google Earth/ ArcMap
5	Dam Freeboard	M	>15	15-5	<5	Google Earth
6	Slope	Degree	<30	30-45	>45	Satellite imagery
7	Distance of lake from steepest slope	M	500-250	250-10	10>	Google Earth/Satellite imagery
8	Snout steepness	Degree	<15	15-25	>25	Satellite imagery
9	Distance between lake and glacier	M	500-250	250-10	10>	Google earth/satellite imagery
10	Lake volume	m^3	$1*10^6$	$1*10^6$-$10*10^6$	$10*10^6$-$100*10^6$	Google earth/satellite imagery + equations

3.3 SMAA-Tri SOFTWARE

Stochastic Multicriteria-Acceptability Analysis (SMAA) is a extension of actually known JSMAA software is a computer program for the analysis of Multi-Criteria Decision Making (MADM) , developed by the Decision Analysis Group of the Finnish Forest Research Institute. It is a tool for analysing and making decisions in complex decision problems with multiple objectives and criteria. It is used to identify the best alternatives according to the preferences of the decision-maker and to determine the relative importance of each criterion. SMAA can be used to assist in decision-making in a wide range of applications, such as environmental management, resource allocation, and project selection. SMAA can be used to perform a sensitivity analysis to identify the criteria that have the most influence on the decision outcome. It can also be used to analyse trade-offs between objectives and criteria and to identify the best alternatives according to the preferences of the decision-maker. In addition, SMAA can be used to compare different decision options and to identify the most suitable one. The software is available in both graphical and command-line versions. The software is available for free on the Decision Analysis Group website. It is available for Windows, Linux, and Mac OS X. SMAA is a powerful tool for decision analysis, but it is important to remember that it is not a substitute for expert judgment and experience. The user should understand the decision problem and its objectives before using the software. SMAA is a useful tool for decision-makers who need to make decisions in complex environments. It can help users to identify the best alternatives and understand the relative importance of different criteria in the decision-making process. SMAA is available in both graphical and command-line versions. The graphical version has a user-friendly interface, while the command line offers more flexibility and control over the analysis (Tervonen, 2014).

For every MCDA problem statement, there is a family of MCDA procedures called SMAA. Inverse parameter space analysis using Monte Carlo simulation is the foundation of the methodologies. The many SMAA techniques enable dealing with issues when the preferences, technical parameters, and criteria measurements are ambiguous, imprecise, and (partially) incomplete. While inaccurate information indicates that a value is present but not with the necessary accuracy, incomplete information indicates that a value is absent. The observer, who is supposed to provide accurate and comprehensive information but is inherently unreliable, is taken into consideration by uncertainty (Smets 1991). The SMAA approaches manage all three sorts of ignorance about the parameter values in comparable ways from a technical standpoint using probability distributions or as ordinal information (Tervonen & Figueira, 2008).

Figure 3.7 is the flow chart for steps which will be used in SMAA-TRI software (Corrente et al., 2021).

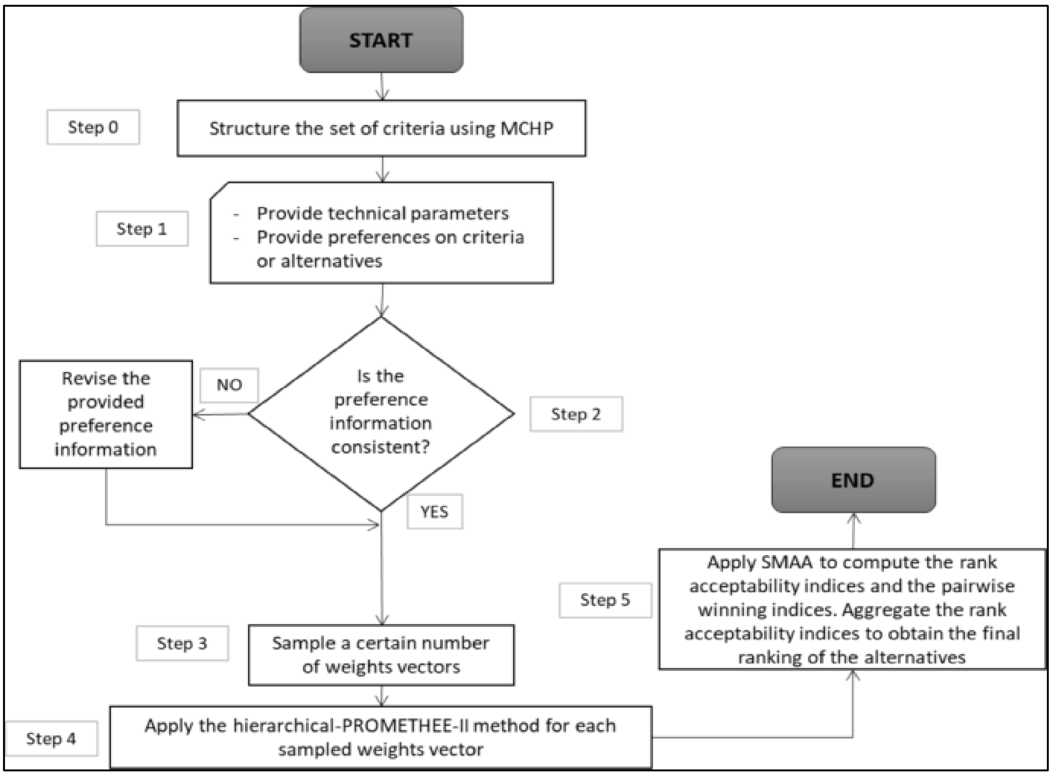

Figure 3. 7 Flow chart of steps of SMAA Method

3.4 SENSITIVITY ANALYSIS

Sensitivity analysis refers to a technique where we can tell how much a changing variable can affect our results. It also tells us the results uncertainty due to the uncertainty in input variables. In this research study, sensitivity analysis was performed using SMAA-2/TRI software.

3.4.1 Criteria weight sensitivity analysis

After finding the confidence factors from SMAA 2 all the quantitative criteria were assigned criteria weights. Different weights were assigned to all the criteria by keeping them on topmost or lowest. Range of weights was 0-1 so overall division was to divide the criteria in such way that sometimes they hit the top line, sometimes medium, and sometimes low.

