University of Central Asia - School of Arts and Sciences

Department of Earth and Environmental Sciences

DIPLOMA THESIS

"Quantifying Contemporary and Future Risks of the Naturally Dammed Lake Rivakkul Using Geoinformatics Technique and Morphometric Indices"

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Abstract

Pamir mountains are considered as the natural laboratory that offers a wide range of opportunities for the researchers and scientists to understand the dynamics of earth processes. The unprecedented global climate changes have threatened these high mountainous communities as it intensifies the melting of glaciers and the glacier-related hazards. Glacial lake outburst flood (GLOF) is one of the most catastrophic glacial hazards in the high mountain regions of Pamir. These sudden catastrophic events release high volume of water and debris at high velocity that poses extreme threat to lives, properties, and infrastructure downstream. Lake Rivakkul is one of the high-altitude glacial lakes in the Pamir mountains that has been listed under the high hazard category by Mergili & Schneider (2011). This study aims to understand the impact of morphometric, climatic, and topographic characteristics of the surrounding catchment on the outburst flood of the lake. It also tries to quantify the contemporary and future risks from the lake outburst flood using the geoinformatics techniques. Remote sensing and GIS technology has made this investigation more efficient as it provides great potential for mapping and monitoring of the remote glacial lakes in the alpine regions. The findings of this research indicate the high flood susceptibility of the catchment. This study can be used as a preliminary hazard assessment approach by local communities and the outburst flood risk management to develop improved awareness and mitigation strategies against devastating hazards, such as GLOFs.

Keywords: GLOF, morphometric, quantify, unprecedented, geoinformatics

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List of abbreviations

AHP	Analytical Hierarchy Process
ALOS	Advanced Land Observing Satellite
ARIMA	Autoregressive Integrated Moving Average
DEM	Digital Elevation Model
DN	Digital Number
ETM+	Enhanced Thematic Mapper Plus
GLOF	Glacial Lake outburst floods
GIS	Geographic Information System
GPS	Global positioning system
HKH	Hindu Kush Himalayan
HMA	High-Mountain Asia
LULC	Land use/land cover
Masl	Meters above sea level
MNDWI	Modified Normalized Difference Water Index
OLI	Operational Land Image
PALSAR	Phased Array type L-band Synthetic Aperture Radar
RS	Remote Sensing
TM	Thematic Mapper
ToA	Top-of-Atmosphere
TWI	Topographic Wetness Index

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Statement of Authorship

I hereby declare that the submitted thesis entitled *"Quantifying Contemporary and Future Risks of the Naturally Dammed Lake Rivakkul Using Geoinformatics Technique and Morphometric Indices"* is my own work written in line with the University's research ethics guidelines and that no other sources than those listed in the references have been used.

Khizer Zakir

Signature:

Date: May 20, 2022

1. Introduction

1.1. Background information

Over the last few decades, Glacial Lake Outburst Floods (GLOFs) have been spawned by the climate change in the sensitive mountainous regions around the world. The High-Mountain Asia (HMA) is one of the most vulnerable and affected regions by the climate change. According to NASA, HMA has the second largest glaciers and snow reserves outside of the Earth's polar ice sheets. These large reservoirs of glaciers and snow have been under a constant threat due to the increase in temperature and the anomalous changes in the global climate. The International Centre for Integrated Mountain Development (ICIMOD) published an extended inventory of glaciers and glacial lakes in 2005 that reports the trend of rising temperature in the HKH region. One of the most significant effects of global warming and climate change in the HMA is the glacial melting, which result in formation of new glacial lakes, and the expansion of the existing glacial lakes. GLOFs are one of the most dynamic and catastrophic natural hazards. GLOF is a form of flash flood associated with a glacier is released suddenly, resulting in the outflow of a huge volume of water and sediment downstream" (Khanal et al., 2015, p. 5) – also see Figure 1. A global assessment of GLOF impacts concludes that "Central Asia is the most vulnerable region to glacier floods causing extreme levels of societal impact" (Carrivick and Tweed, 2016). Out of all the HMA regions, Central Asia, especially the Pamir mountains have been the least discussed mountain ranges when it comes to the assessment of risks associated with the GLOFs. Similar to the high ranges of Himalayas and Karakoram, Pamir mountains have also been listed as the most vulnerable areas to the GLOFs as the glaciers keep receding at a higher rate. Mergili & Schneider (2011) reports that the volume of the glaciers in the Central Asia is decreasing at an alarming rate of around 0.2 – 1% per year (p. 6), which results in the naturally dammed glacial lakes. Due to glacier melting and lake formation, there is an increased danger of GLOFs, which confound and exacerbate water-related threats to mountain communities in, their settlements, livelihood, and infrastructure located on the river floodplain areas in Pamirs.

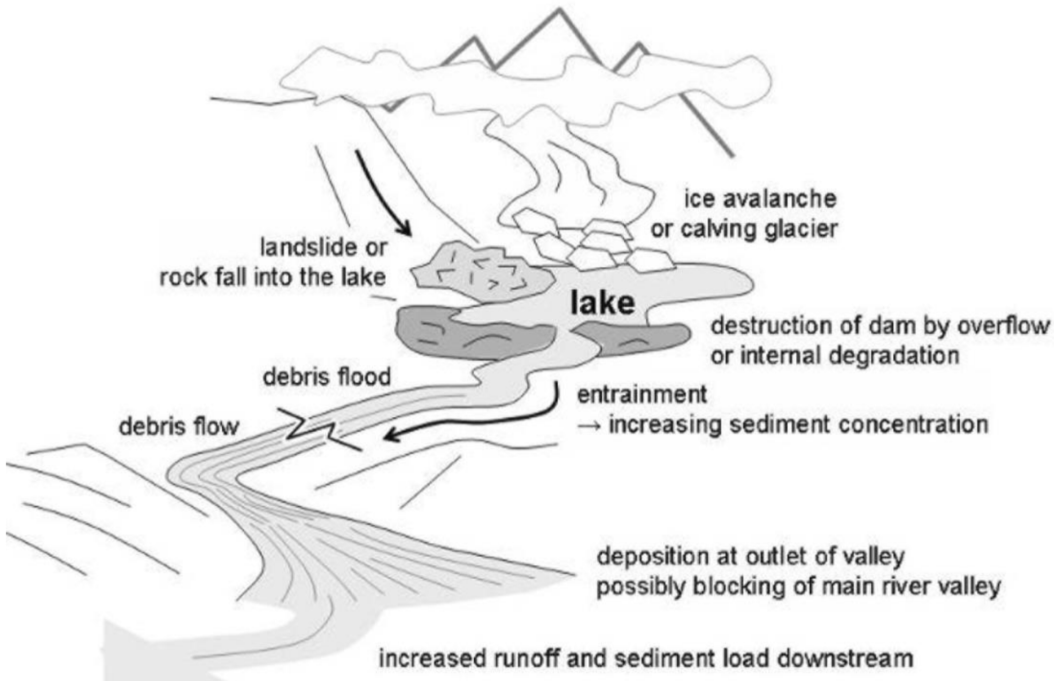

Figure 1. Schematic representation of a Glacial Lake Outburst Flood (GLOF)

Image courtesy: (Mergili et al., 2011)

1.2. GLOFs in Tajik Pamir region

At least 270,000 people, upstream and downstream, are dependent on the survival of the high mountainous glaciers of Pamir. The meltwater from these high glaciers plays a key role in modulating stream flow throughout the year, and they serve as the primary source of freshwater for irrigation, electricity production, and for household consumption downstream. The increasing risk of the GLOFs in the incised valleys of Pamirs poses the most significant threat to the communities along the river and especially in the valleys downstream. However, the sensitive mountain community of Pamir has one of the lowest adaptive capacities against natural hazards in the region. The most significant GLOFs resulting in fatalities and severe damage have occurred during the previous decades, particularly in the Himalayas, the mountains of Central Asia, the North American mountains, New Zealand, and the Alps (Richardson & Reynolds, 2000). A 2009 study by the World Bank found that Tajikistan and Uzbekistan had the highest degree of sensitivity to climate change in Europe and Central Asia and the lowest degree of adaptive capacity. In 2002, a GLOF in Dasht, Tajikistan caused huge damage to the settlements downstream and killed dozens of local inhabitants. Similarly, in the case of the Zyndan GLOF, the lake formed over a period of only two and a half months and lead to huge damage upon its failure. “The GLOF from this small lake killed three dozen people and numerous livestock, destroyed infrastructure, and devastated potato and barley crops as well as pastures” (Narama et al., 2010, p. 3). More recently, high temperatures and rapid melting in July 2015 triggered debris flows in the mountainous regions of Tajikistan. Across the region, experts estimate that nearly 200,000 people in mountainous areas of Pamir face GLOF threats directly, with many others at risk downstream (Diebold, 2014). Such GLOFs are single-source hazards that suddenly release meltwater at peak discharges often several times higher than those of hydro-meteorological floods, and entrain, transport and deposit exceptional amounts of sediments downstream. Bajracharya & Mool, (2009) has predicted that at least one GLOF event will occur every 3-10 years in this region given the recent anomalous changes in the climate and temperature.

The mountains of Pamirs are located in one of the most seismically active zones in the world (Emmer & Cochachin, 2013). This active seismic zone experiences numerous shallow and deep earthquakes that lead to multitude of natural hazards in the region as an aftershock, like landslides, debris flow, and the rockslides. In addition, many scientists are convinced that the Pamir glaciers are retreating at an alarming rate due to the global climatic variations (Diebold, 2014). Frequent avalanches, melting of the permafrost, and the increased discharge rate the major tributaries in various watersheds across Pamir justify the change in the climate of the region. The high discharge rate and the increased number of landslides lead to the formation of glacial lakes upstream in the mountainous valleys. As temperature rises, new lakes form, while the expansion rate increases for the existing ones and they even merge sometimes, which increases the potential flood volumes in the high mountains of Pamirs. The increasing formation and expansion of glacial lakes in the region demands an extensive assessment of glacier-related hazards in the Tajik Pamir. According to Veh et al. (2018), there are around 335 lakes with GLOF potential only in the south-west of the Pamir region. Although GLOFs are not a recent phenomenon in the Pamir Mountains, they remain a persistent threat to downstream communities and infrastructure. Hence, GLOFs must be an essential part of any planning in the lower reaches. In the upcoming years, the frequency of GLOFs and risk from potential GLOFs are expected to increase as the climate continues to change. Therefore, the risk assessment for the GLOFs is significant for the safety and security of the mountainous communities of this region. However, the remoteness of the high mountain terrain and the limited accessibility of data makes it difficult to make precise and accurate assessments.

1.3. Existing issues & modelling techniques

Over the years, geoscientists and environmentalists have worked on various schemes, hazard assessment techniques, and numerous models to develop effective frameworks and approaches to assess the potential risks associated with GLOFs more accurately and effectively. Field works, data collection, and running models are accepted as the conventional methods to assess the contemporary risks, while reducing the future risks. Nowadays, remotely sensed data has made it easier and more convenient for the scientific community to do the risk assessment using the satellite imagery. “After 2000, scientists started to research the glacial lakes using the method of global positioning system (GPS) and remote sensing (RS)” (Xie et al., 2013, p. 229). The latest GIS technologies serve as a promising tool to understand the dynamics of glacier-related hazards and the associated risks. Despite the topographic complexity and general inaccessibility of these high mountain ranges, GIS and RS have given an opportunity to the community of natural scientists to study and understand the dynamics of GLOFs in this region. The satellite remote sensing provides an efficient and objective tool to map glacial lakes, their changes, and understand the dynamics of it. The RS data makes the study of glacial lakes in remote regions more feasible and cost-effective (Li & Sheng, 2012). Around the world, scientists have constructed and applied various kinds of models and frameworks based on the data availability either from field works or the remotely sensed data. to understand the changes in the glacial lakes and assess the risks upon its failure. NWS-BREACH, HEC-RAS, and RAMMS are the most common models that are used to access the impact of GLOF on downstream areas. Some of these models are complex and require huge amount of input data. On the other side, they have not been highly recommended for the mountainous terrain due to the topographic complexity. Moreover, Huge inventories of regional GLOFs have been reconstructed using the data and estimation of previous GLOFs using different models and projections have been derived for the potential GLOFs.

1.4. Approach of this paper

GLOFs are extremely complex phenomena, over the years, the scientific community have strived hard to understand the dynamics of the GLOFs; however, they could only develop and adapt a handful of frameworks and approaches that can help identify and detect the glacial lakes as well as the estimation of the risks associated with its outburst. GLOFs are one of the many earth processes that occurs very frequently in the Pamir mountains due to various reasons, such as increase in average temperature and precipitation, high elevation, steep slopes, morphotectonic, geologic and dynamic hydrological characteristics. These factors are involved in the formation and expansion of glacial lakes. As mentioned earlier, there is a huge abundance of glacial lakes in the Tajik Pamir region, which need serious attention with the unprecedented changes in the global climate. Lake Rivakkul is one of the hundreds of glacial lakes that has a potential for a huge outburst. This lake is located in the Rivakdara catchment, in the Gunt valley with an elevation of around 3800 masl. It is similar to the Sarez lake, the highest natural dam in the world (Alford et al., 2000). This research has been dedicated to the study of this naturally dammed glacier lake. There are only a couple of literature and scientific papers are available for the "Lake Rivakkul" that applies morphological and hydrological models to predict the possible outburst and the potential risks it may pose on the downstream communities. However, in this paper, a great emphasis has been given to the physical climatic parameters, like temperature and precipitation. In addition, morphometric and geomorphological parameters have been studied along with the essential indices, such as the Topographic Wetness Index (TWI) and the Normalized Difference Water Index (NDWI) to estimate the area and volume of the lake and the runoff in the studied catchment. Due to several limitations, starting from the accessibility of the data to the unavailability of them to set up sophisticated hydrological and flood simulation models; a fairly simple integrated geoinformatics technique has been adapted to study the changes in the lake due to aforementioned physical, morphometric, and geomorphological factors. With the help of GIS and RS technology, NDWI, TWI, Land Use and Land Cover (LULC), temperature, precipitation, and other morphometric and geomorphic indices were analyzed and mapped for the study area. Later, these observations were integrated into the statistical models to correlate the respective variables with the physical changes in the lake and predict the future changes and risks. The time series and forecast for the climatic variables was conducted by ARIMA (Autoregressive Integrated Moving Average) using R programming utility. The novelty and the main purpose of this study is to quantify the contemporary and future risks of the GLOF for the studied lake caused by the climatic stressors. This will eventually contribute to the sustainability of the mountainous communities and to develop effective mitigation measures to protect human lives, settlements, and infrastructure from destructive forces of the GLOF surge.

