Assessment of Glacier retreat and Glacial Lake Development Trend in Western Nepal

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Key words: glacial lake, remote sensing, NDWI, GLOF, climate change

SUMMARY

Due to rising temperatures, the shrinkage of Himalayan glaciers has shown accelerating trend. This has resulted in the formation of new glacial lakes and the enlargement of existing ones. Glacier lakes are good storehouse of fresh water but they are also hazardous to living beings, as they can cause devastating glacial lake outburst floods (GLOFs) downstream. So, glacial lakes need to be mapped and monitored to asses both their potential hazard and their resource value. Remote sensing been proven to be the quickest and useful method for the mapping glacial lakes and monitoring lake dynamics in remote mountain region compared to the traditional in-situ observations.

In this study, we have used remote sensing data for analyzing the trend of expansion of Glacial Lake in Himalayas of Western Nepal. Our study was focused on a glacial lake called 'Diki Cho' of Myagdi district. Sentinel-2 images from 2016 to 2023, spanning eight-time points (2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023) and PALSAR DEM was used in this study for delineation of glacier lake boundary. Change in glacial lake area from 2016-2023 was used to determine the glacier retreat rate.

It was found that glacial lake area was increase from 2016 to 2023. The results show that glacial lake expansion can have some association with temperature and precipitation data. For explaining the cause for variation of glacial lake area insitu measurements has to be carried out and further factors has to be studied for properly explaining the change in area

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1. INTRODUCTION

Glacier lakes, which are formed by melting of glaciers, are a common phenomenon in mountain region. But the natural behaviour of glacial lakes has been changing in recent decades. Studies made by NASA in 2016 shows that global average temperature in 2016 was higher than the mean temperature of mid-20th century by 0.99 degrees. Due to rising temperatures, the shrinkage of Himalayan glaciers has shown accelerating trend. This has resulted in the formation of new glacial lakes and the enlargement of existing ones. Glacier lakes are good storehouse of fresh water but they are also hazardous to living beings, as they can cause devastating glacial lake outburst floods (GLOFs) downstream. So, glacial lakes need to be mapped and monitored to asses both their potential hazard and their resource value.

Studying glacier velocity is essential for understanding the behavior of glaciers and their response to climate change. By measuring glacier velocity, scientists can identify areas where glaciers are at risk of accelerating or retreating, which can inform conservation efforts and policies to mitigate the impact of climate change on the environment.

Satellite remote sensing can be used to measure glacier velocity by tracking the displacement of surface features such as crevasses and ice cliffs. It provides a broader view of the glacier and allows for the measurement of velocity at a larger scale. It has been proven to be the quickest, accurate and useful method for mapping glacial lakes and monitoring glacier velocity and dynamics in remote mountain region [22] compared to the traditional in-situ observations. Researches based on remote sensing have been done for assessment of glacial lake distribution, evolution and risk in various parts of Hindu Kush Himalayan range. DEM were used in those researches to classify lakes into different types on basis of nature – glacier fed lakes (moraine, supraglacial, proglacial) and non-glacier fed lakes (periglacial lake), altitude, extent and risk. Various attempts have also been made to analyse the relationship of glacial area/volume with climatic factors like- precipitation, temperature, evaporation, etc.

Background of the study

Glaciers and glacial lakes are distributed in several regions of the world, including the Arctic, the Antarctic, the Andes, the Alps, and the Himalayas. Nepal is home to numerous glaciers and glacial lakes, many of which are located in the Himalayan region. The study of glacier velocity and glacial lake expansion in Nepal is an important area of research, as these glaciers are highly vulnerable to the impacts of climate change, including changes in temperature and precipitation patterns. In recent years, researchers have been conducting studies on glacier velocity and glaical lake expansion in Nepal using a variety of methods. These studies involve measurements of the movement of glaciers over time, often using techniques such as remote sensing, ground-based surveys, and computer modeling.

This research uses remote sensing techniques for analysing the trend of expansion of a glacial lake in Himalayas of Western Nepal from 2016 to 2023 at one year interval, spanning eight time points (2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023) as well as the velocity study of the adjoining glacier. Sentinel 2 multispectral images from 2016 -2023 has been used for the determination of lake expansion and glacier retreat. There are many glaciers in the Himalayas that are untouched by researchers and academicians. North Annapurna glacier is also one of the virgin glaciers that haven't been studied. Preliminarily, this glacier is being observed through optical satellite image by the help of Google Earth. Though Google earth doesn't have a high temporal resolution, it can be judged easily that it may have active movement due to the slope, ambient temperatures, and bed surface. The glacial lake at the foot of the glacier has been also expanding gradually.