3.4.2 Sensitivity analysis OF Lambda (ג) Cutting Value

Lambda cutting level tells us the distance between the measured and threshold value. It shows how much weight a certain alternative has at a specific lambda interval to be better than other alternative. ג cutting value ranges from 0.5 to 1 (Damart et al., 2007) i.e., where 0.6 means that at 60% of Monti-Carlo Simulations.

3.4.3 Criteria threshold sensitivty analysis

Criteria threshold sensitivity analysis refers to analysis where the threshold value selected is changed according to the selected criteria (Kougkoulos, Cook, Edwards, et al., 2018) shown in Table 3.3

Here λ cutting value is kept constant i.e., 0.65, and the threshold value is changed to see their effect on the results. (Here Q refers to qualitative research where sensitivity analysis wasn't applied)

Table 3-3 Threshold values used for Sensitivity Analysis of Results

SR. NO.	Criteria	Low	Medium	High
1	Earthquake	<0.5	0.5-1.9	>1.9
2	Precipitation	<25	25-75	>75
3	Temperature	<25	25-75	>75
4	Dam type	Q	Q	Q
5	Dam freeboard	Q	Q	Q
6	Slope	<20	20-30	>30
7	Distance of lake from Glacier	500-250	250-50	<50
8	Snout steepness	N/A	N/A	N/A
9	Distance of lake from steepest slope	500-250	250-50	<50
10	Lake volume	$<0.1*10^6$	$0.1*10^6-1*10^6$	$>1*10^6$

Chapter 4

RESULTS & DISCUSSION

4.1 RESULTS

4.1.1 Criteria Framework

With the help of previous literature review and the study area specifications a specific set of criteria was developed to study the lake risks associated with these criterias. These criteria was best choosen for areas where less field observations and data was available, it was at high risk of GLOF's and the data was freely available. So for Chitral these criteria was best suited for lake risks upstream study.

4.1.2 Results flow

First, trend analysis of temperature and precipitation was performed to see how much changes have occurred in the area to know the exact environmental conditions of Chitral. The digitization maps were made to identify water bodies, snow cover, vegetation, and land use/land cover within the area. Results were found for all criteria.

4.1.3 Trend analysis

Trend analysis was performed to see the temperature and precipitation trends. It was basically not related to any of our criteria, but it helped to see the variations of climatic changes within this area. The temperature and precipitation data acquired from ERA-5 and GPCC was analyzed with the help of Mann Kendall test which is used to identify monotonic trends to see variations, whether trend is increasing or decreasing. P and Sen slope values were observed.

P value was set at the confidence level of 95%. $P<0.05$ significance factor was taken which shows that at $p<0.05$ the trend is significant i.e., there is an increasing and decreasing trend most probably while at $p>0.05$ there is not enough evidence to declare increasing or decreasing trend.

Sen's slope gives the magnitude of trend whether its increasing, decreasing trend with negative and positive values. i.e., Sen's slope positive then $P<0.05$ shows increasing trend and vice versa. Over 144 grid points trend analysis was observed which shows that during the period of 1993-2017 there was a significant increase in the temperature trend for both minimum and maximum temperature. While for precipitation it shows that precipitation faces decreasing trend for period of 1993-2017. Here Figure 4.1 & Figure 4.2 show the trend analysis graphs during the period of 1993-2017 where the temperature trend increased for both minimum and maximum. While Figure 4.3 shows the decreasing trend for precipitation.