2. Literature review

2.1. Background

Climate change has induced serious threats in the high-mountain areas of Central Asia. The regional temperature has taken an increasing trend that results in an unprecedented rate of glacier retreat in the region. The Tajik Pamir mountains experience a greater influence as the glacial lakes are emerging and increasing following the glacier retreat. Many glaciologists believe that the Central Asian glaciers are melting at an alarming rate, while some have a firm belief that glacier mass balance has been steady for the region (Knoche et al., 2017). According to Knoche et al. (2017), the glacier areas in the Gunt River Basin has shrank by 14 percent between 1998 and 2011, almost at a double rate from 1969 to 2002. Moreover, parts of Shugnan in the Gunt River Basin have been reported of rapid retreat in comparison to the other parts. The authors have also predicted that the glaciers in the catchment are expected to disappear before 2100. Besides glacier retreat, permafrost melt, and other factors, such as frequent earthquakes, and climatic stressors are reducing the stability of mountain slopes. This instability can lead to frequent landslide hazard that might potentially strike lakes, triggering far-reaching and deadly outburst floods. Indeed, in most of the cases the landslide itself has caused only minor damage to the inhabitants and the infrastructure, but the "formation of the lake upstream and the flooding downstream following the dam breaches have provoked momentaneous or permanent destructions that are reported in several archive documents or are known through expert reports" (Bonnard, 2011). Considering all the possible causes, mechanisms, and the outcomes, it is essential to understand the dynamic of GLOFs in the high mountains of Pamirs. Naturally occurring landslide dams are very common and fairly frequent phenomena in the high mountain areas; however, they often go unnoticed or not recorded because of their frequently temporary character. This temporary characteristic make the GLOFs more dangerous, as it can vanish the whole community and the infrastructure up to 100 kilometers downstream in the matter of a few minutes to a couple of hours.

2.2. Glacial Lake and Glacial Lake Outburst Floods

Glacial lakes or the naturally dammed lakes are defined as the vast natural reservoirs that typically forms at the foot of a glacier. They are generated by glacial processes, when ice melts at the frontal zone, leaving an empty region that is filled with melt water and finally becomes a lake owing to progressive buildup of water. Also, the naturally dammed lakes can form as a consequence of another mass movement events, for instance, a landslide, a mudslide, and a rockfall. The large slide masses can block the affluent of the river fed by the surrounding glaciers, impounding a lake which has huge potential to be overflow, into the original gorge. Glacial lakes can be found in practically every glaciated region on the planet. The majority of glacial lakes in the Tajik Pamir region are the consequence of glacier ice and snow melting, as well as the deposition of unstable lateral moraines due to slope movement processes, which will result in more glacial lakes in the future (Amin et al., 2020). GLOF, on the other hand, can be described as the catastrophic event with massive outpouring of debris mix water from a glacial lake that flows downstream (ICIMOD, 2011). According to Khanal et al. (2015), “Glacial Lake Outburst Flood is a form of flash flood associated with a glacier is released suddenly, resulting in the outflow of a huge volume of water and sediment downstream” (p.3). While Emmer & Cochachin (2013) define GLOF as a the sudden water release from any form of glacial lake and a form of flood with higher peak discharge rate than a typical hydrometeorological flood, which makes GLOF more deadly and more catastrophic. In recent times, GLOFs have become a frequent phenomenon in the high mountainous region due to the unusual climatic changes. It is no surprise that the high mountain ranges of Pamir face the risk of GLOF everyday as it homes many glacial lakes in the lap of high Pamir glaciers.

2.3. Causes and Mechanisms of GLOF

There are numerous causes behind the GLOFs depending on the nature of the lake, and the tectonic, geological, and hydrological setting of the glacial lake. Climatic variations, like increase in temperature, precipitation have been the most common causes of the outburst as it affect the mass balance of glaciers (Bajracharya & Mool, 2009; Khanal et al., 2015; Prakash & Nagarajan, 2018; Richardson & Reynolds, 2000; Shakya, 2020; Song et al., 2022), and “induces enhanced snow and glacier melt runoff leading to expansion of glacial lakes due to increased water supplies to the lake” (Prakash & Nagarajan, 2018, p. 343). Other various factors such as high elevation, steep slopes, morphotectonic, and hydrological characteristics are involved in the formation and expansion of the lakes. Morphotectonic activities lead to strong earthquakes, which subsequently result in various mass movements into the lake, progressive lake enlargement, rising lake levels leading to overflow, dam mechanical rupture/failure, hydrostatic failure, and dam degradation. Slope movements can lead to dam failure or sudden surge in the discharge rate from the glacial lake (Emmer & Cochachin, 2013; Narama et al., 2010; Prakash & Nagarajan, 2018; Richardson & Reynolds, 2000; Sharafi et al., 2019; Song et al., 2022). The mountain regions of Central Asia remain sensitive to temperature and precipitation variations, as the risk of GLOFs is heightened by the unprecedented climate change, and their frequency appears to be increasing (Bajracharya & Mool, 2009). The dynamic mechanisms of the GLOFs also vary with respective to topographic, geologic, hydrologic, tectonic setting. Many of them form by the direct melting of glaciers either at the foot or in the incised valley between the glaciers. However, due to the active seismicity of the region, some of the naturally dammed lake form due to the slope movements into the main river channel, which blocks the flow of the main river and accumulates large volume of water, these dynamic mechanisms were named as "quasicoincidental" by Walder & O'Connor (1997). "The occurrence of landslides in the direction of rivers are processes that block rivers and form dam lakes" (Sharafi et al., 2019, p. 2393). The dam composition from the weak and unconsolidated morainic material makes this type of lake relatively more threatening and unstable, a relatively moderate trigger might cause the dam to fall, resulting in a GLOF.

2.4. Consequences and Examples of GLOF

These naturally dammed lakes in the mountain regions are extremely threatening the communities downstream. Emmer & Cochachin, 2013; Narama et al., 2010; Prakash & Nagarajan, 2018; Richardson & Reynolds, 2000; Sharafi et al., 2019; Song et al., 2022, provide an overview of the destructive potentials and consequences of GLOFs. A large amount of water is released within a short time, with a high capacity to erode loose debris, potentially leading to a powerful flow with a long travel distance can be life threatening for the communities downstream. Such catastrophic flooding frequently causes significant loss of life and property damage in the downstream areas, the frequent and intensive occurrences of GLOF might result in significant financial losses (Khanal et al., 2015). The disastrous phenomena of GLOFs are generally associated with high human mortality, and greater risks to the settlements in mountain regions. Since these lakes are located in remote high-altitude areas, people downstream rarely visit the lake site and sometimes cannot even perceive the danger of the potential outburst. (Li & Sheng, 2012). The communities in the high mountain ranges of Pamir are one of the most vulnerable communities from the GLOF. Pamir, particularly, the Gunt Catchment is extremely prone to GLOF as it has the highest rate of glacial retreat and relatively high abundancy of the glacial lakes (Knoche et al., 2017). There are so many examples of the GLOF events in the glaciological history of the Tajik Pamir region. Some of them have already failed, while the others are on the verge of potential outburst given the recent climate variability. As an example, it was reported that the flood wave arrived in Dasht in three stages, a phenomenon that can be explained by temporary backwater in the canyon of the lower transitional zone due to blockage of large boulders transported by the GLOF or by lateral slope failures followed by vigorous breakthroughs. The event destroyed a large portion of the village of Dasht, killed a few dozens of people, and dammed a small lake at the Shakhdara river. The event hit the village completely unexpected, as there was no awareness of the hazard and preparedness for the event.

2.5. Review of the existing methods

With the ever-increasing risk of GLOF in the global mountainous communities, there is dire need to construct sustainable risk assessment models and methods to develop long-lasting mitigation measures. Most literatures discuss at least one model that relates to either sediment flow or the meteorological flood to simulate GLOFs. Most of the time geoscientists look for cost-effective and parsimonious options due to data paucity, like use of simulation models available with the ArcGIS suite to mitigate the risks. There are different approaches that use the assessment or remodeling of previous GLOFs to assess the risk and vulnerability using topographic maps and some geomorphological and morphometric indices. These models consider all the elements that are at risk according to their respective monetary values (Khanal, 2015). Alford (2007) discussed the tools and techniques required for developing a risk management strategy in mountain areas in general and highlighted the importance of preparing a socio-economic vulnerability assessment together with the hazard and physical risk assessment. But the procedures and methods for assessing vulnerability and estimating risk from potential GLOF events in downstream areas are scanty. Many other natural scientists have thought that long-term mapping and monitoring of these glacial lakes will improve our understanding of regional climate changes and glacier-related hazards. However, rigorous field-based survey of these glacial lakes in remote mountainous areas is restricted because of their limited accessibility (Junli Li, 2012). Therefore, for the time being, the emphasis is on the importance of remotely sensed data, as the Satellite products provide provide an efficient and objective tool to map glacial lakes and their changes. The RS data makes the study of glacial lake in remote regions more feasible and cost-effective. (Junli Li, 2012). After all these years and scientific progress, we still lack an understanding about impact of climate change and glacier recession on glacier lake dynamics in mountain regions. (Prakash, 2018). The scanty of data and remoteness of the region makes it extremely challenging for the scientific community to make any progress in the mapping and monitoring of glacial lakes and assessment of the risks associated with it.

3. Problem Statement and Significance of the Study

Lake outburst floods from the natural dams can be extremely devastating and much larger in extent with a shorter peak time compared to the usual meteorological floods. This sudden high magnitude water discharge poses extreme threat to lives, properties, and infrastructure, as it can carry high volume of sediments at high velocity. It is hard to predict such events and then mitigate them due to the remoteness of the study sites and the inaccessibility and unavailability of the reliable data. Lake Rivakkul is one of the naturally dammed lakes in the high mountains of the Pamir that poses a serious threat to the communities downstream. According to Mergili & Schneider (2011), lake Rivakkul has been identified in the high hazard category with moderate flood susceptibility.

This study holds huge significance in terms of identifying and quantifying the risks associated with lake outburst flood. Because any sudden breach or overflow from the lake can damage the Rivak village ($22\ km$ downstream) within a shorter time. And, the flood can increase discharge of the Gunt river that flows through villages, like Barsem, Manem, Bogev, and towards the capital of GBAO, Khorog, which is about $60\ km$ downstream at the confluence of Panj and Gunt river (Shakya, 2020). This outburst can be very devastating that it can potentially wash away village after village destroying everything come along their path. All the human lives, hydropower plants, infrastructure, and the Pamir highway will be under serious threat, as will take few hours for the destruction but it can take years for the community to recover from the losses. This study can be used as a preliminary hazard assessment approach by local communities and the outburst flood risk management to develop improved awareness and mitigation strategies against devastating hazards, like glacial lake outburst floods and avoid huge losses.

4. Research questions

This research is trying to answer the two following questions:

1- What are the various triggering factors that can change water balance of the Rivak Lake over time and increase the threat of lake outburst floods?

2- How and in what capacity does the morphometric, climatic, and topographic parameters affect the expansion of the lake?

5. Methodology

5.1. Study Area

The main study site for this research is the Lake Rivakkul that lies in the Rivakdara catchment in the Shugnan district of GBAO region, Tajikistan at the coordinates $37°36'57.8"N$ and $72°04'25.5"E$ with at an estimated terrain elevation of 3820 masl. In addition, the Rivakdara catchement itself in whole is the focus of this research, which lies at the coordinates $37°36'54.7"N$ and $71°51'53.9"E$ with an average terrain elevation of 4300 masl (also see Figure 2 and Figure 3). The google earth images for the study sites are presented in Figure 19 and Figure 20 in Appendix A. Lake Rivakkul is in NE of the Rivakdara catchment with an average lake area of 1.2 km^2. Since there is no bathymetric information available for the lake, empirical equations by Huggel et al. (2002) has been utilized to estimate the depth and the volume of the lake, which measures 35 m and 0.045 km^3 respectively. The study site is located at a ground distance of roughly 22 km away from the nearest village of Rivak and about 60 km away from Khorog, the capital of the Shugnan district. This study region can be classified as a cold climate region with hot and dry summers (Shakya, 2020).

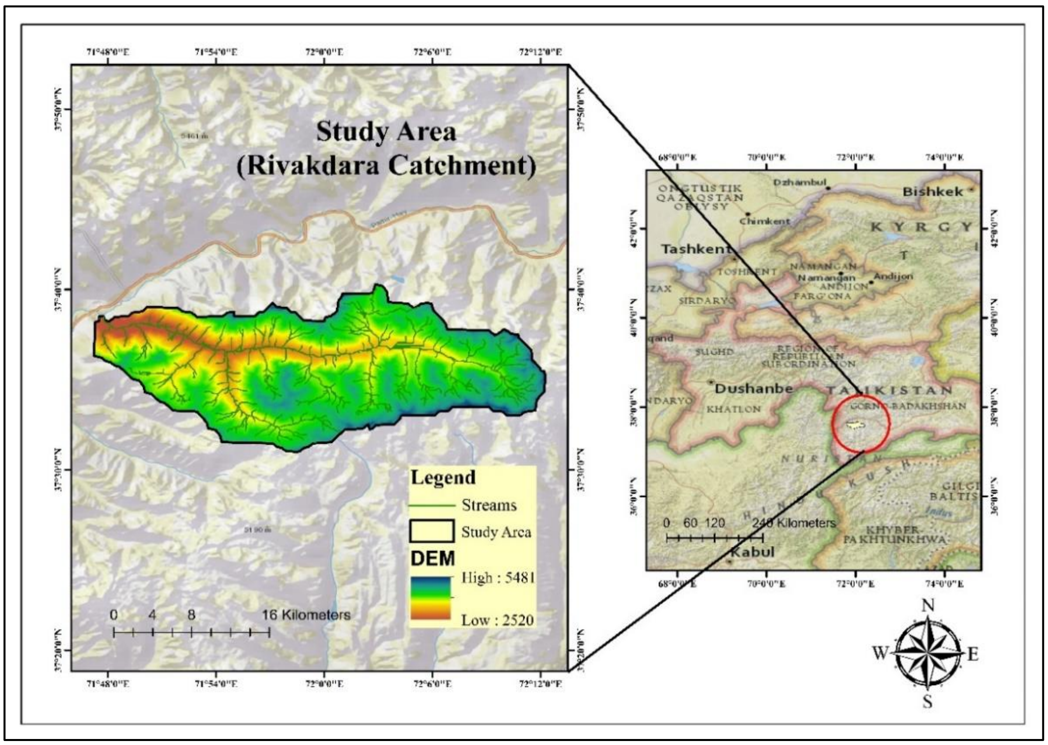

Figure 2. Study area map - I. Rivakdara Catchment

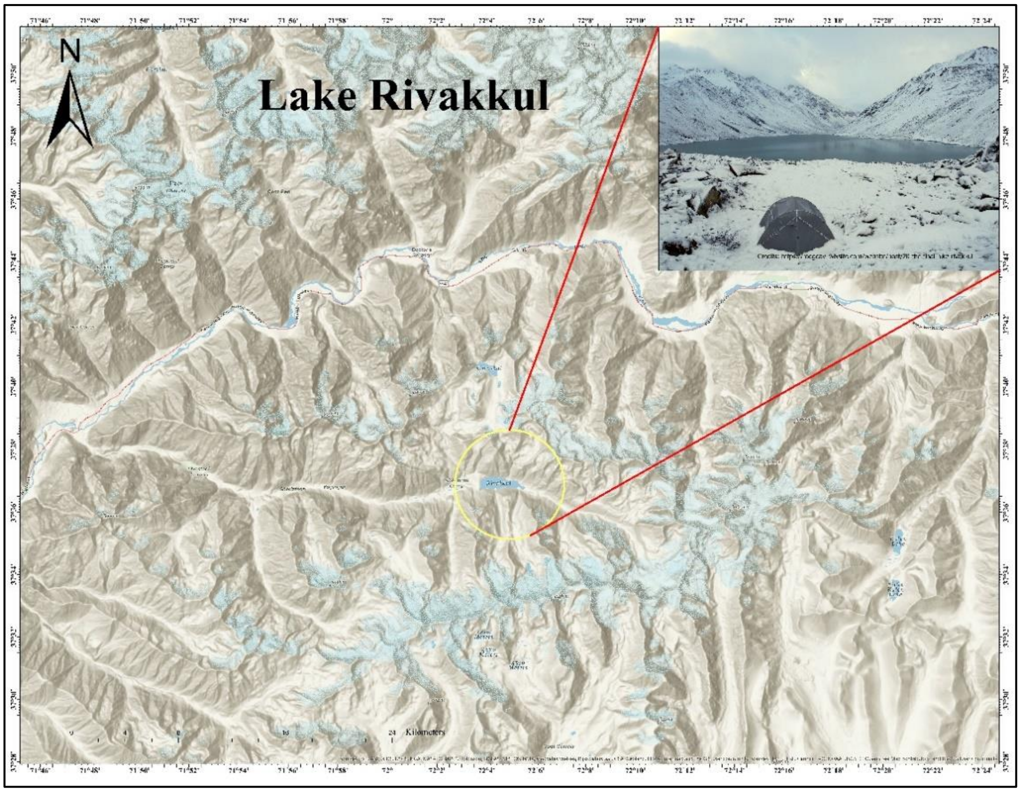

Figure 3. Study area map - II. The main study site, ‘Lake Rivakkul’

5.2. Data

All the data for this research was collected through the remotely sensed data specially satellite images. Different datasets have been used for distinct purposes in this study. For instance, the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (DEM) with the spatial resolution of 12.5 m has been used to extract the morphometric indices for the catchment, including Topographic Wetness Index (TWI). While Landsat imagery has been used to estimate the surface and evolution of the lake area from 2000-2021 through the extracted NDWI. The entire Landsat archive was scanned on the USGS EarthExplorer web portal to acquire the data having less than 20 % of cloud cover for the month of June to October (2000-2021), this is time when the snow cover is the least. The Landsat scenes were also used to validate the Land Use and Land Cover (LULC) maps that has been collected from the Copernicus worldwide land cover maps based on Sentinel 1 and 2 datasets with the spatial resolution of 30 m and 10 m respectively. Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS) and Climate Hazards Center InfraRed Temperature with Station data

(CHIRTS) products were used to extract monthly mean precipitation and mean temperature respectively. Google Earth Images and Google Earth Pro was utilized to produce the longitudinal river profile. The whole processing chain for this study was built on the following open-source data sets that are listed in Table 1.