This research aims to provide insights into the behavior of glaciers and glacial lakes in Nepal, as well as the potential impacts of climate change on these systems. By better understanding the dynamics of glaciers and glacial lakes, the researchs findings can inform strategies for managing water resources and reducing the risks of GLOFs in Nepal.

2. LITERATURE REVIEW

Glacial Lake:

Glacial lakes are formed on glaciers surface which has low inclination and large surface lowering by melting of glacier ice (Sakai, 2012). Himalayan region contains many lakes- some isolated lakes found in the mountains and valleys far from the glaciers may not have a glacial origin. Only water bodies above 3500m (tree line) are considered to be originated by glacial activities and are called glacial lakes (Raj, Remya, & Kumar, 2013). Glacial lakes in the Himalayas of Asia, are mainly of following types-

1)Proglacial lakes - which are formed at the glacier front. Some proglacial lakes are ice-dammed, i.e. in contact with ice and some are moraine dammed. Moraine dammed lakes are usually formed by merging of supraglacial lakes over a long period of time.

(Sakai, 2012). They are blocked by the debris of glacier itself called moraine. These lakes store large quantity of water and are vulnerable to GLOF and almost all globally originated GLOFs are due to moraine dammed lakes (Raj, Remya, & Kumar, 2013).

2)Supraglacial lakes - which develop on surface of downstream portion of glacier by the merging of small supraglacial ponds. They tend to develop on long, flat, debris covered valley glaciers (Gardelle, Arnaud, & Berthier, 2011). Shifting, merging and draining are the characteristic features of supraglacial lakes. (Raj, Remya, & Kumar, 2013).

Gardelle J.et al in their study 'Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009' suggests that Supraglacial lakes are more dynamic and vary in time and space. Therefore, it is more meaningful and relevant to consider the temporal evolution of the total area of supra-glacial lakes located on a given glacier. The study also says that the expansion rate of supra-glacial lakes is always higher than the one of pro-glacial lakes which are not in contact with the glacier termini. On the other hand, pro-glacial lakes which are in contact with a glacier have a similar (or even higher) expansion rate than supra-glacial lakes. As supra-glacial lakes are more variable and less stable over time, their opportunity to expand over long time-scales is limited.

Monitoring of supraglacial lakes help for studying the glacier lakes dynamics. Aakiko Sakai, on her study ‘Glacial lake in Himalayas: A review on formation and expansion process’ explains that study of rapid changing supraglacial lakes should be done in order to predict fluctuations of debris-covered glaciers and formation of glacial lakes

Remote Sensing Techniques for Glacial Lake Mapping:

Remote sensing techniques in combination with Geographic Information Systems (GIS) can satisfy the needs for large area detection and monitoring of such phenomena. Photographs, optical satellite data and satellite radar data have been utilized in glaciological research over a long period. Usually multispectral imagery is used for detection of water bodies/glacial lakes. Such detection involves discriminating between water and other surface types by using spectral differences of the features. For eg. Water strongly absorbs in the near and middle-infrared wavelengths (0.8–2.5 μm) whereas vegetation strongly reflects these waves. Remotely sensed images are thus useful in monitoring glacial lakes. Frequent multi-temporal imaging will help for understanding the underlying expansion mechanisms of glacial lakes in detail (Ashraf, Rustam, Khan, Adnan, & Naz, 2016).

In past researches, glacial lakes are digitized from satellite imageries by adopting automated methods (eg. Supervised classification) or semi-automated methods (eg. NDWI). These methods are suitable to larger areas. But, cloud, snow, and mountain shadows in the Himalayan region can complicate the process. It is because the spectral signature of the shadow areas is very similar to the glacial lakes with low turbidity (Gardelle, Arnaud, & Berthier, 2011) (Zhang G. , Yao, Xie, Wang, & Yang, 2015). So, manual correction must be applied in these processes.