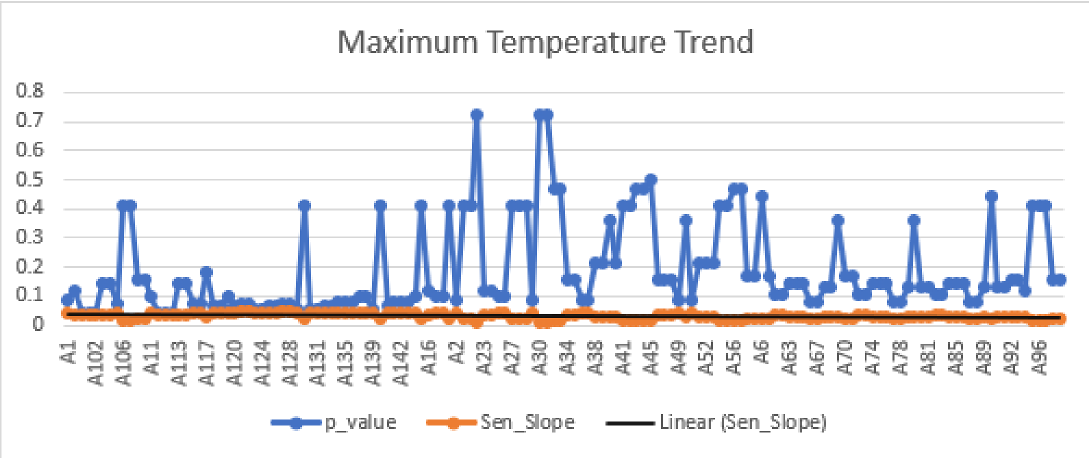

Figure 4. 1 shows the maximum temperature trend over period of 1993-2017

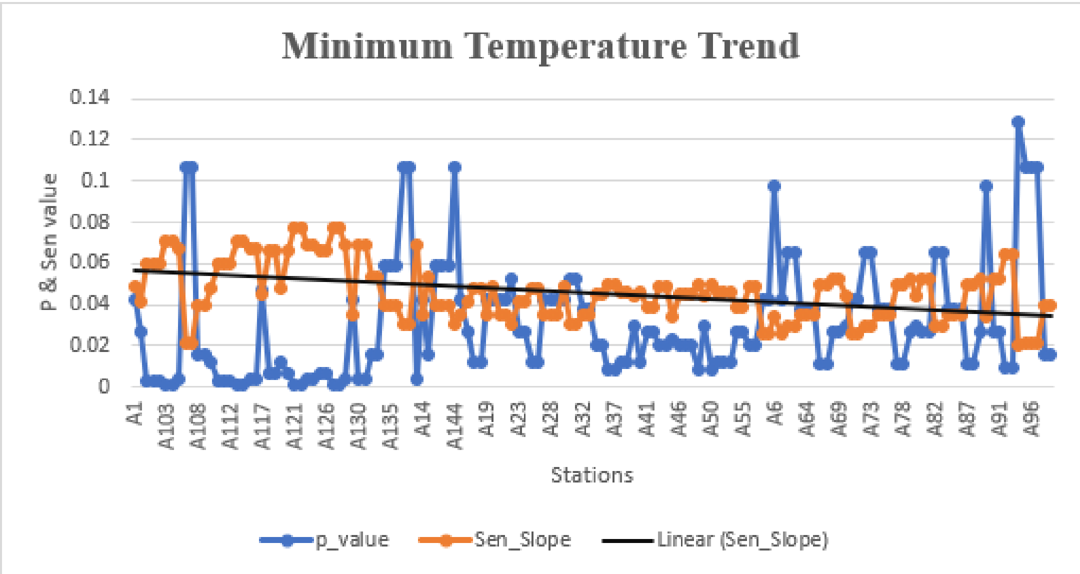

Figure 4. 2 Minimum temperature trend over period of 1993-2017

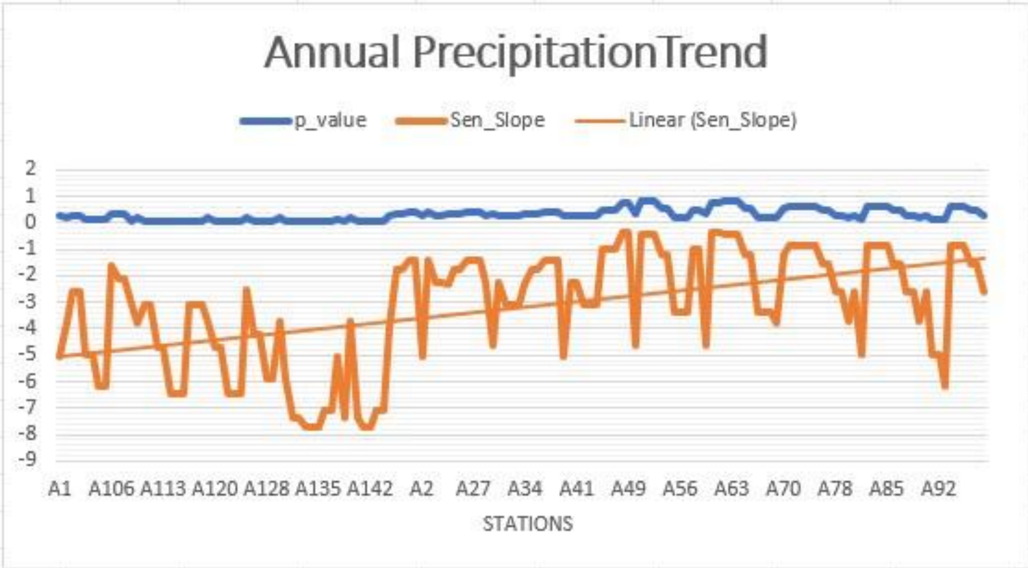

Figure 4. 3 shows Average annual Precipitation Trend over period of 1993-2017

4.1.4 Why MCDA for this study

When it comes to Chitral no specific research was conducted on all the lakes to identify them. So, MCDA was used to identify hazard-prone lakes in Chitral. Several previous studies were done on MCDA (A. Emmer & Vilímek, 2013; Huggel, Kääb, Haeberli, & Teysseire, 2002; Mergili & Schneider, 2011; Rounce et al., 2016; Worni et al., 2013) on different areas. MCDA is mostly preferred for areas where there is a lack of observed and field data. But if needed field data can be incorporated instead of freely available data (Aggarwal et al., 2016; Fujita et al., 2008). MCDA approach is good to find lakes that will need further study in the future. The lakes that have been listed as high-risk zones will be considered for study next.

MCDA approach was first described then robust techniques were used to identify criteria to study lakes. Further the software we used SMAA-TRI was good and free to use to identify risk zones related to lakes and their criteria results were studied in its SMAA-2.

But as with all MCDA also has some lagging and challenges. For example, if we talk about risk, it just tells us that a lake is under a specific risk category. It doesn't define whether it's in the very high medium-high or low-high-risk category. It makes it difficult and lays all lakes in one plate to study them.

Secondly, all the dam types and freeboards that were studied have a drawback in that they can't be properly and exactly studied remotely. Most of the work was done with the bird eye view technique and previous literature review. The threshold values set for all the criteria were all taken from previous literature reviews so it's not possible to completely give specific criteria a rank that which rank is most dangerous or not. A detailed study was done to assign criteria ranking but still future study is needed.

4.1.5 Digitization

With help of manual digitization, NDWI and NDSI all lakes were identified. By keeping the lake selection criteria hazarduous lakes were selected.

4.1.5.1 Normalized Difference Water Index (NDWI)

NDWI stands for Normalized Difference Water Index. It is a remote sensing index that is commonly used to identify and quantify the presence of water in an image. NDWI was used to find out water bodies within Chitral boundary. NDWI values are calculated using the reflectance values of two spectral bands, typically the green and near-infrared (NIR) bands.

Here, NDWI was used to identify lakes with the help of manual digitization. NDWI values show that negative values from -1 to 0 shows non water (vegetation, population, barren lands etc.) area while values form 0-1 shows water and glaciated area. Figure 4.4.

The following formula was used for NDWI for sentinel 2:

NDWI = (B3 - B8) / (B3 + B8)

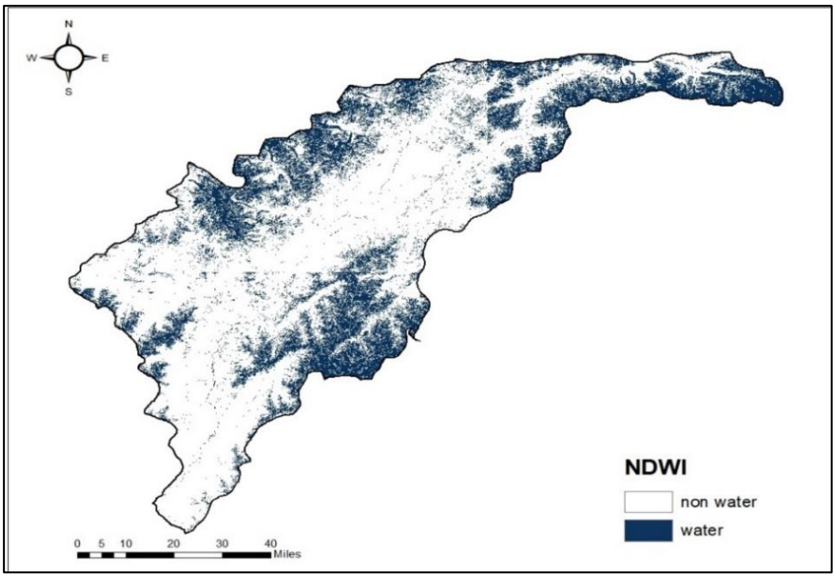

Figure 4. 4 Normalized Difference Water Index to identify lakes for Chitral Basin

4.1.5.2 Normalized Difference Snow Index (NDSI)

NDSI stands for Normalized Difference Snow Index. It is a remote sensing index that is commonly used to identify and map the presence of snow and ice in an image. It was used to find out the glacier cover of Chitral basin. NDSI values are calculated using the reflectance values of two spectral bands, typically the green and mid-infrared (MIR) bands. Figure 4.5 the values higher than 0.4 show the snow-covered area in white colour.