Table 1. Complete list of the data used for this research with its respective details.

Sensors/sources	Product	Date	Resolution
Landsat 4-5	Band 2 and Band 4	2000 - 2011	30 m
Landsat 7	Band 2 and Band 4	2012 – 2015	30 m
Landsat 8-9	Band 3 and Band 5	2015 - 2021	30 m
Sentinel 1 & 2	Land use and land cover maps	2015 - 2021	30 m and 10 m
CHIRPS	Global monthly mean precipitation	2000 - 2021	1 km
CHIRTS	Global monthly mean temperature	2000 - 2021	1 km
ALOS PALSAR	Digital Elevation Model (DEM)	2020	12.5 m
Google Earth Images	Google images	2021	It varies

All the data was processed using the remote sensing techniques and the ArcGIS utilities. Later, the R and Python programming utility was employed to compute the time series for temperature, precipitation, and the changes in the area of the lake and forecast the changes in all three physical variables. The data from all the sources were acquired free of cost. The extraction of morphometric indices using DEM, the identification and temporal delineation of the glacial lake using the Landsat imagery, and mapping of land cover changes were done on the ArcMap 10.7 software. The data was then clipped to the area of interest and used in flood modeling to develop GLOF simulation to anticipate downstream risks.

5.3. Analytical Methods

The following information provides the detail of all the indices explored in this study and it explains their respective significance while studying GLOFs.

Terrain Mapping

Terrain mapping is the most important step in the topographic analysis of a watershed/catchment. This allows us to understand the surface and other topographic characteristics of the watershed. Slope, aspect, hillshade, and elevation are the primary components of the terrain mapping (also see Figure 21 in Appendix A). Besides interpreting the topography, the slope can be used to find other essential morphometric indices. To find the terrain features of the studies area, a DEM with 12.5 m spatial resolution was processed using the surface toolset in the ArcMap 10.7 software.

Extraction of Morphometric Indices

Morphometric indices are important indicators to understand hydrological and geomorphological characteristic of a catchment. These indices provide a quantitative analysis of the drainage basin under different topographic and geomorphic settings (Mahala, 2020). In the current study, the morphometric indices will help identify the controls of the geomorphic and topographic characteristics on the Rivakdara drainage basin. The study employs the efficient GIS and RS tools to perform drainage morphometric analysis. It will eventually explain the discharge density of the river flowing from the Rivakkul lake to the downstream valleys. Several morphometric parameters were calculated to quantify linear, areal and relief aspects of study area (Figure 4).

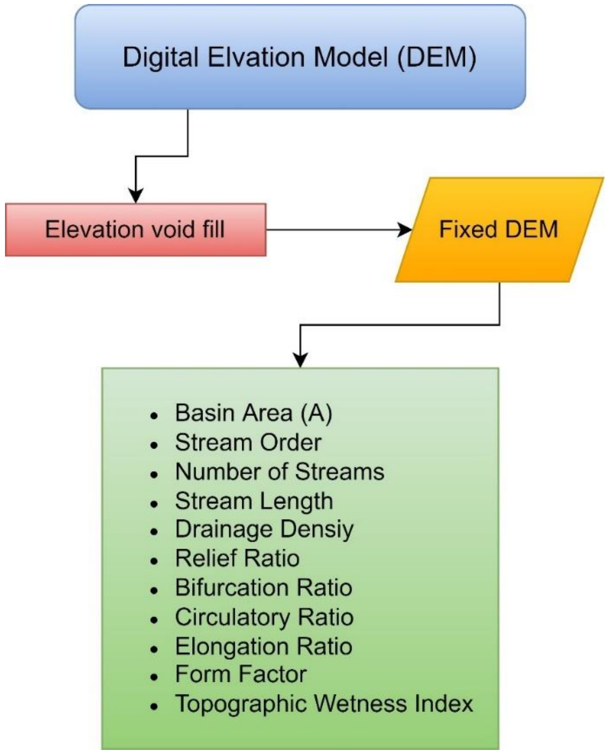

Figure 4. Flow-chart representation to extract the morphometric indices

Linear Aspects

The linear aspect of the drainage morphometric analysis includes, stream order, stream length, mean stream length, stream length ratio, and bifurcation ratio of the study area, which reveals the behavior of the river and its tributaries. The concept of the stream order was coined by Newell Strahler in 1952 as a way to define the size of perennial and recurring streams in the watershed. It reflects the size and steepness of the tributary, the higher the order the greater is the steepness and size of the tributary. Using the Strahler's formula, segments with no tributaries identified as a first-order stream. When two 1st-order stream joins form a 2nd-order stream and so on (Mahala, 2020). The stream length is represented by its total length of streams of a specific order. While the bifurcation ratio (R_b) is defined as the number of streams of a particular order to the number of streams of a next lowest order. It describes the geological formation of the watershed and the variation R_b can critically influence the maximum flood discharge of the watershed. All the linear aspects have been measured using the hydrology toolset in the ArcMap 10.7 software. ALOS PALSAR DEM of 12.5 m spatial resolution was used to delineate the watershed first and then estimate all the parameters of the linear aspect of the watershed according to their respective formulae given in the table.

Areal and Relief Aspects

Areal aspect of a watershed defines the relationship between the stream length, drainage density, and the shape and the area of the basin/watershed. On the other hand, relief aspects describe the structural elevation difference of the catchment. Areal aspects include, the basin shape, drainage density, stream frequency, circulatory ratio, elongation ratio, and the form factor. Basin shape is the simply the shape of the boundary line of the watershed. It is important in determining the stream-discharge relationship. Drainage density can be defined as the "ratio of total length of all stream segments and an important factor for indication of landscape dissection and peak runoff potential of basin"(Veeranna et al., 2017). Relief aspect includes the relief ratio, which can be defined as the ratio between the total relief and the longest basin length. These parameters are critical in identifying the runoff density, structural changes in the catchment, and the stream-discharge relationship. It will determine the course of the outflow from the lake into the river basin and the intensity of the outflow. These parameters were also estimated using the Hydrology toolset in the ArcMap 10.7 with the help of the 12.5 m spatial resolution digital elevation model. Most of the values were determined by their respective formulae (Table 2).

Table 2. Morphometric parameters of the catchment

Morphometric Indices	Formula	References
Basin perimeter(P)	Using the “calculate geometry” tool in ArcGIS	ArcMap 10.7
Length of basin(L)	Using the “calculate geometry” tool in ArcGIS	ArcMap 10.7
Basin area(A)	Using the “calculate geometry” tool in ArcGIS	ArcMap10.7
Stream order (u)	Hierarchal rank	Strahler (1964)
Stream number(N_u)	N_u = number of streams of a particular order u	Strahler (1964)
Bifurcation ratio (R_b)	$R_b = \left(\frac{N_u}{N_{u+1}}\right)$	Schumm (1956)
Mean bifurcation ratio (R_{bm})	Mean of all R_b	Schumm (1956)
Stream length(L_s)	L_s =total length of streams of a particular order u	Horton (1945)
Mean stream length(L_{um})	$L_{um} = \left(\frac{L_u}{N_u}\right)$	Horton (1945)
Drainage density(D_d)	$D_d = \left(\frac{L_{um}}{A}\right)$	Horton (1945)
Circulatory ratio(R_c)	$R_c = \left(\frac{4\pi A}{P^2}\right)$	Strahler (1964)
Elongation ratio(R_e)	$R_e = \left(\frac{P}{\pi L}\right)$	Strahler (1964)
Form factor(F_f)	$F_f = \left(\frac{A}{L^2}\right)$	Horton (1945)
Relative relief (H)	$H = R - r$, $R \equiv$ highest relief, $r \equiv$ lowest relief	Schumm (1956)
Relief ratio (R_r)	$R_r = \frac{H}{L}$	Schumm (1956)

Topographic Wetness Index

Topographic Wetness Index (TWI) is another morphometric index that defines the areas prone to water accumulation. The TWI is a physically based index or indicator of the effect of local topography on runoff flow direction and accumulation (Ballerine, 2017). The distribution of this indicator on a terrain profile is based on the topographic slope, low slope angle will be linked with high TWI values. "This index can be used as cost-effective approach compared to conventional hydrodynamic models to identify the flood-prone areas" (Pourali et al., 2016, p. 9). This is one of the important morphometric indices that is critical while developing the flood susceptibility map, as it carries a relatively higher weight in determining the flood prone areas. This index has been extracted using a simple 12.5 m DEM. The Arc Hydrology tools were used to pre-process the DEM through, fill, flow direction, and flow accumulation. The slope from the terrain mapping was used here to input the value into the raster calculator to estimate TWI using the following formula, where α is the upslope contributing area and β is the topographic gradient.

$$TWI = \ln\left(\frac{\alpha}{\tan\beta}\right)$$

Longitudinal profile of the river

The longitudinal profile is another important aspect to know about the river basin. This profile helps in developing the relationship between the slope steepness and the distance from the upper to lower reaches. It is a simple plot produced using the Google Earth Pro. Using the stream order output from the analysis of the morphometric indices, the profile for the stream with the highest order was constructed to establish a relation between the elevation and the distance from the stream mouth. Figure 5 shows the river profile flowing out of the lake under investigation. The total length of the profiled river is 16.8 km. While the maximum, minimum, and the average elevation for the river long profile are 3735 m, 3149 m, and 3487 m respectively. The average slope across the profiled river is 2.3 % with a maximum slope of 11.6 %.

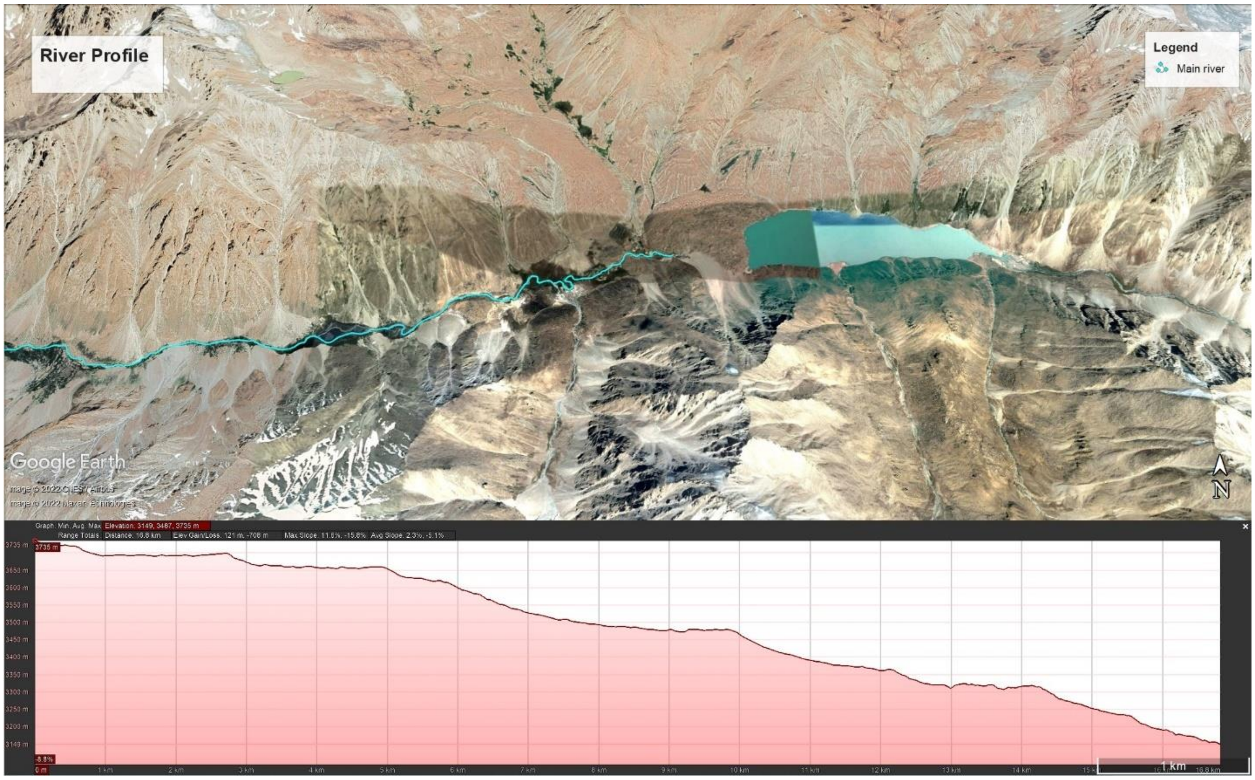

Figure 5. Longitudinal river profile for the main Rivakdara stream

Time Series of Temperature and Precipitation

Temperature and precipitation are the two most important physical parameters that controls the expansion of the lake, as it increases the glacier recession. These two climatic factors for the study area were extracted from the global monthly products of CHIRPS and CHIRTS. The extraction process starts with the construction of the model builder to convert the ".nc" extension to the raster format and clip the raster datasets for the respective area of interest. The raster datasets were processed through the zonal statistics using the python code (Appendix B) to generate a table with unique monthly mean values. The resulting tables were then passed into the R programming utility to prepare time series and forecast the temperature and precipitation trend for the next 5 years (codes in the Appendix B). The forecasts of the series are conducted using ARIMA. The time series data were further used to estimate the correlation for evolution of the lake area against the annual change in temperature and precipitation (codes in Appendix B).