The formula used to calculate NDSI for sentinel 2 imagery is:

NDSI = (B3 – B11) / (B3 + B11)

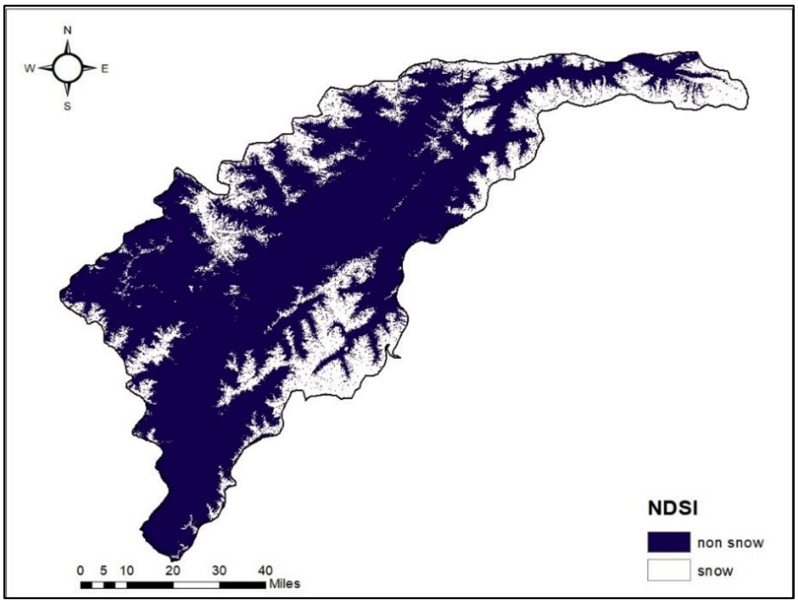

Figure 4. 5 Normalized Difference Snow Index Map to identify snow cover for Chitral basin.

4.1.5.3 Identified lakes

Due to the increase in temperature across the globe glaciers are melting rapidly. Some glacial lakes can be a source of great destruction as due to excessive glacier melting the number of glacial lakes is increasing which can be dangerous sometimes for the people and infrastructure nearby. There were almost 130 glacial lakes found in the boundary of Chitral River Basin. Out of these, only 13 were found to be completing the requirements of our lake selection criteria.

With the help of NDWI (Tobias Bolch, 2011) and NDSI lakes and their adjacent glaciers were identified.

4.1.6 Mechanism for Triggers

4.1.6.1 Slope

The slope shows the slope angle of a particular area using Digital Elevation Model (DEM). It can be used to identify areas of high slope that may be prone to landslides or erosion, or to locate potential sites for infrastructure development, such as roads or buildings, that require relatively flat terrain. Here, the slope map of Chitral was divided into 8 classes from 5^{o} to $80^{o.}$

The northern and southern periphery parts have the steepest slope. Figure 4.6.The areas with the greatest slope are potentially more hazardous (Aslam et al., 2022).

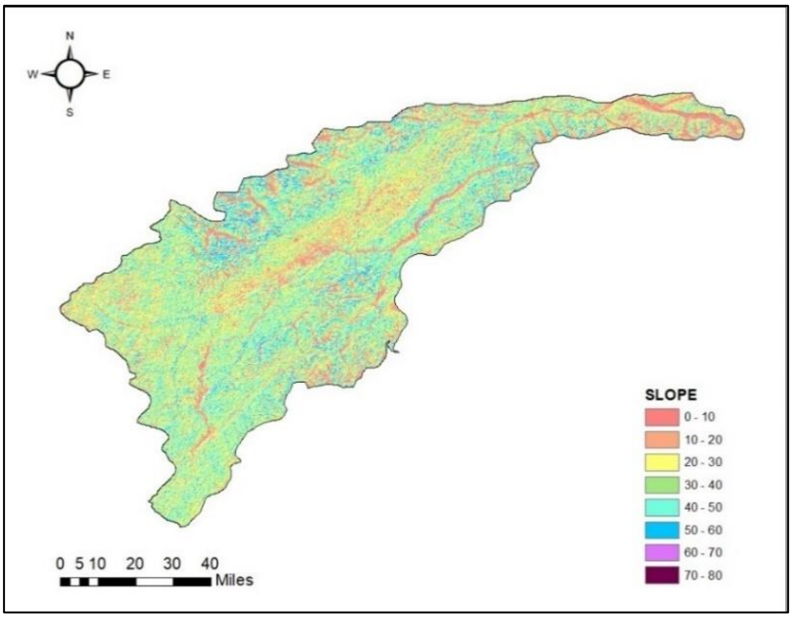

Figure 4. 6 Slope Map of Chitral Basin

Table 4.1 & Table 4.2 shows results for different criteria applied to lakes of Chitral basin.