ARIMA MODEL

ARIMA (p, d, q) model is a combination of two models, AR(p) (Autoregressive) and MA(q) (Moving Average) where p and q are orders of the methods which represent number of lagged dependent variables. ARIMA model is applicable to times series that are stationary. A time series is stationary if the long-run mean, variance, and co-variance are constant over time. Some types of non-stationarities can be made stationary by a process called differencing denoted by d which refers to the number of differences needed to make an integrated series of order d stationary. Based on ACF (autocorrelation function) and PACF (partial autocorrelation function) patterns, an ARMA (p, q) process is identified for the given time series. In other words, best values for p and q are selected based on the ACF and PACF patterns.

The ARIMA(p, d, q) process for a time series Y_t with immediate past error u_t is given by

$$Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{t-p} + u_t + \theta_1 u_{t-1} + \theta_2 u_{t-2} + \cdots + \theta_q u_{t-q}$$

where ϕ_i are coefficients, p and q are the number of lags in Y_t and u_t respectively. The above equation can be rewritten as

$$Y_t = \sum_{i=1}^{p} \phi_i Y_{t-i} + u_t + \sum_{j=1}^{q} \phi_j u_{t-j}$$

Evolution of the lake through NDWI

In this study, Normalized Difference Water Index (NDWI) proposed by McFeeters in 1996 was used for delineation of the lake Rivakkul area. The main purpose of NDWI is to highlight and estimate the water feature area from the satellite images. Many scientists have suggested the use of Modified Normalized Water Index (MNDWI) over the NDWI because MNDWI reduces the built-up area and land noise from the satellite image. It is better for enhancing and extracting water information for a water region with a background dominated by built-up land areas compare to NDWI. The MNDWI/NDWI value ranges from -1 to +1, where all the values greater than 0.3 are referred as the pixel value for the water bodies (Amin et al., 2020; Bano et al., n.d.). Band 2 and Band 4 for the Landsat 4-5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Band 3 and Band 5 for Landsat 8-9 Operational Land Image (OLI) went through the image correction process (also see Figure 6). These kind of satellite images are used to analyze the temporal changes. During the image correction process, DN (Digital Number) to ToA (Top of Atmosphere) reflectance and surface reflectance has been considered significant to reduce atmospheric impacts on the reflected wavelengths and derive the desired indices to use. Conversion from DN to ToA: After the atmospheric corrections, image data are composed of ground reflectance only which helps in identification of water pixels more accurately and differentiating the same from shadowed area having similar spectral characteristics. Since NDWI can be used for various hydrological purposes, the specific band combination has been used to determine the lake expansion effect. After the image correction, the respective combinations of bands help estimate the NDWI (Figure 6), in simple words the surface area of the region of interest. It is a simple process in the ArcGIS suite, where the raster calculator tool finds the respective NDWI values using the following formulae.

$$MNDWI = \frac{Band\ 2 - Band\ 4}{Band\ 2 + Band\ 4}\ for\ landsat\ 4, 5, and\ 7$$

$$MNDWI = \frac{Band\ 3 - Band\ 5}{Band\ 3 - Band\ 5}\ for\ landsat\ 8\ and\ 9$$

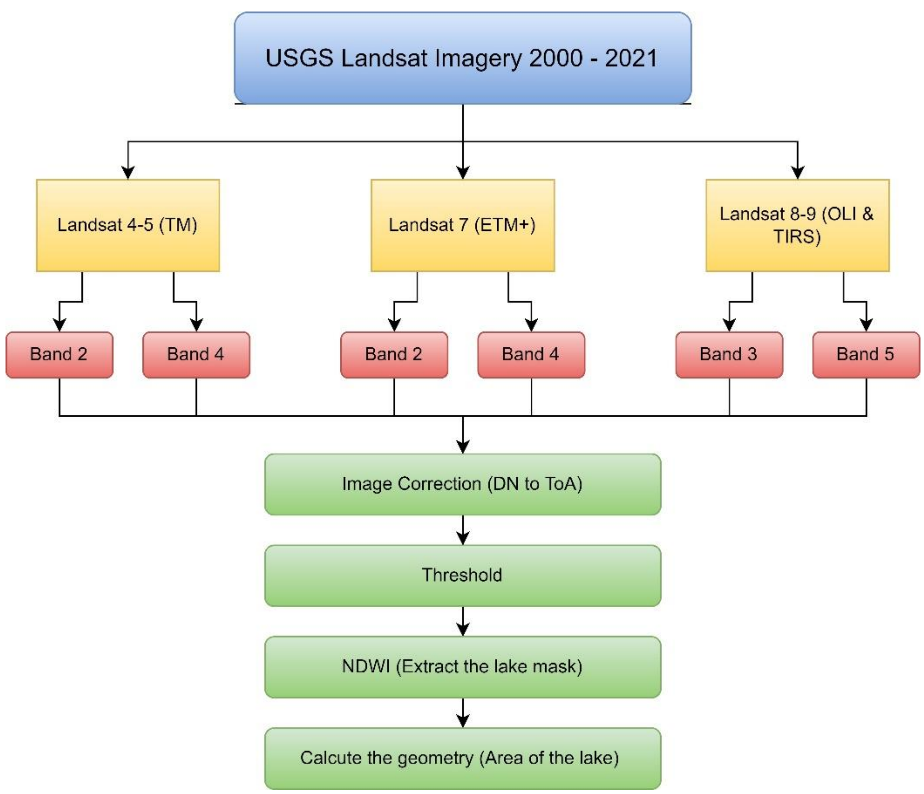

Figure 6. Flow-chart representation to calculate MNDWI using Landsat images.

Lake volume and depth

There is no bathymetry data available to calculate volume of glacial lakes in the high mountain regions, Huggel et al., however, provide some estimations for glacier lakes in the Swiss Alps (2002). With limited to no bathymetric data available it is thought suitable to estimate the water volume for these lakes using the similar correlations discovered for lakes in the Swiss Alps (Shakya, 2020). The empirical equation study by Huggel et al. (2002) is given as:

$V = 0.104\ A^{1.42}$, where V is the volume and A is the area of the lake.

Estimation of LULC

This is one of the simplest yet the important parameter to calculate for the study area. The free access and availability of the global land cover data by Sentinel 1 & 2 has made it easier to estimate the Land Use and Land Cover (LULC) changes. Collect the LULC product for the desired time period and clip it based on the area of interest. While estimating the risk of GLOF, it is essential to understand the LULC of the catchment, as it can determine the potential risk zones.

Flood Modelling using Analytical Hierarchy Process (AHP)

The flood hazard map was prepared using GIS and the application of AHP to identify the optimal selection of weights for the factors that contribute to flood risk. The flooding causative factors used in this study were rainfall, distance to the river, DEM, slope, LULC, drainage density, and TWI (also see Figure 7). These layers were converted into raster format and reclassified using the ‘Reclassify’ command under the ‘Spatial Analyst Tools’ in ArcMap 10.7. All the causative factors were assigned distinct weights using the AHP method, as described by (Maskey et al., 2020). The reclassified layers were combined using the “overlay by sum” tool in ArcMap 10.7, to create distinct zones for the flood susceptibility (Figure 7). The derived flood hazard map consisted of five distinct categories (zones), very high, high, intermediate, low, and very low.

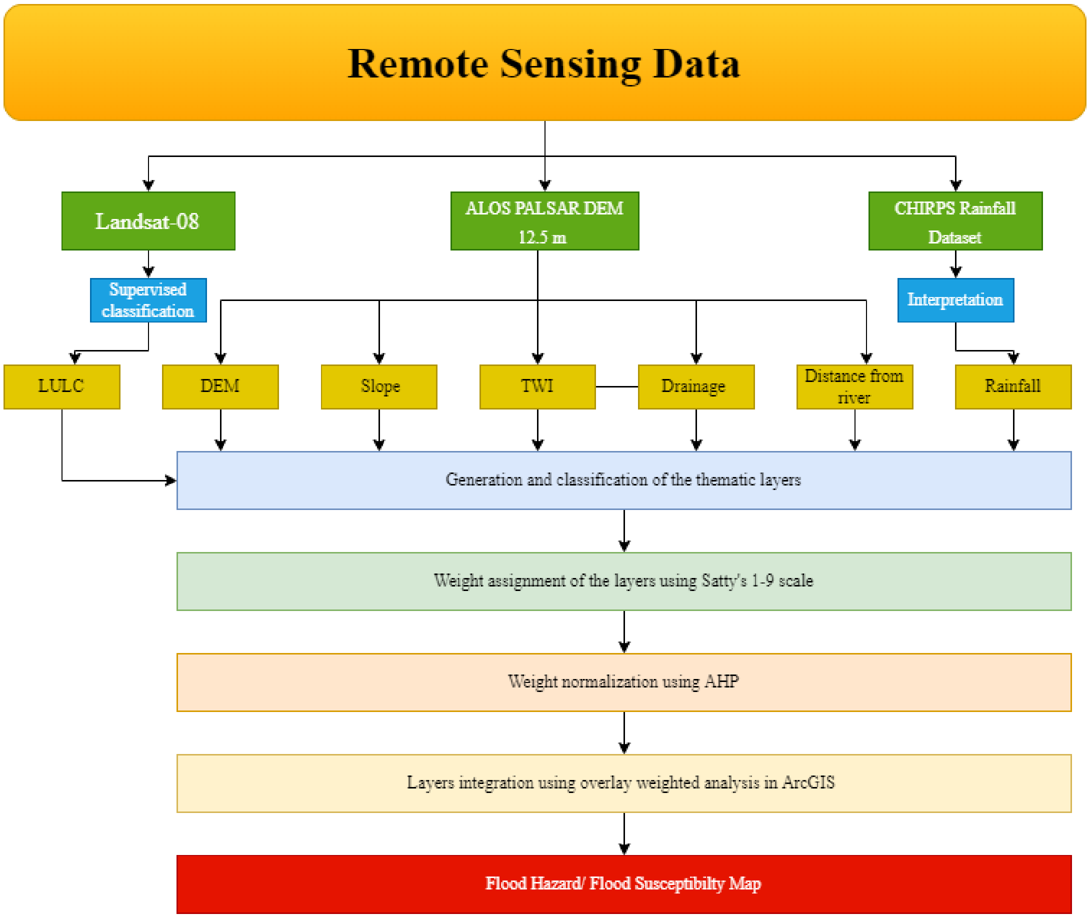

Figure 7. Flow-chart representation to understand the "Flood Susceptibility" mapping using AHP method

6. Results and Discussion:

6.1. Morphometric Analysis

Table 3 lists all the extracted values for the respective morphometric parameters that determine the geomorphology of the region. According to the results, there are 667 streams in total that are divided into 4 groups as per their respective stream orders. The streams have been ranked using the Strahler's (1964) classification (figure 10). Using the Strahler's formula, segments with no tributaries identified as a first-order stream. When two 1st-order stream joins form a 2nd-order stream and so on (Mahala, 2020). Bifurcation ratio is another important morphometric index that identifies the control of the geological structures on the drainage network and drainage pattern. The values generally lie between 3 and 5, which indicates the almost negligible control of geological structure on the drainage networks and drainage patterns and it is the same for the mean bifurcation ratio (Veeranna et al., 2017).The bifurcation ratios of Rivakdara catchment varies from 1.295 to 2.536 (Table 3) that is indicative of some strong influence of geological on the drainage networks and systematic branching pattern of the streams. The values of these linear aspects of the basin resonate to a sensitive river basin that is very susceptible upon any outburst. The areal aspects of a drainage basin reflect the influence of lithology, geological structure, climatic conditions, and denudation history of the basin. Morphometric parameters such as drainage density (D_d), elongation ratio (R_e), and circulatory ratio (R_c), form factor (F_f) define the areal aspect of the basin. The value of D_d indicates the potential for run-off and the infliltration. High values mean greater run-off with lower infiltration, while lower D_d values indicate lower run-off with higher infiltration (Mahala, 2020). The $D_d = 0.799$ for the Rivakdara catchment, which is perhaps due to high alluvial thickness throughout the catchment. The value for the drainage density does not complement the linear aspects of the catchment, as it suggests a relatively lower run-off for the basin. In addition, the elongation ratio, the circulatory ratio, and the form factor for the study goes hand in hand, as they describe the controls on the shape and size of the catchment. The $R_e = 0.072$, makes the catchment less elongated according to the values defined by Veeranna et al. (2017), circular (>0.9), oval (0.9 – 0.8), and less elongated (<0.8). The lower R_e value also suggests lesser vulnerability to flash floods (Markose et al., 2014). $R_c = 0.471$ that describes the differences in the geomorphological features, strong relief, and slope occurring in the Rivakdara catchment; however, the $F_f = 0.0041$ which suggests a narrower catchment. The values of the areal aspects indicate lower outburst susceptibility. To understand the stream-discharge relationship, and the intensity of the outflow, it is important to understand the relief aspect of the catchment. The relief aspect includes relative relief $(H)$and relief ratio (R_r), values are presented in Table 3. Lowest relief point in the catchment is 2520 m, while the highest relief point is 5481 m. The relative relief (H) is 2961, while the $R_r = 9.666$. In general the relief ratio ranges from 3.06 to 15.57 (Veeranna et al., 2017). High relief values, closer to 15 shows low infiltration and high run-off conditions (Patton, 1988). Overall, the morphometric indices explained the structural and geomorphological aspects of the catchment under investigation. Although the areal aspects deviated slightly from the linear and relief aspect, the catchment is still susceptible to the outburst from the naturally dammed lake of Rivakkul.