Table 4. 1 results for selected criteria of lakes GLOF mechanisms (cont. in table 4.2)

Lake	**Area (Km^2)**	**Slope**	**Distance (m)**	**Dam type**	**Dam FB (m)**	**Snout steepness of parent Glacier**	**Long**	**Lat**
Lake 1	0.085	45	0	Bedrock-dammed	3	45	71.99	35.81
Lake 2	1.593939	50	873	Bedrock Dammed	12	55	72.32	35.91
Lake 3	0.100121	45	50	Bedrock Dammed	6	50	71.99	35.83
Lake 4	0.207339	45	0	Moraine dammed	6	15	71.80	36.18
Lake 5	0.044173	25	200	Moraine dammed	12	17	71.78	36.16
Lake 6	0.0243	30	900	Moraine dammed	5	25	71.77	36.13

Lake 7	0.062463	30	520	Bedrock dammed	8	20	71.35	36.13
Lake 8	0.1	20	0	Bedrock dammed	5	15	73.28	36.81
Lake 9	0.053981	20	449	Bedrock dammed	0	25	71.76	36.13
Lake 10	0.032132	25	0	Bedrock dammed	3	25	71.34	36.15
Lake 11	0.03323	30	0	Moraine dammed	5	30	71.77	36.13
Lake 12	0.060363	25	0	N/A	5	20	71.38	36.18
Lake 13	0.022127	35	92	N/A	4	15	71.95	36.34

Table 4. 2 results for selected criteria of lakes GLOF mechanisms

Lake ID	**Distance b/w lake and steepest slope (m)**	**Volume (km^3)**	**Q_{max} (km^3)**
Lake 1	3000	1.0744	0.7479
Lake 2	5000	20.14746518	3.536464605
Lake 3	2800	1.265529741	0.815711988
Lake 4	935	2.62076625	1.199774117
Lake 5	97	0.558346779	0.52867847
Lake 6	376	0.30765	0.3854
Lake 7	1028	0.789532437	0.635241093
Lake 8	50	1.2640003	0.815189356
Lake 9	180	0.681182327	0.587438064
Lake 10	550	0.4	1.331805549
Lake 11	272	0.42	1.351641622
Lake 12	221	0.0019	1.75762966
Lake 13	926	0.0005	0.36649445

4.1.7 Triggers of GLOF

From all selected criteria seismic activity, precipitation seasonality and temperature seasonality are considered to be the main triggering factors. While all others were considered as the mechnisms for these certein criterias.

4.1.7.1 Seismic data

Seismic data was downloaded from USGS for period of 1998-2022. That showed the magnitude of earthquakes that occurred in Chitral. The overall area faced almost 0-10 Richter/magnitude scale earthquakes. The map of Chitral seismic activities in Figure 4.7 shows Peak Ground Movement (PGA), that is corelation between the magnitude and distance from the epicentre, during that period. The unit of PGA is same as of acceleration. With the help of interpolation techniques all the values were found for the whole area.

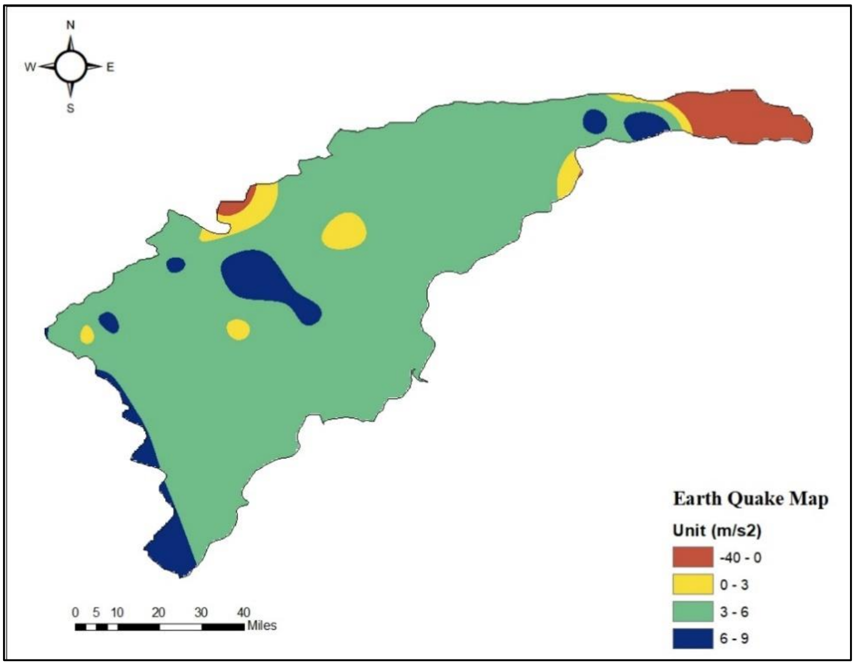

Figure 4. 7 Seismic Map of Chitral Basin

4.1.7.2 Temperature seasonality (BIO 4a)

Reanalysis data from ERA-5 was converted to Bioclimatic variable BIO 4a to properly monitor the variations in temperature along with its effect on the topography as our criteria was developed to check out the coefficient of variation of area for temperature. The formula used was taken from (O'Donnell & Ignizio, 2012)

$$\textbf{BIO 4a} = \textbf{SD}\ \{Tkavg_1 \ldots\ldots, Tkavg_{12}\} / (\textbf{BIO}\ 1 + 273.5)$$

where BIO 1 is the total mean temperature. Units of BIO 4a were in percentages of coefficient of variation.

The area of Chitral Basin was divided into 144 grid points with the help of fishnets in ArcMap. Figure 4.8 shows the interpolation technique that was used to the land value of temperature seasonality over specified grid point. Values were added in map as in form of percentages calculated with BI O-4 (Ives et al., 2010).

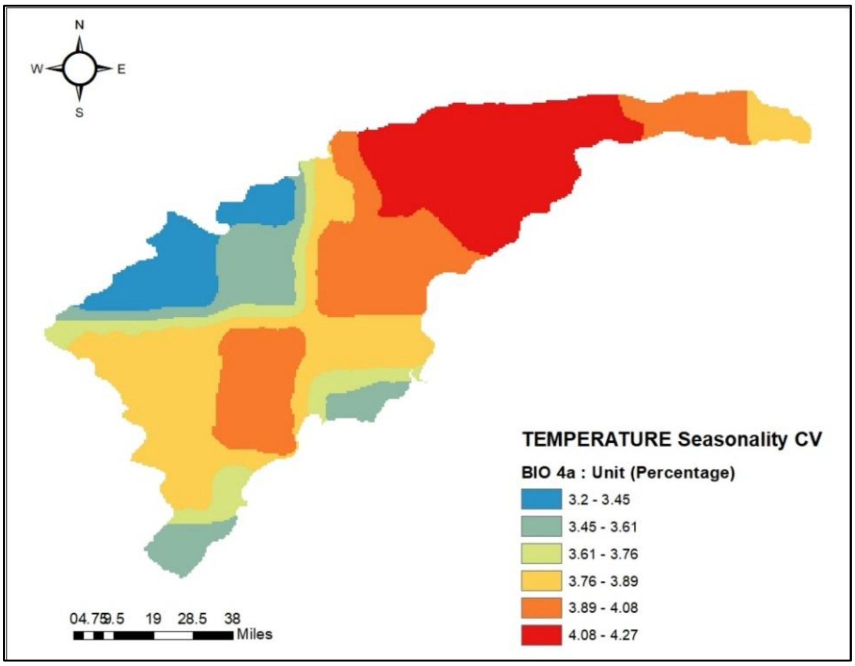

Figure 4. 8 Temperature Seasonality map of Chitral basin

4.1.7.3 Precipitation seasonality (BIO 15)

The precipitation data from GPCC was extracted over 144 gird points extracted from ArcMap. The data was converted to Bioclimatic Variable Bio 15, that is precipitation seasonality (Ives et al., 2010).

BIO 15= [SD {PPT_1…...PPT_{12}}/1+(BIO12/12)] *100

The interpolation technique was used to find precipitation from all gridded points over the Chitral area to find out a specified amount of precipitation seasonality was performed over the specific area of lake. Figure 4.9

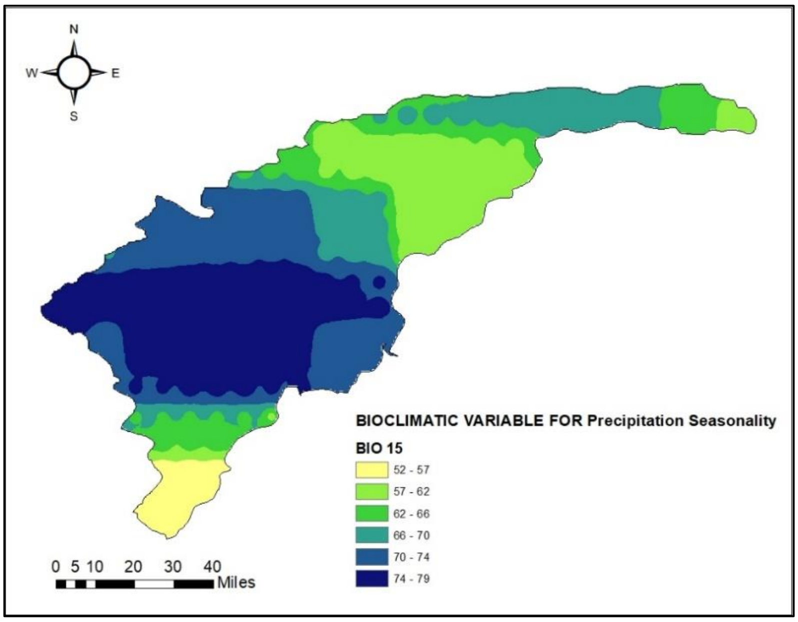

Figure 4. 9 Precipitation Seasonality Map of Chitral basin

4.1.8 Results for GLOF triggers

Table 4.3 shows values for triggering factors of GLOF i.e., EQ, PPT & Temperature events evaluated by interpolation over Chitral basin. With the help of interpolation/kriging method the data over a particular lake was extracted.

Table 4. 3 Triggers of GLOF

ID	CRITERIA	RESULTS	ID	CRITERIA	RESULTS
Lake1	Earthquake	4.11	Lake 7	Earthquake	4.90
	BIO 4a	3.92		BIO 4a	3.45
	BIO 15	76.05		BIO 15	75.2
Lake 2	Earthquake	4.90	Lake 8	Earthquake	5.6
	BIO 4a	3.72		BIO 4a	4.055
	BIO 15	73.7		BIO 15	67.6
Lake 3	Earthquake	4.11	Lake 9	Earthquake	4.11
	BIO 4a	3.92		BIO 4a	3.49
	BIO 15	73.7		BIO 15	78.3
Lake 4	Earthquake	4.11	Lake 10	Earthquake	4.90
	BIO 4a	3.43		BIO 4a	3.42
	BIO 15	77.8		BIO 15	75.2
Lake 5	Earthquake	4.12	Lake 11	Earthquake	4.11
	BIO 4a	3.385		BIO 4a	3.48
	BIO 15	78.9		BIO 15	78.9
Lake 6	Earthquake	4.11	Lake 12	Earthquake	3.11
	BIO 4a	3.5		BIO 4a	3.311
	BIO 15	78.9		BIO 15	75.2
Lake 13	Earthquake	6.18			
	BIO 4a	3.56			
	BIO 15	72			

4.1.9 SMAA-2 model results

SMAA-2 extension of JSMAA was used to identify lakes on basis of confidence factors and their ranks indices. The confidence factors showed that which lake was in high proportion of risk and vice versa.

Table 4.4 shows Confidence factors (C.F) and the highest criteria in the selected lakes. While Figure 4.10 highlights the lakes within Chitral basin with risks.

Table 4. 4 Confidence factors (C.F) and the highest criteria the in the following lake. Green: Low risk, Orange: medium risk, Red: high risk

SR NO.	LAKE	C.F	Highest criteria weightage
1	Lake 1	0.99	Distance from Glacier
2	Lake 2	1.00	Lake volume
3	Lake 3	0.56	Snout steepness
4	Lake 4	1.00	Distance between the lake and the steepest slope
5	Lake 5	0.2	Distance between the lake and the steepest slope
6	Lake 6	0.29	Precipitation Seasonality (BIO 15)
7	Lake 7	0.02	Earthquake
8	Lake 8	1.00	Distance between the lake and the steepest slope
9	Lake 9	0.06	Distance between the lake and the steepest slope
10	Lake 10	0.27	Distance between the lake and the steepest slope
11	Lake 11	0.90	Precipitation Seasonality (BIO 15)
12	Lake 12	0.18	Distance between the lake and the steepest slope
13	Lake 13	0.87	Earthquake