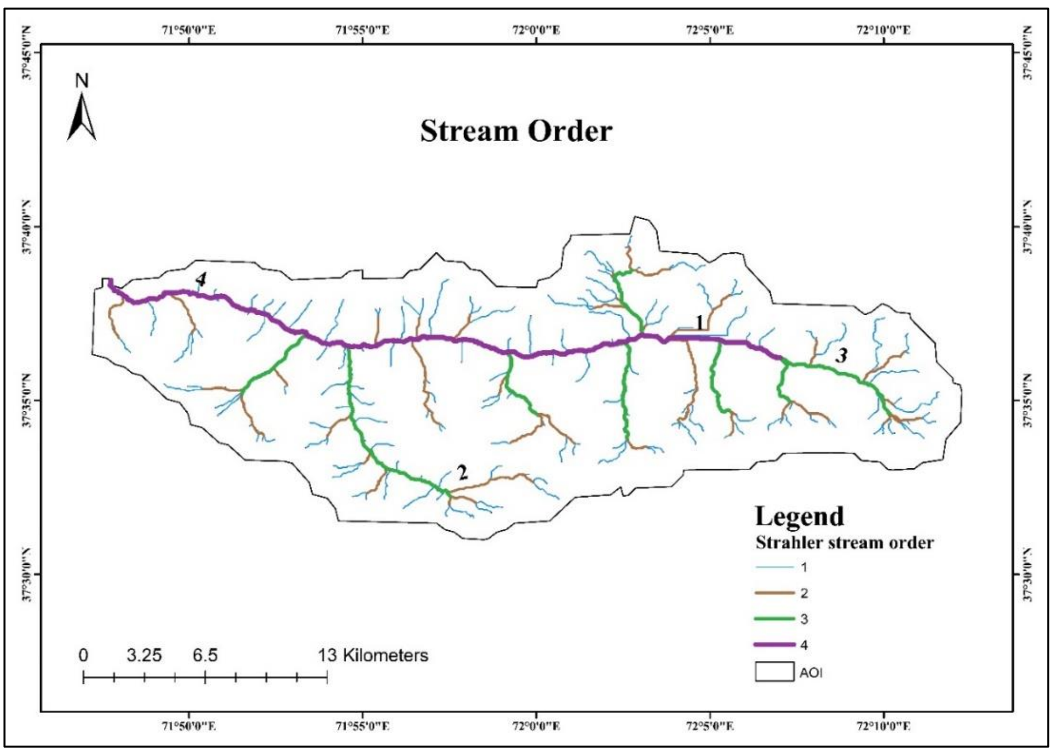

Figure 8. Stream order map based on Strahler's stream order classification

Table 3. The results for all the morphometric parameters of the Rivakdara catchment

Morphometric Indices	Values
Basin Perimeter(P)	$101.0959\ Km^2$
Length of basin(L)	$306.33\ Km$
Basin area(A)	$382.93\ Km^2$
Stream order (u)	$1st, 2nd, 3rd, and\ 4th$
Stream number(N_u)	$N_1 = 350, N_2 = 138, N_3 = 101, N_4 = 78$
Bifurcation ratio (R_b)	$R_{1\rightarrow 2} = 2.536, R_{2\rightarrow 3} = 1.366, R_{3\rightarrow 4} = 1.295$
Mean bifurcation ratio (R_{bm})	1.732
Stream length(L_u)	$L_1 = 161.47, L_2 = 67.04, L_3 = 43.96, L_4 = 33.86$
Mean stream length(L_{um})	$L_{1m} = 0.875, L_{2m} = 2.22, L_{3m} = 3.033, L_{4m} = 3.93$
Drainage density(D_d)	$D_d = 0.799$
Circulatory ratio(R_c)	$R_c = 0.471$
Elongation ratio(R_e)	$R_e = 0.072$
Form factor(F_f)	$F_f = 0.0041$
Relative relief(H)	$2961\ m$
Relief ratio(R_r)	9.66

6.2. Topographic Wetness Index

Topographic Wetness Index (TWI) is another morphometric index that defines the areas prone to water accumulation. This index can be used as cost-effective approach compared to conventional hydrodynamic models to identify the flood-prone areas (Pourali et al., 2016). This is one of the important topographic indices that is critical while developing the flood susceptibility map, as it carries a relatively higher weight in determining the flood prone areas. Figure 9 represents the TWI map for the Rivakdara catchment. According to Ballerine (2017), the smaller values of TWI indicate less potential for accumulation, while greater values indicate steep upslope but gentle local slope and higher accumulation. The TWI values from the map depicts the steepness of the catchment as most of the area is covered in the dark blue color that is for the steep upslope with lesser potential to accumulate. Please see Figure 21 in Appendix A to share the slope distribution of the catchment in more details. The index value of ≤ -6.58 corresponds to areas with higher slope and it demonstrates area that accumulates least water. Higher index values refer to lower slope areas that accumulates the most water. With reference to the map, most of the area in the catchment does not accumulate and have high potential of run-off (Figure 9). Therefore, TWI is an essential index in determining flood prone areas based on the steepness and topography of the region.

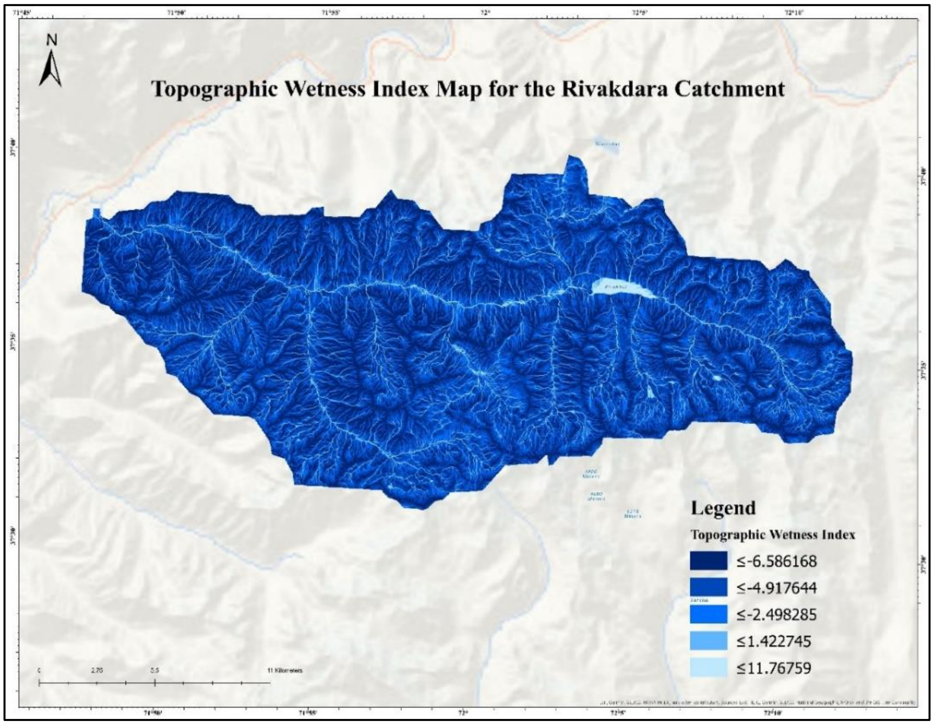

Figure 9. Topographic wetness index (TWI) map for the RIvakdara catchment

6.3. Changes in Land Use and Land Cover

This sub-section section discusses the findings of LULC and the importance of this parameter in identifying flood prone areas. Figure 10 represents the LULC map of the catchment for 2021. LULC maps for 2017 to 2020 have can be seen in Figure 22 in the Appendix A. The LULC have been mapped from 2017 to 2021. As mentioned in the study site section that the catchment can be classified as hot and dry during summers, while it can get extremely cold during winters. Hence, there is no chance to observe any dense vegetation in the region. The LULC from 2017 to 2021 indicates that the snow/ice cover has lost almost 26 % of its volume, while there is clear evidence of increase in the water volume, as it rises around 26 % from 2017 to 2021. LULC is another critical indicator to check the flood susceptibility for the region. These values will assist while preparing the flood susceptibility map, as it also holds a significant weight in determining the flood prone areas.

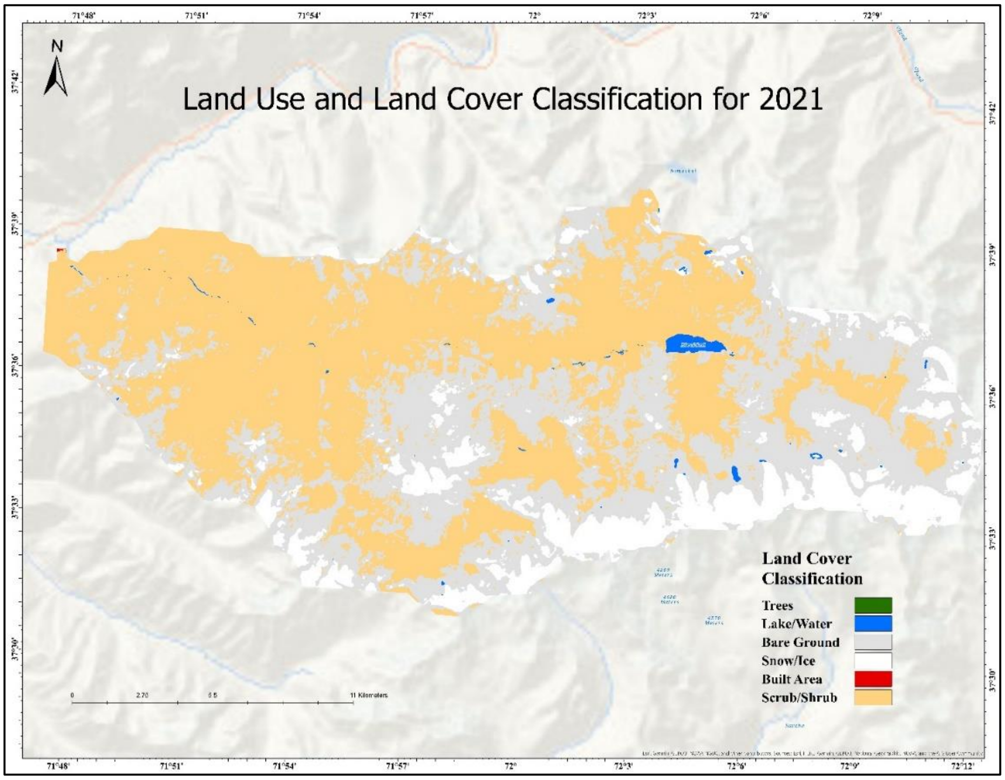

Figure 10. Land use and land cover classification map for the year 2021

6.4. Temperature and Precipitation

In high mountain regions, temperature and precipitation are the two most essential physical parameters, especially when glaciers are involved in the study. With the unprecedented changes in the global climate, it is very likely to observe some anomalous changes in temperature and precipitation. It has been hypothesized that the increase in temperature and precipitation will impact the area of the lake. Lake Rivakkul is part of the Rivakdara catchment; therefore, all the physical, geomorphic, and topographic parameters of the catchment influence the behavior of the lake. A comprehensive analysis of the CHIRPS and CHIRTS data products demonstrate stationarity in the temperature and seasonality in the precipitation plot (Figure 11 and Figure12). The time series presented in the figures show no significant trend in either of the physical parameters. The time series for the precipitation and the temperature data was generated using the ARIMA model. This model analyzes the time series data to better understand the data set and to predict future trends based on the past values of the data. Figure 13 and figure 14 present the forecast for the change in temperature and precipitation for the next 5 years. The results for the monthly mean temperature for the Rivakdara catchment show that the average temperature from 2000 to 2021 is -2.82 degrees of Centigrade ($°C$) with a maximum value of 11.725 ($°C$) and a minimum value of -19.287 ($°C$). On the other hand, the monthly mean precipitation values for the last 22 years, show an average of 43 mm with the maximum and minimum values of 141 mm and 0.6 mm respectively. The bulkiness of the data does not show distinct and huge changes neither in the temperature plot nor in the precipitation plot. However, the distinct values signify the changes over the period of time. These changes might not be very significant, but they influence the change in the lake area. As temperature and precipitation increases, the discharge or the input into the lake will increase as well. Unless the seepage or the free board at the moraine of the lake expands, they lake will accumulate more water as a result. To develop coherency between the temperature, precipitation, and area of the lake, the monthly mean temperature and precipitation values were estimated annually.