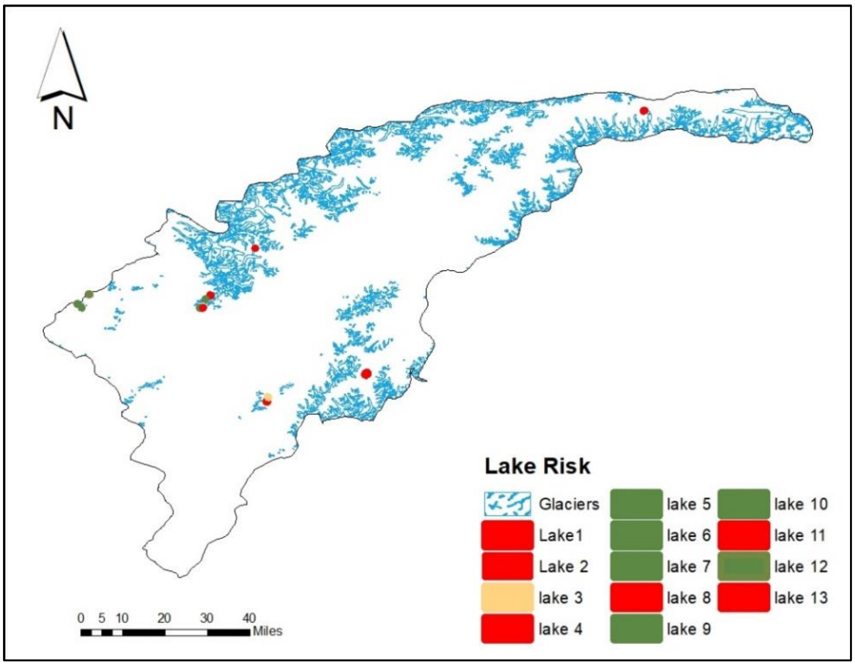

Figure 4. 10 shows the lakes identified after the completion of criteria. The Red colour shows high risk while Orange & Green shows medium and low risk lake respectively.

4.1.10 Model sensitivity

The sensitivity of the model was done to know the accuracy of the model and its future impacts on the results. Sensitivity shows how many of the models will be affected if the body changes. Here in this study sensitivity analysis was performed with the help of three parameters. One was the change of criteria weights and the other was the change of lambda cutting value while other was change of threshold values. All analyses have reliable results and show 6 lakes out of 13 first belonged to the high-risk category but if we change the values of ג or criteria weights all ultimately fall into the high-risk category.

4.1.10.1 Sensitivity analysis

In SMAA-2 & SMAA-Tri extension of JSMAA sensitivity analysis was performed for weighted criteria and lambda cutting, criteria threshold respectively. With the help of sensitivity analysis future impact of changing different parameters was found. Values preferences, iterations rate and changed threshold values assigning showed the changing results in all three sensitivity analysis results.

First different weights were assignd to see which criteria was ought to be the most riskier one for this area. then lambda cutting intervals assigned importance to particular criterias and at end by chnaging the threshold values risk level for lakes was found.

4.1.10.2 Weighted criteria sensitivity analysis

In this step different weights were assigned to all criteria. This step was repeated several times. After iterations, the weighted criteria and confidence factors were chosen which showed the risk level of lake after this step and gave us the rank of different criteria. Table 4.5 shows the results of confidence factors after the criteria sensitivity analysis.

Table 4. 5 Confidence Factors after Criteria Sensitivity Analysis

SR. NO.	LAKES	CONFIDENCE FACTORS
1	Lake 1	0.92
2	Lake 2	0.97
3	Lake 3	054
4	Lake 4	0.84
5	Lake 5	0.15
6	Lake 6	0.24
7	Lake 7	0.02
8	Lake 8	0.91
9	Lake 9	0.04
10	Lake 10	0.24
11	Lake 11	0.88
12	Lake 12	0.68
13	Lake 13	0.84

The results show that only lake 12 was the one that directly shifted from low risk to high risk when criteria weights were changed. The criteria ranks were assigned according to the criteria weights assigned to each criterion. Table 4.6 shows the ranks and weights for each criterion.

Table 4. 6 Ranks and Weights for each criterion.

SR No.	CRITERIA	RANK	Criteria Weights
1	Distance between the lake and the steepest slope	1	0.23
2	Precipitation Seasonality (BIO 15)	2	0.15
3	Earthquake	3	0.12
4	Snout steepness	4	0.11
5	Distance of the lake from the glacier	5	0.1
6	Volume	6	0.1
7	Temperature Seasonality (BIO 4a)	7	0.09
8	Slope	8	0.08

4.1.10.3 Lambda cutting & criteria threshold sensitivity analysis

The results shows that while in lambda cutting sensitivity analysis only initial hazardous lakes 1-4,10 & 11 were in high risk while all other lied in medium risk category. As we go on increasing the Lambda interval, we are giving importance to even slight changes in our results. So ultimately, all the lakes ended up being in high risk for future assessment.

When the threshold values were changed while keeping the lambda at 0.65 it was observed that the lake 5,8,12, & 13 that at first belonged to medium risk during previous analysis now have jumped towards higher risk classes as threshold limits have changed and now, they can be more prone to danger. Lambda cutting sensitivity analysis was performed over five different Intervals of lambda. As shown in Table 4.7

Table 4. 7 shows lake risks over different lambda value and after changing threshold values over a single lambda value. Here Red shows high risk, yellow shows medium risk and green shows low risk.

Lakes	0.5	0.6	0.7	0.8	0.9	Criteria threshold Sensitivity Analysis with lambda 0.65
Lake 1	0.89	0.96	0.99	1.00	1.00	0.86
Lake 2	0.72	0.86	0.95	0.99	1.00	0.73
Lake 3	0.86	0.94	0.98	1.00	1.00	0.87
Lake 4	0.72	0.85	0.99	0.99	1.00	0.82
Lake 5	0.58	0.53	0.72	0.89	0.98	0.67
Lake 6	0.49	0.46	0.67	0.88	0.99	0.54
Lake 7	0.54	0.48	0.67	0.86	0.98	0.53
Lake 8	0.64	0.81	0.92	0.98	1.00	0.78
Lake 9	0.47	0.63	0.82	0.95	1.00	0.63
Lake 10	0.61	0.68	0.84	0.95	1.00	0.67
Lake 11	0.64	0.74	0.88	0.97	1.00	0.81
Lake 12	0.53	0.65	0.82	0.94	1.00	0.7
Lake 13	0.59	0.53	0.63	0.93	0.97	0.74

4.2 DISCUSSION

As we all know, Chitral is facing high issues for the GLOF events every year in the summer and monsoon season. It mostly happens due to global warming when the temperature of the area increases. GLOF occurs when a glacial lake faces some triggering pattern, and it bursts out.