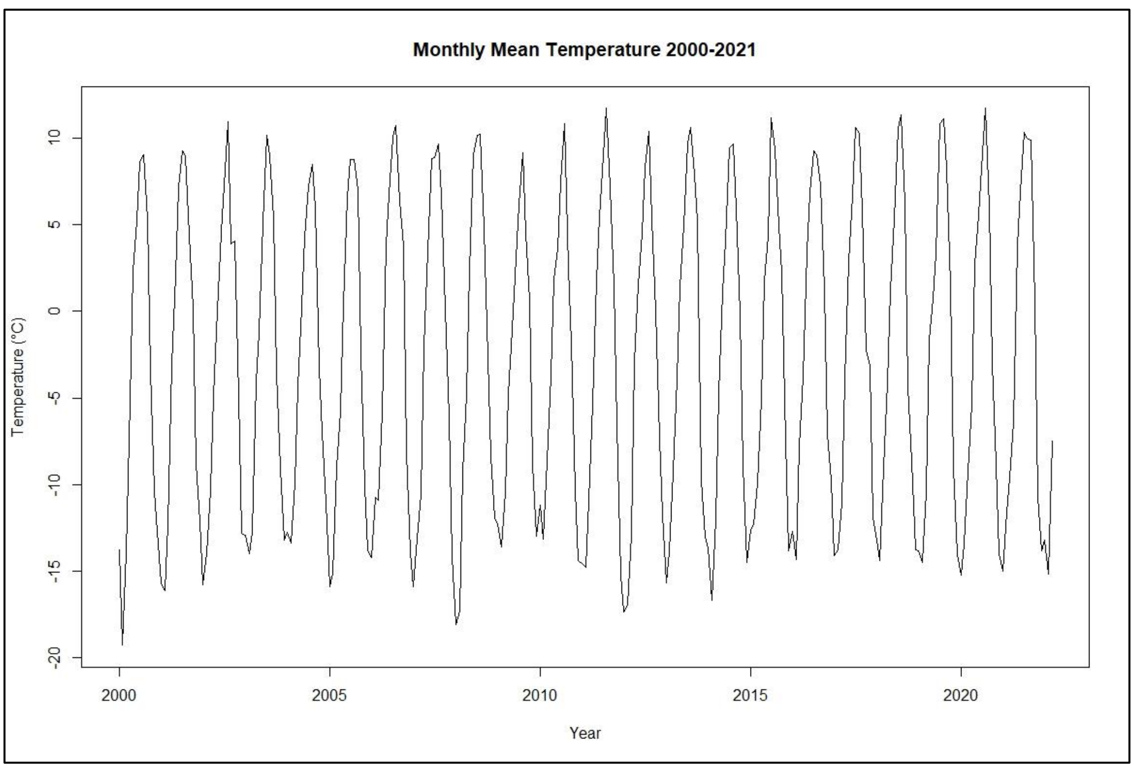

Figure 11. Time series for the monthly mean temperature from 2000-2021

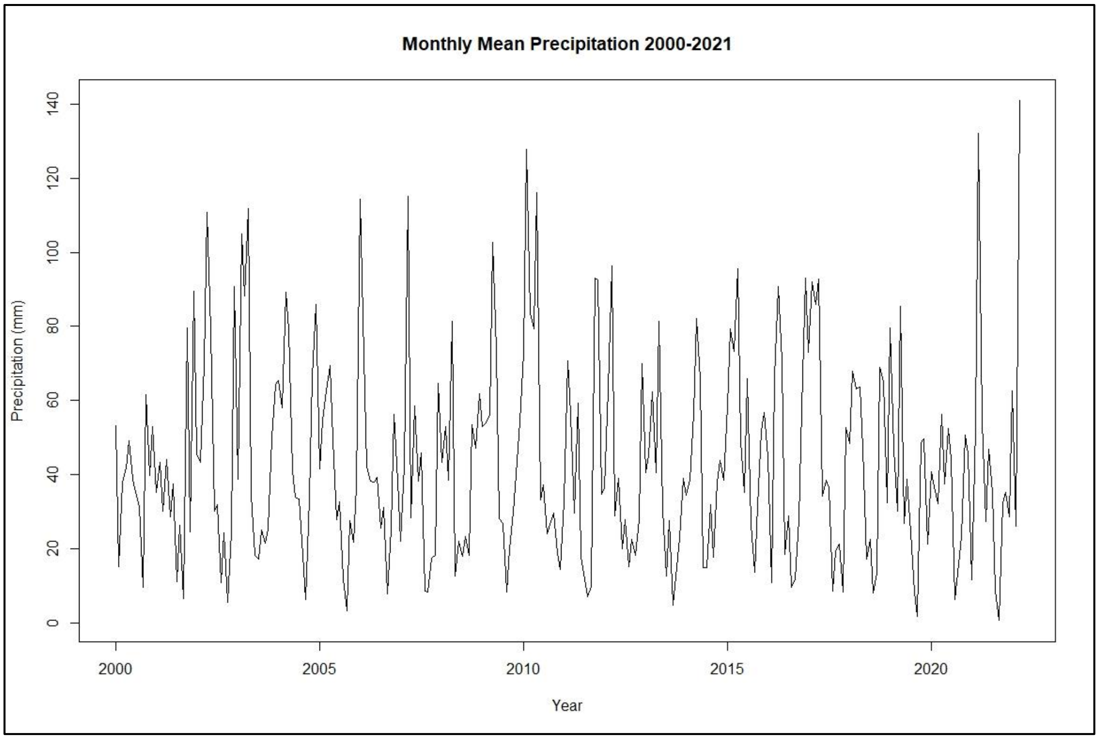

Figure 12. Time series for the monthly mean precipitation from 2000-2021

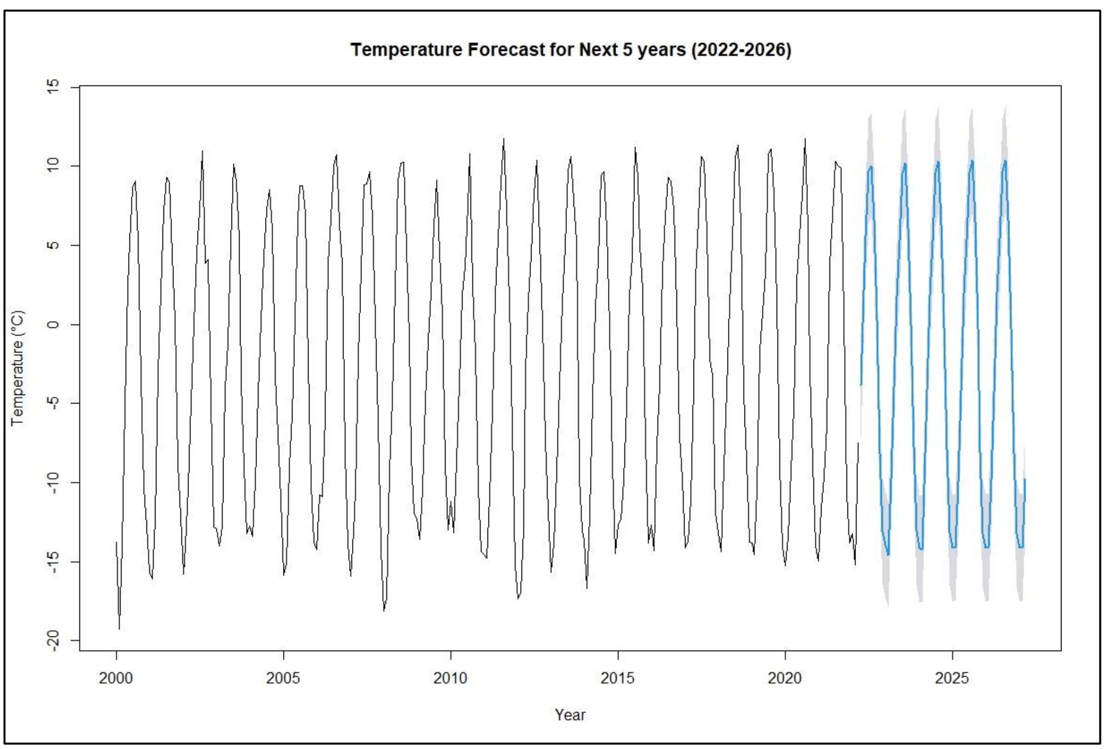

Figure 13. Monthly temperature forecast using ARIMA model for 2022-2026

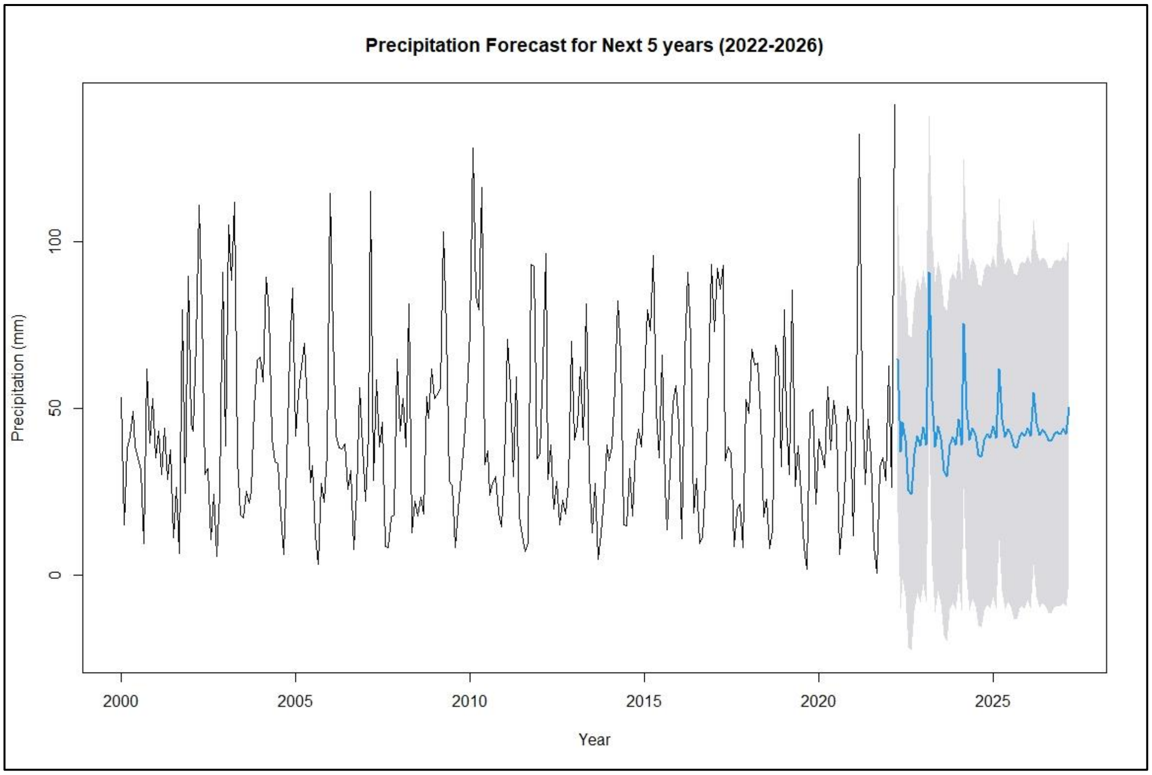

Figure 14. Monthly precipitation forecast using ARIMA model for 2022-2026

The annual mean temperature and precipitation values are presented in Table 4 (also see Figure 23 and Figure 24 in Appendix A). Due to the inaccessibility and limited data sources, especially for a remote region like Pamir, this study had to rely on the open source, free access data. In the later section, the correlation between the temperature, precipitation, and the lake area will be discussed in detail.

Table 4. Annual mean temperature, precipitation, and lake area values from 2000-2021

Temperature $(°C)$	**Precipitation** (mm)	**Lake Area** (km)
-4.00833	38.84375	0.9585
-2.98854	38.03125	1.05525
-2.6625	47.16458	1.1277
-3.42292	49.99792	1.1025
-2.95104	50.87604	0.9585
-3.37083	36.63125	1.01925
-1.85	44.02083	1.1025
-2.0125	38.95	1.01925
-2.82292	39.37604	1.01925
-3.44896	45.54792	1.02285
-3.075	55.34688	1.1928
-2.54792	42.99688	1.0689
-3.25521	38.75417	1.0689
-2.14063	34.98646	1.17
-3.35286	39.75	1.1826
-2.27396	53.1125	1.13445
-1.51042	44.22292	1.1367
-1.98854	46.9125	1.22085
-2.73646	43.13542	1.1421
-2.30833	38.47083	1.34343
-2.89219	36.79688	1.1475
-2.13568	38.79479	1.30779

6.5. Area Changes of Lake Rivakkul

Based on the observations using NDWI, the area of lake has increased at an average of 2 % annually with a maximum value of 1.3434 km^2 for 2019 (Figure 15). The change is not very significant; this is due to steep slope of the area surrounding the lake; there is a little change in area due to almost vertical walls around lake. Table 5 shows the percentage change in the lake area from 2000 to 2021. Although there is not enough data to build a time series for the evolution of the lake area, an effort has been made to predict the change in the area of the lake for the upcoming 5 years using the ARIMA model (Figure 16). Evidently, almost all the observations demonstrate increase in the lake area, which could perhaps be the result of the average change in temperature and precipitation. The graphical representation (figure 17) also depicts a trend line in the average change in the area of the lake Rivakkul. Due to several limitations, the bathymetric techniques cannot be employed to explore the volumetric changes of the lake, which would have provided a much analysis in terms of its potential outburst.

Table 5. Percentage change in the area of the lake from 2000-2021

Year	**MNDWI: Lake Area(km)**	**% Changes in the lake area**
2000	0.9585	6.075003 ↑
2005	1.01925	17.355 ↑
2010	1.1928	-5.835 ↓
2015	1.13445	1.305 ↑
2020	1.1475	16.029 ↑
2021	1.30779	6.075003 ↑

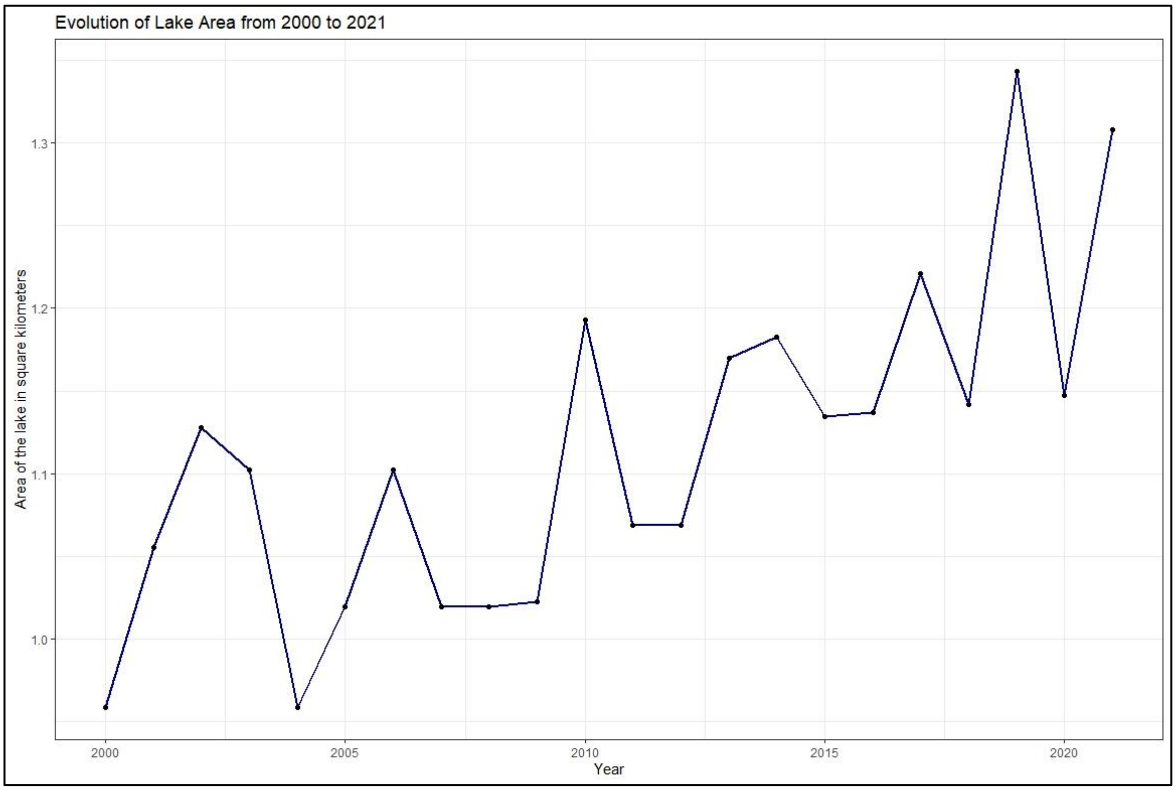

Figure 15. Graphical representation of the evolution of the lake area from 2000-2021

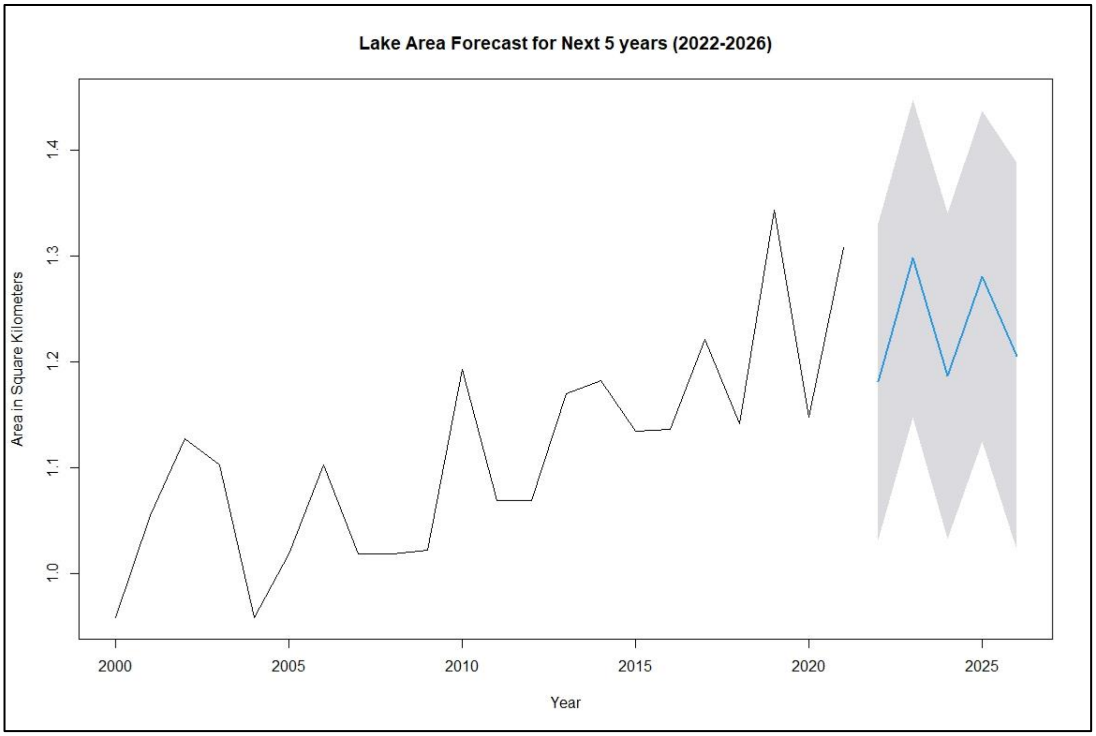

Figure 16. Forecast for the lake area using ARIMA model for 2022-2026

Correlation

The temperature and precipitation are considered as the most valuable contributors to the increase in the lake area. Hypothetically, this assumption is reasonable because with increase in temperature and precipitation, the melting of glaciers will increase as well. Consequently, the discharge and the input from the tributaries into the lake will increase as well. However, this is not as simple as it may sound. Precipitation and temperature are potentially the main contributors, but there are dozens of other variables and factors that might reciprocate their impact on the evolution of the lake area. Figure 17 demonstrates a simple corrogram that explains the correlation between temperature, precipitation, and the change in the lake area. As per assumption, the lake area must have had a stronger correlation with both temperature and precipitation. However, the results show a slight correlation between temperature and the lake area with almost negligible correlation with precipitation.