The increase in temperature each year is 0.0015 K/year while the decrease in precipitation is 0.0097 mm/year. The increase in temperature can ultimately lead to snow melting which can cause glacier retreat, snow avalanches or land sliding can occur. While a decrease in precipitation can lead to landslides, water scarcity in some cases affects glacier mass balance so instead of forming new ice or snow layers glaciers will depend on the temperature and melt more rapidly.

4.2.1 Study on MCDA

According to (Kougkoulos, Cook, Jomelli, et al., 2018b) different criteria were used to identify Hazardous lakes in Chitral valley along with lake selection criteria. With the help of this research, we were able to identify GLOF-prone lakes in Chitral with different risk zones.

Sensitivity analysis of results showed that these lakes can be of great risk in the future if the present values are changed according to specific criteria or methods. We saw that of 6 high risk lakes and one medium risk lake, after sensitivity all 13 lakes belonged to a high-risk category. This research will help for future assessments required on these lakes and to take safety measures before any incident takes place.

4.3 RESULTS COMPARED TO PREVIOUS STUDIES

4.3.1 Model validation for lakes

Based on our findings around 6 out of 13 lakes were found to be potentially hazardous. Some of our results in Table 4 were compared with previous studies. For Lake 2 the highest rank criteria were found to be lake volume after sensitivity analysis. The previous study (Bajracharya & Mool, 2009) found that lake volume was the most dangerous factor for Imja Glacier Lake, Nepal.

For lakes 4,5,8,9,10 and 12 results were found to be consistent with (W. Wang et al., 2022) for Cirenmaco lake central Himalaya in which the main trigger was found to be the avalanches, glacier collapse, and land sliding long with intense precipitation events which all combine for the greater risk in distance between the lake and the steepest slope.

For lake 11, & 6 BIO 15 was found to be the greatest threat as in previous studies (Muneeb et al., 2021) for the Hunza basin precipitation was found to be the greatest threat for GLOF.

(Rounce et al., 2016) accessed eight lakes in Nepal which are nearby of glaciers and steep slopes and potential triggers that were found were the intense precipitation events. According to our criteria distribution calving of the glacier, temperature, slope, steepest slope distance, landslide, rock fall and dam collapse all lies in this category.

4.3.2 Validation for datasets

For the temperature and precipitation data, different studies were used to validate the findings. Validation was important for the study as different reanalysis data was present with different resolution which if used might give different results. So, validation was the most important part in the selection of a specific dataset for a particular area depending on its geography and climatic conditions. The datasets chosen was found to be best suited to our surrounding environment and present climatic conditions especially for Hindukush mountains range.

In this study for precipitation data GPCC was preferred as in (Ahmed et al., 2019) GPCC was found to be better than all other datasets as it uses a greater number of observed stations than any other datasets to find gridded precipitation. For ERA-5 precipitation was found to be overestimating than other datasets (Hamm et al., 2020; Palazzi et al., 2013) that's why we used GPCC in this study rather than ERA-5 Land.

For temperature ERA-5 temperature data was preferred to be used to find out extreme temperature events and trends. The study (Zhao et al., 2023) showed that ERA-5 would be the suitable choice for mountainous areas where there are fewer stations present and it can capture observational daily data better than all other datasets.

In 2021 (Syed et al., 2022) worked on the Chitral with ERA-5 reanalysis data for temperature and precipitation. The data was bias-corrected and compared to previous studies done by gauging station data (Dahri et al., 2018). The resulting trend was the same for precipitation and temperature. The annual temperature showed an increasing trend while the precipitation showed a decreasing trend annually.

While (Khan et al., 2022) studied Chitral temperature and precipitation for the years 1990-2019. The results showed different trends during all three decades. For the decade 2000-2009 precipitation showed a decreasing trend in mm/year in summer and annually while temperature showed an increasing trend for both min and max temperature for the decade 2010-2019.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study aimed to find hazard-prone lakes in Chitral with the help of MCDA. MCDA has been beneficial over other methods due to its accuracy and ease to use. It has many advantages i.e., it required freely available data without the requirement of field observation, the MCDA technique can be applied to any part of the world without any issue, this technique can be applied to lakes that have never been into a GLOF event before to predict future hazard lakes, sensitivity was done to predict the behaviour of present lakes in future. MCDA involves the technique to identify criteria that are exhaustive, non-redundant, robust, and consistent. As we know in previous studies most of the criteria used were repetitive and non-exhaustive so the method of (Kougkoulos, Cook, Jomelli, et al., 2018b) was used.

In this study, 13 lakes were identified which fulfilled the lake selection criteria and further study was conducted on them. None of the lakes went through GLOF in history so the results were compared to the previous studies done in Nepal, Hunza, China, and the Indian HKH region. As the climatic and the terrain geographical features of the HKH region are mostly alike. Our study showed that MCDA can be applied to areas where no events have occurred previously, but they are in red zones for the future. Our study described 6 out of 13 lakes that were found to be critically at high risk while one lake was found to be in medium risk. Criteria weights define how much criteria weight is assigned to a specific criterion showing its importance. That is how much of criteria contribute to making a lake a high, medium, or low-risk lake.

Sensitivity analysis were undertaken to know the impacts of changing parameters on the area and its lakes. Three sensitivity analyses were performed one was the weighted criteria to find outranking and weights of criteria individually where distance between lake and steepest slope was found to be the greatest reason for suspected GLOF events while the other one was ג cutting sensitivity analysis in which values of lambda were changed from 0.5-1. These values showed that with increasing the lambda value the smaller changes were kept in mind to identify the lake risks. In the end criteria threshold sensitivity analysis was performed in which lambda cutting value was kept constant i.e., at 0.65 and the threshold values changed the results showed that almost all the lakes shifted to high risk only lake 6 and 7,9 lied in the medium risk zone.

This opened the path for lakes 5,6,7,9, & 12 that readily changed their class from low to high risk. These lakes could be dangerous in the future and might need further study.

5.2 RECOMMENDATIONS

The following recommendations are made from this study.

- All the lakes that lie in the high-risk category should be further studied with the help of field investigations and should be regularly monitored to avoid any future hazard.
- Lakes that were in low risk should be properly investigated to know their exact risk.
- Future studies can be done on these lakes along with field observations.
- Collaboration should be done between researchers and government organizations.
- Any other criteria can be further used to study Glacial Lakes based on the topography of the Area.
- The same technique can be used in any part of the world having lack of field investigations to save them from future GLOF events.

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