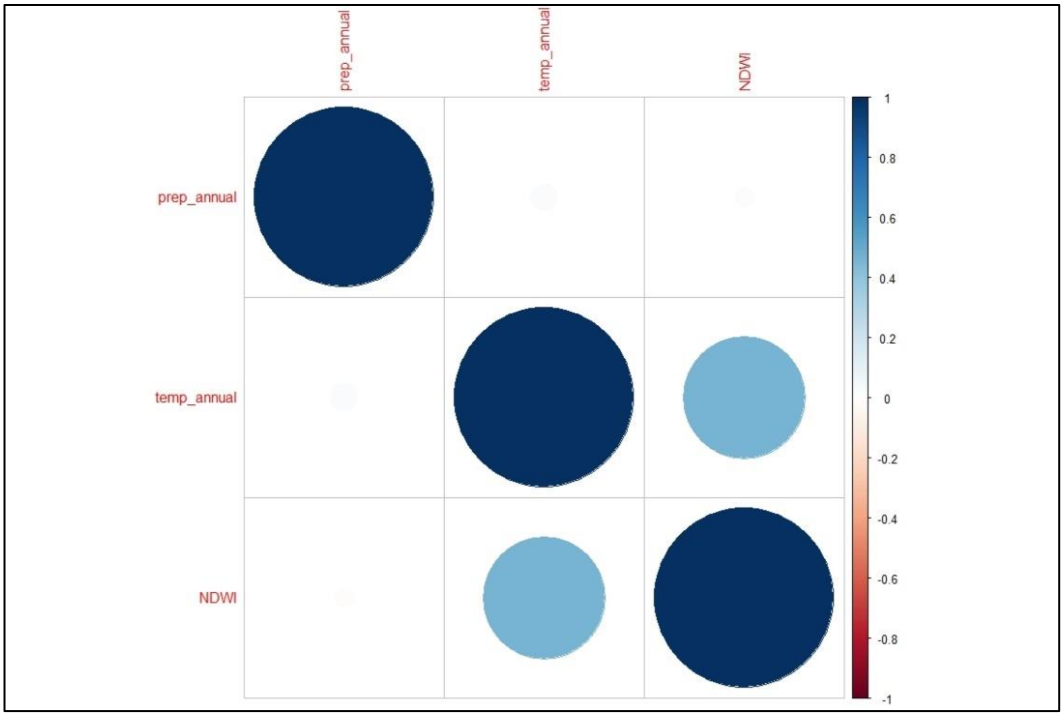

Figure 17. A simple corrogram that shows the correlation between temperature = “temp_annual”, preciptaion = “prep_annual”, and lake area = “NDWI”

6.6. Flood Susceptibility Mapping using Analytical Hierarchy Process

All the preliminary analysis has been done to prepare the flood susceptibility map to identify all the areas at higher risk. The flood susceptibility map was prepared using geographical information systems (GIS) and the application of AHP method to identify the optimal selection of weights for the factors that contribute to flood risk. The flooding causative factors used in this study were rainfall, distance to the river, topography, slope, land use/land cover LULC, drainage density, and topographic wetness index. This map combines all the topographic, climatic, and geomorphic analysis that have been done for the catchment. This map holds huge significance as it can identify the areas that are relatively more prone to the outburst flood upon the moraine failure of the lake Rivakkul. Although this is not the ideal way to assess risk for a glacial lake outburst flood, this is best way given the limited data and sources available. This considers all the essential parameters and indices that can influence the properties and behavior of the lake. The AHP method has been employed to assess the susceptibility because it considers unique weightage for distinct parameters, not all parameters contribute to the flood equally. The map in Figure 18 shows that most of the downstream area is susceptible to flooding compared to the area closer to the lake, perhaps due to the higher relative relief. This is not the best approach, yet it provides the head start for a more sophisticated lake outburst flood analysis.

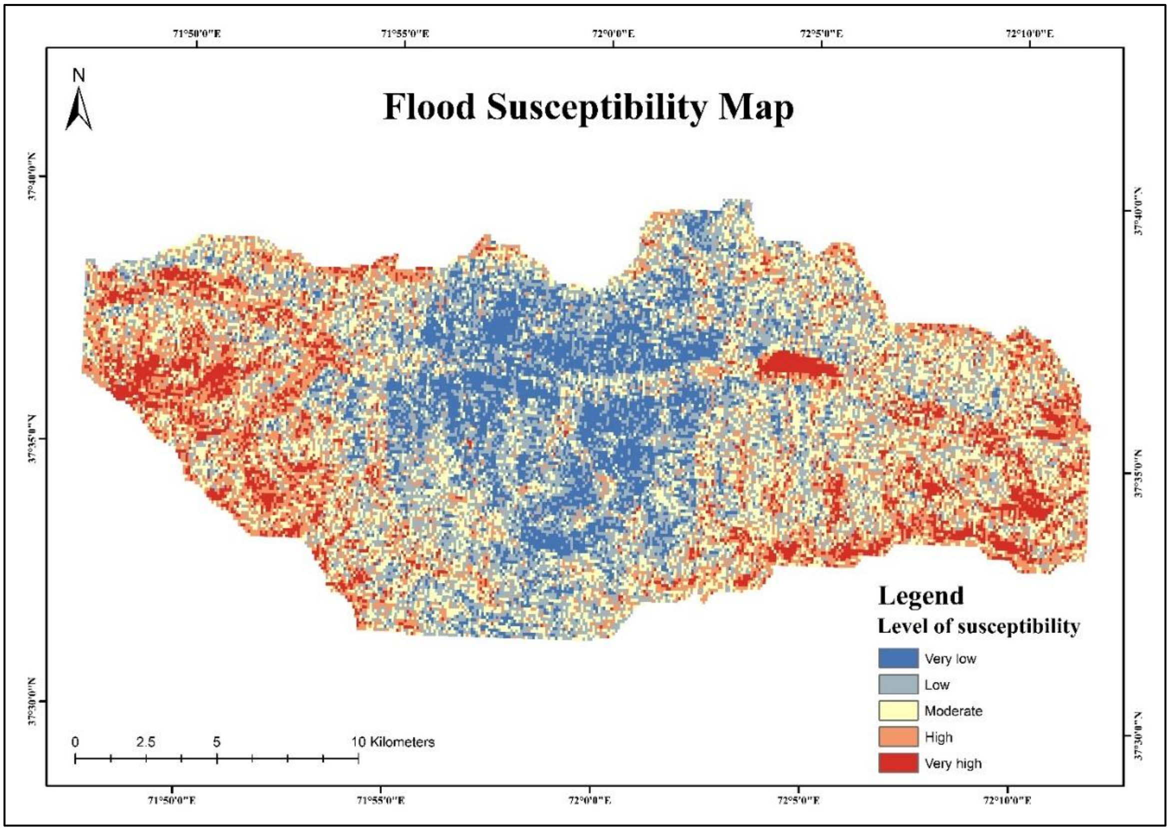

Figure 18. Flood susceptibility map using the AHP method

7. Conclusion

The unprecedented changes in the global climate have raised so many questions for the scientific community, especially with regards to the preparedness against extreme natural hazards, like glacial lake outburst floods. GLOFs are the most devastating kind of outburst flood that can cause extreme damage in a matter of few minutes to a few hours. This study explores the possibility of GLOF in the high mountain ranges of Pamir, Lake Rivakkul a naturally dammed lake with a huge potential of GLOF. To understand and quantify the contemporary and future risks of the potential GLOF, the geoinformatics technique and the morphometric analysis have been employed to understand the possibility of GLOF while studying the characteristics of the lake catchment. All the analysis has been done using the satellite imagery and the efficient remote sensing and GIS technology. The analysis show that Rivakdara is a 4^{th} order catchment with a total of 667 streams flowing through it. The morphometric parameters described the linear, areal, and the relief aspect of the catchment. The parameters, elongation ratio, drainage density, bifurcation ratio, relief ratio, and the topographic wetness index indicated that the catchment is susceptible to flood. The study could not develop a strong correlation between the climatic factors, such as temperature, precipitation with the changes in the area of the lake. Perhaps, the data accessibility and remoteness of the study area are the two major limitations behind this particular outcome. To understand the changes in the lake area, the Modified NDWI was analyzed for the lake mask. According to the results, the lake area has not changed significantly, only a 2 % change has been observed for the last 22 years. The harsh climate and the complex terrain make its humanly impossible to record and collect ground-based data manually throughout the year. Therefore, remote sensing provided helpful source of information for studying remote regions. The results of this study can be used as a preliminary hazard assessment approach to better prepare the communities against the devastating hazards, like glacial lake outburst floods.

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Appendix A: ***Figures and Tables***

Figure 19. Google Earth image of RIvakdara Catchment

Source: (Shakya, 2020)

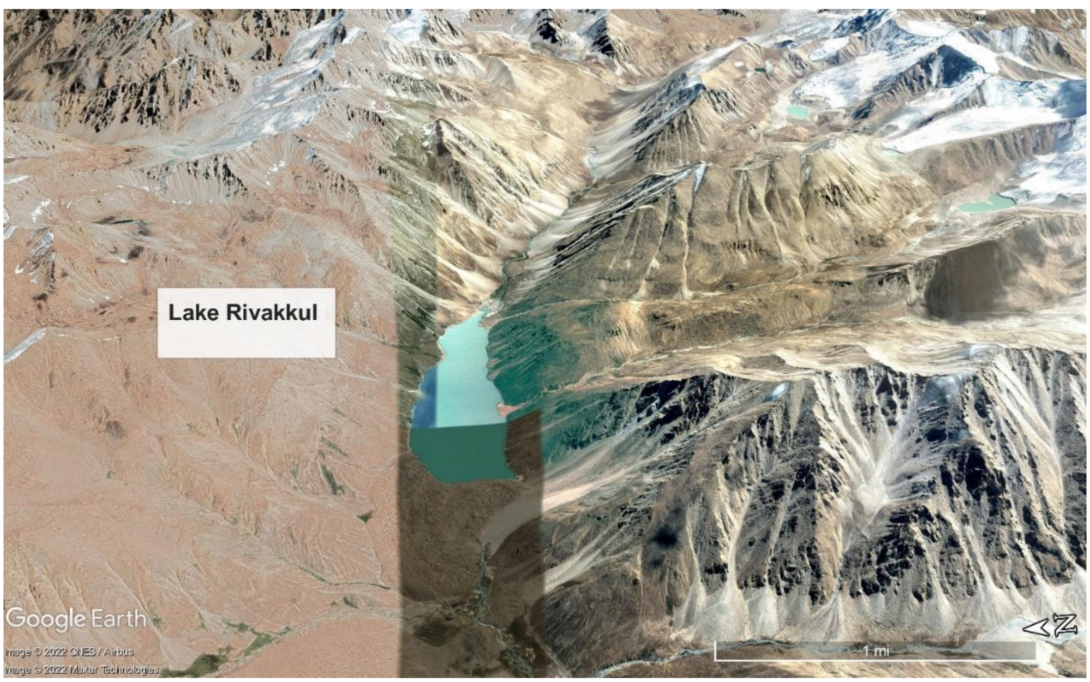

Figure 20. Google Earth image for the lake. This also demonstrates the contribution of other smaller glacial lakes into Rivakkul

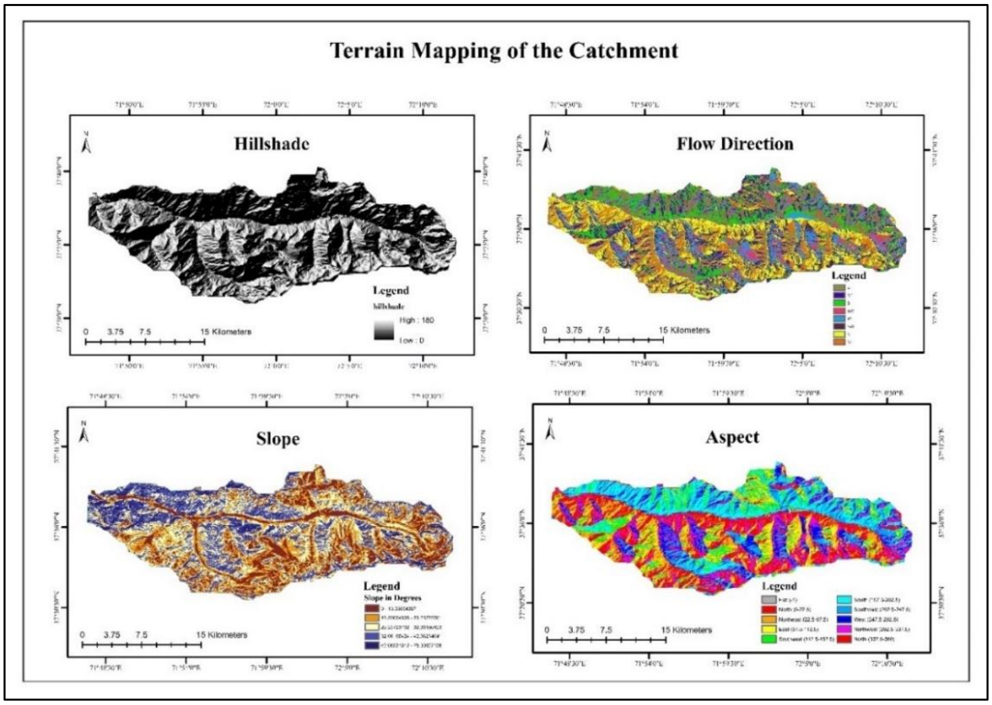

Figure 21. Terrain maps for the Rivakdara catchment

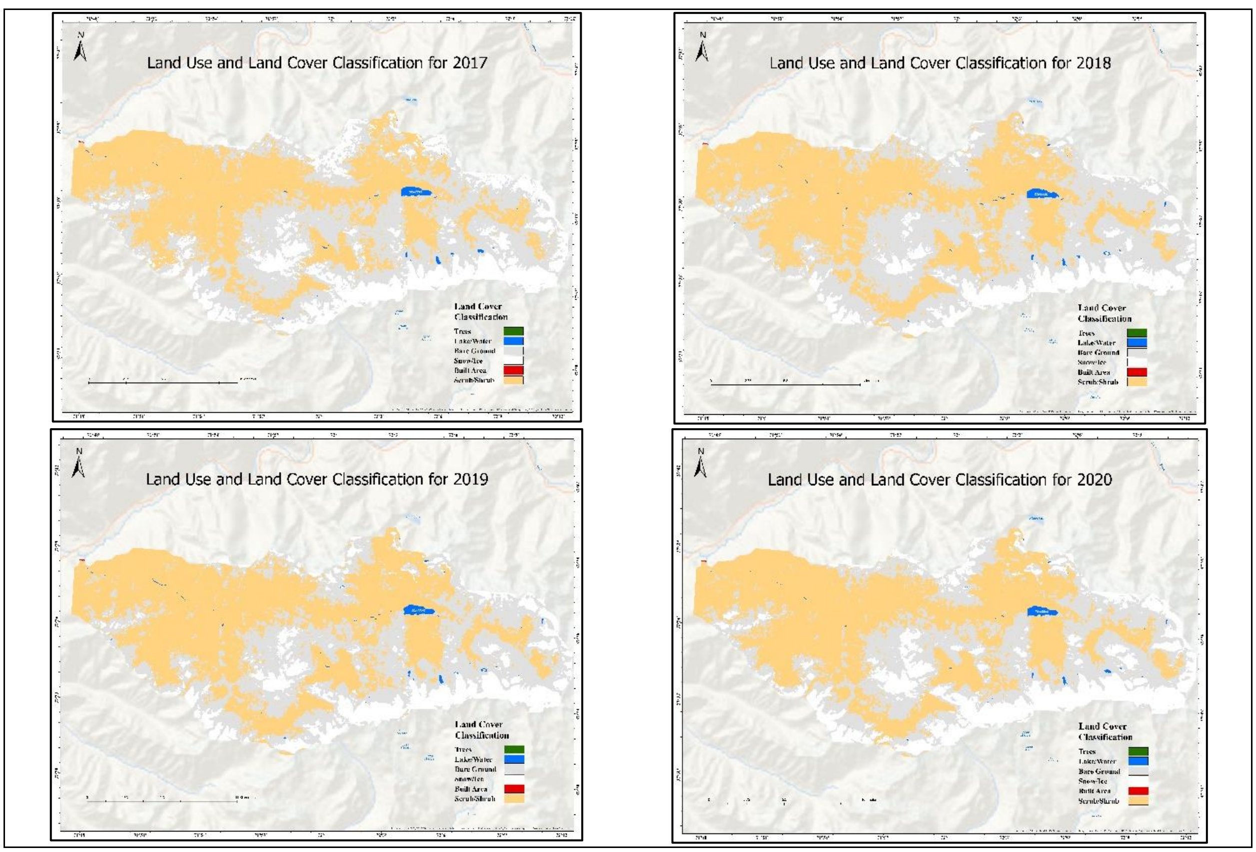

Figure 22.Land use and land cover classification maps for 2017-2020

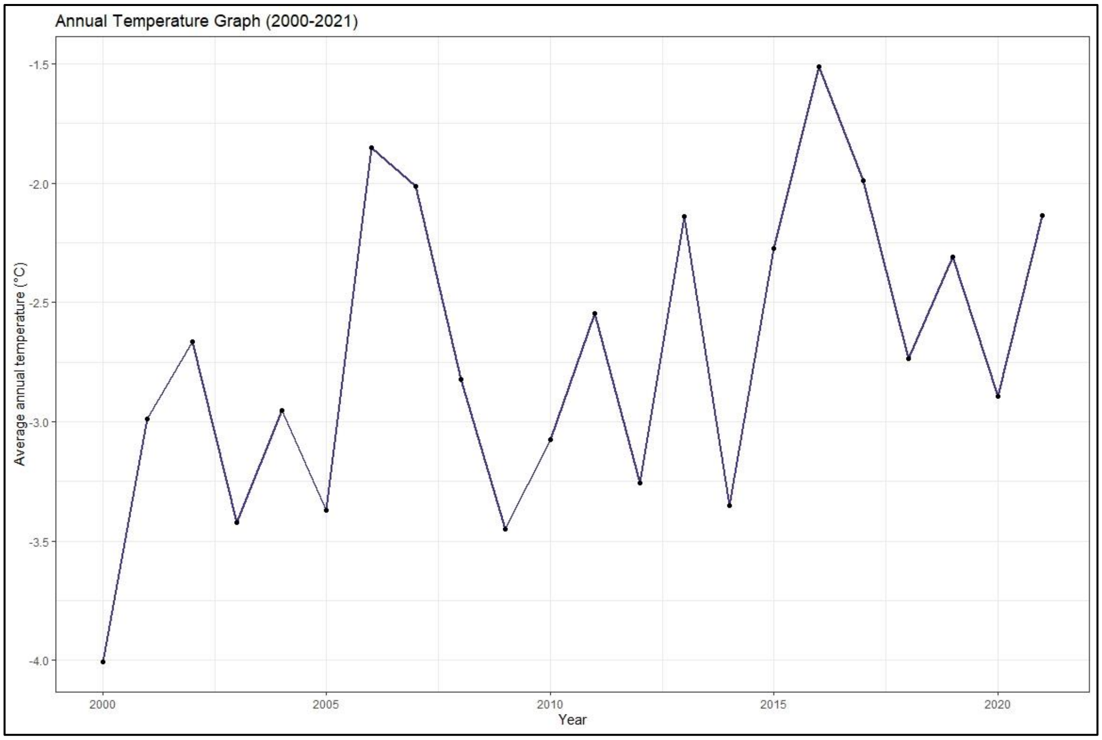

Figure 23. Annual temperature graph from 2000 to 2021

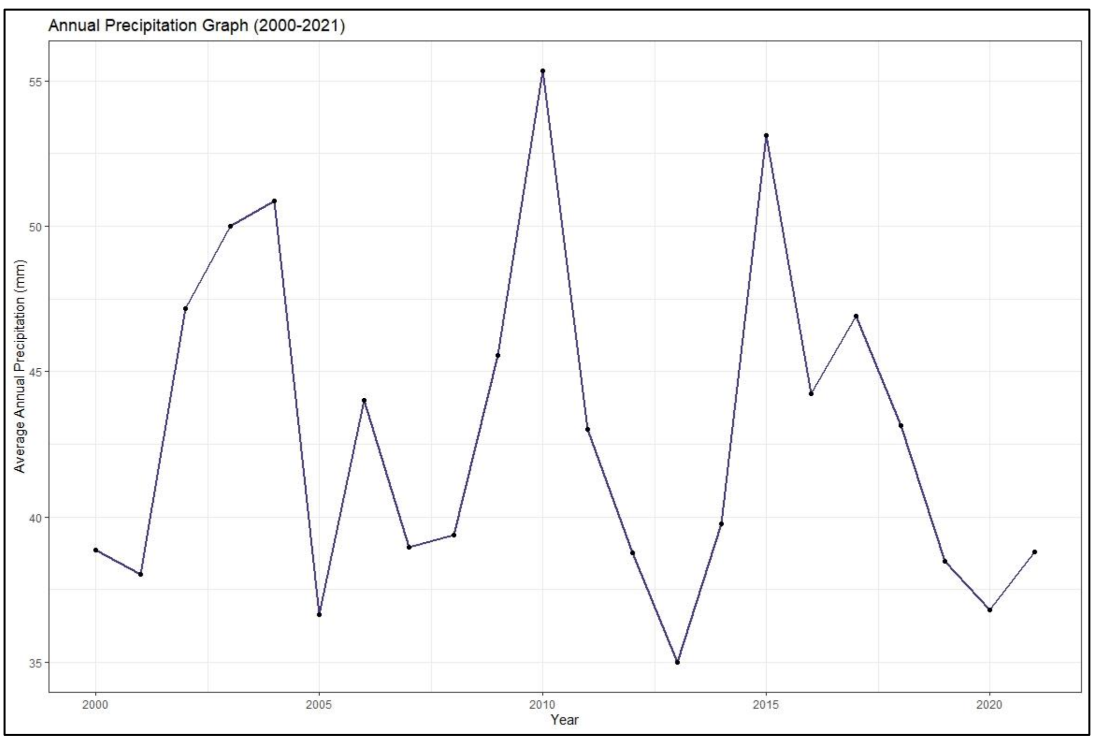

Figure 24. Annual precipitation graph from 2000 to 2021

Appendix B: ***R and Python Codes***

Python code to estimate "Zonal Statistics"

```
arcpy.env.workspace=r'C:\Users\uca_k_public\Desktop\Monthly-20220418T064259Z-001\clip2'
... path_to_SHP = r"C:\Users\uca_k_public\Documents\ArcGIS\Export_Output_2.shp"
... for raster in arcpy.ListRasters("*.tif*"):
... name=str(raster)
... output_path = r"C:\Users\uca_k_public\Desktop\Monthly-20220418T064259Z-001\table_batch"+name
... arcpy.gp.ZonalStatisticsAsTable_sa(path_to_SHP, "FID", raster, output_path, "DATA","MEAN")
```

R codes to estimate and plot time series of temperature and precipitaion

```
### load libraries
library(mice)
library(tseries)
library(forecast)
library(ggplot2)
library(ggthemes)
library(plotly)
library(ggpmisc)
### Load data
precip <-
read.csv("C:\\Users\\uca_k_public\\Desktop\\khizer\\Precipitation.csv")
temp<-
read.csv("C:\\Users\\uca_k_public\\Desktop\\khizer\\temp_2000_2022.csv")
NDWI<- read.csv("C:\\Users\\uca_k_public\\Desktop\\khizer\\NDWI_yearly.csv")
###Impute data
imputed_precip <- mice(precip, m=5, maxit = 50, method = 'pmm', seed = 500)
summary(imputed_precip)
imputed_temp <- mice(temp, m=5, maxit = 50, method = 'pmm', seed = 500)
summary(imputed_temp)
imputed_NDWI <- mice(NDWI, m=5, maxit = 50, method = 'pmm', seed = 500)
summary(imputed_NDWI)
precip <- complete(imputed_precip,3)
temp <- complete(imputed_temp,3)
NDWI <- complete(imputed_NDWI,3)
### make vectors
precip = as.vector(precip)
temp = as.vector(temp)
NDWI = as.vector(NDWI)
###time series
temp_ts = ts(temp$MEAN,start=2000, freq=12)
precip_ts = ts(precip$MEAN,start=2000, freq=12)
NDWI_ts = ts(NDWI$NDWI,start=2000, freq=1)
plot(temp_ts, main="Monthly Mean Temperature 2000-2021", ylab="Temperature
(°C)", xlab="Year")
plot(precip_ts, main="Monthly Mean Precipitation 2000-2021",
ylab="Precipitation (mm)", xlab="Year")
# autocorrelation function and partial autocorrelation function
acf(data_ts, mar=c(3.5,3,1.9,0))
pacf(data_ts, mar=c(3.5,3,1.9,0))
adf_precip <- adf.test(precip_ts, alternative = "stationary")
adf_precip
adf_temp <- adf.test(temp_ts, alternative = "stationary")
adf_temp
```

```
kpss.test(precip_ts)
kpss.test(temp_ts)
## forecast precipitation
plot(precip_ts)
acf(precip_ts) # shows slight non stationarity
pacf(precip_ts) # show slight stationarity
adf.test(precip_ts)
# autoarima fun does take care of stationarity
precip_model<- auto.arima(precip_ts, ic = "aic", trace = TRUE)
precip_model
# check stationarity
acf(ts(precip_model$residuals))
pacf(ts(precip_model$residuals))
### from ARIMA(0,0,1)(2,0,0)[12]
precip_forecast <- forecast(precip_model, level = c(95), h = 5*12)
plot(precip_forecast, main="Precipitation Forecast for Next 5 years (2022-
2026)", ylab="Precipitation (mm)", xlab="Year")
# Validate the forecast
# pvalue should be > 0.05
Box.test(precip_forecast$residuals, lag = 1, type = "Ljung-Box" )
## forecasting temp
plot(temp_ts)
acf(temp_ts) # shows slight non stationarity
pacf(temp_ts) # show slight stationarity
adf.test(temp_ts)
# autoarima fun does take care of stationarity
temp_model<- auto.arima(temp_ts, ic = "aic", trace = TRUE)
temp_model
# check stationarity
acf(ts(temp_model$residuals))
pacf(ts(temp_model$residuals))
temp_forecast <- forecast(temp_model, level = c(95), h = 5*12)
plot(temp_forecast, main="Temperature Forecast for Next 5 years (2022-2026)",
ylab="Temperature (°C)", xlab="Year")
# Validate the forecast
# pvalue should be > 0.05
Box.test(temp_forecast$residuals, lag = 3, type = "Ljung-Box" )
## forecasting NDWI
plot(NDWI_ts)
acf(NDWI_ts) # shows slight non stationarity
pacf(NDWI_ts)# show slight stationarity
adf.test(NDWI_ts)
# autoarima fun does take care of stationarity
ndwi_model<- auto.arima(NDWI_ts, ic = "aic", trace = TRUE)
ndwi_model
# check stationarity
acf(ts(ndwi_model$residuals))
pacf(ts(ndwi_model$residuals))
ndwi_forecast <- forecast(ndwi_model, level = c(95), h = 5)
plot(ndwi_forecast, main="Lake Area Forecast for Next 5 years (2022-2026)",
ylab="Area in Square Kilometers", xlab="Year")
# Validate the forecast
# pvalue should be > 0.05
Box.test(ndwi_forecast$residuals, lag = 10, type = "Ljung-Box" )
```

R codes to estimate and plot annual temperature, precipitaion, and lake area values

```
### Loading the data
Preci <- read.csv("Precipitation.csv")
temp <- read.csv("temp_2000_2022.csv")
NDWI <- read.csv("NDWI_yearly.csv")
### Function for annual aggregation
myfunction<-function(df){
  obs <- nrow(df)
  mean = rep(0,obs)
  k=0
  j=1
  for (i in 1:obs){
    if (i %% 12 == 0){
      k=i
      mean[i]<-mean(df[,2][j:k])
      j=k+1
    }
  }
  annual_mean = mean [ mean!=0]
  mean_ts = ts(as.numeric(annual_mean),start=2000, freq=1)
  plot(mean_ts, main = "main title", xlab = "Year", ylab = "dfitation",type =
"l")
  return(mean_ts)

}
### Monthly to Annual for Temp/Precipitation
myfunction(temp)
myfunction(Preci)
### plotting
temp_annual <- as.vector(myfunction(temp))
year <- c(2000, 2001, 2002, 2003, 2004, 2005,2006,2007,2008,2009, 2010, 2011,
          2012, 2013,
          2014, 2015, 2016, 2017, 2018, 2019, 2020,2021)
dt <- data.frame(year,temp_annual) #this can be converted back to ts by using
as.ts(dt)
### plotting
### loading libraries
library(ggplot2)
library(ggthemes)
library(plotly)
library(ggpmisc)
plot1 <- ggplot(dt) +
  aes(x = year, y = temp_annual) +
  geom_line(size = 1, colour = "#46338E") +
  labs(
    x = "Year",
    y = "Average annual temperature (°C)",
    title = "Annual Temperature Graph (2000-2021)"
  ) +
  theme_bw() ## you can change the theme using *theme_* and this will give u the
options
plot1 + geom_point()
ggplotly(plot1)
### plot for precipitation
prep_annual <- as.vector(myfunction(Preci))
dp <- data.frame(year, prep_annual)
```

```
## plot
plot2 <- ggplot(dp) +
  aes(x = year, y = prep_annual) +
  geom_line(size = 1, colour = "#46348E") +
  labs(
    x = "Year",
    y = "Average Annual Precipitation (mm)",
    title = "Annual Precipitation Graph (2000-2021)"
  ) +
  theme_bw() ## you can change the theme using *theme_* and this will give u the
options
plot2 +geom_point()
ggplotly(plot2) ## dynamic plot
### NDWI imputations
summary(NDWI)
imputed_NDWI <- mice(NDWI, m=5, maxit = 50, method = 'pmm', seed = 500)
summary(imputed_NDWI)
NDWI <- complete(imputed_NDWI,3)
### plotting
nd_plot <- ggplot(NDWI) +
  aes(x = year, y = NDWI) +
  geom_line(size = 1, colour = "dark blue") +
  labs(
    x = "Year",
    y = "Area of the lake in square kilometers",
    title = "Evolution of Lake Area from 2000 to 2021"
  ) +
  theme_bw()
nd_plot+geom_point()
ggplotly(nd_plot)
```

R codes to find correlation

```
final_df <- data.frame(prep_annual, temp_annual, NDWI)
final_df<-final_df[,-3]
cor_df <- cor(final_df,final_df)
library(corrplot)
library(ggcorrplot)
ggcorrplot(cor_df)
corrplot(cor_df, method = 'circle')
ggcorrplot(cor_df,ggtheme = theme_gray(),title = "dddd", outline.color =
"grey")
```