Manual interpretation technique is used by majority of the researches on glacial lake identification. Properties of features like – shape, texture, colour, size, etc. are considered during the process (Raj, Remya, & Kumar, 2013). For eg. In general, glacial lakes exhibit a fine smoother texture in contrast to the surrounding rough texture of hills. The tone of glacial lakes is light/dark blue or black in satellite images and white for snow/ice covered lakes. A lake shows a regular circular, semi-circular or elongated shape.

In research done by Zhang Guoqing et al. called ‘An inventory of glacial lakes in the Third Pole region and their changes in response to global warming’, the inventory of glacial lakes in third pole was prepared using both manual interpretation and semi- automated method(NDWI). Glacial lakes were carefully identified and manually digitized by a single expert by using

ArcGIS. The study says that- “although labour- intensive, this method guaranteed the consistent examination and high-quality control.”

Huggel et al (2002) also applied the NDWI equation in LANDSAT images to study the glacier hazards in Swiss Alps. However, they noticed that with this method, glacial lakes could be misclassified as shadow area. Therefore, it was concluded that a visual inspection is necessary to browse and detect unclassified lakes from semi-automatic method.

In study by Wang Shijin et al. for analysis of evolution of moraine dammed lake, Landsat satellite data (Multispectral Scanner (MSS)/Thematic Mapper (TM)/ Enhanced TM Plus (ETM+)/Operational Land Imager (OLI)) were used as the main source for extracting information about glaciers and glacial lakes. By doing comparisons of the different band combinations they found that the standard false color composite (FCC) images made from combining (NIR, Red, Green) bands

Similar approach was used by Gardelle at al. in 2001. They used DEM data also to distinguish Lake Surface from mountain shadows. In view of the gentle lake surface and steeper hill shade, lakes were assumed to be those areas only where the slope is less than 10%. DEM is used similarly in other researches also for distinguishing lakes, more correctly.

In the study of Yong Nie et al. on 2013 also it is said that “after the automatic extraction of glacial lake features, visual inspection and correction based upon the field experience on glacial lakes and Google Earth images must be employed to eliminate the misinterpretation of lakes due to shadow, lake ice formation, cloud and snow cover features.” It emphasizes that the accuracy assessment of the classification/ lake delineation process is difficult since the field measurements of most glacial lake outlines are impossible due to their steep edges in high and cold mountainous areas. However, visual inspection through google earth will help in confirming the locations and shapes of glacial lakes.

NDWI

NDWI is a multi-band method that combine different reflective bands for surface water extraction (Rokni, Ahmad, Selamat, & Hazini, 2014). NDWI value ranges from -1 to +1. Many formulaes for NDWI has been developed by many researches for delinating surface water features. McFeeters (1996) developed NDWI defined as:

NDWI= (Green band- NIR band) / (Green band+NIR band) Xu (2006) modified this formula as :

NDWI= (Green band- SWIR band) / (Green band+SWIR band) Various other formula are also exist for NDWI calculation (Rokni, Ahmad, Selamat, & Hazini, 2014).

It is important to note that, the threshold value for each formula vary depending upon the area and time used (Rokni, Ahmad, Selamat, & Hazini, 2014). Threshold value for a single formula also can vary on the basis of area, spatial resolution and other factors.

Ji. L. et al. in 2009 in their study ‘Analysis of Dynamic Thresholds for the Normalized Difference Water Index’, analysed those all formulas and concluded that NDWI calculated from

Xu (2006) technique has the most suitable threshold. They also recommended to use McFeeters formula for NDWI if Xu's formula doesn't work.

Nie et al in their study 'Glacial Lake Expansion in the Central Himalayas by Landsat Images, 1990-2010' also used the formula, NDWI= (Green-NIR) / (Green + NIR) for extraction of glacial lakes.

3. Study area and Datasets

Gandaki Province in Nepal is known for its stunning mountainous landscapes, which include several glaciers. Some major glaciers are Annapurna Glacier, Dhaulagiri Glacier, Thulagi Glacier and Tilicho Glacier. Our study area is North Annapurna Glacier which is located at an altitude ranging over 4050 meters to 6400 meter and covers an area of about 9 square kilometers and 8 km in length. It is one of the less explored glaciers in the Annapurna region and can be accessed via several trekking routes and the North Annapurna Base Camp trek.

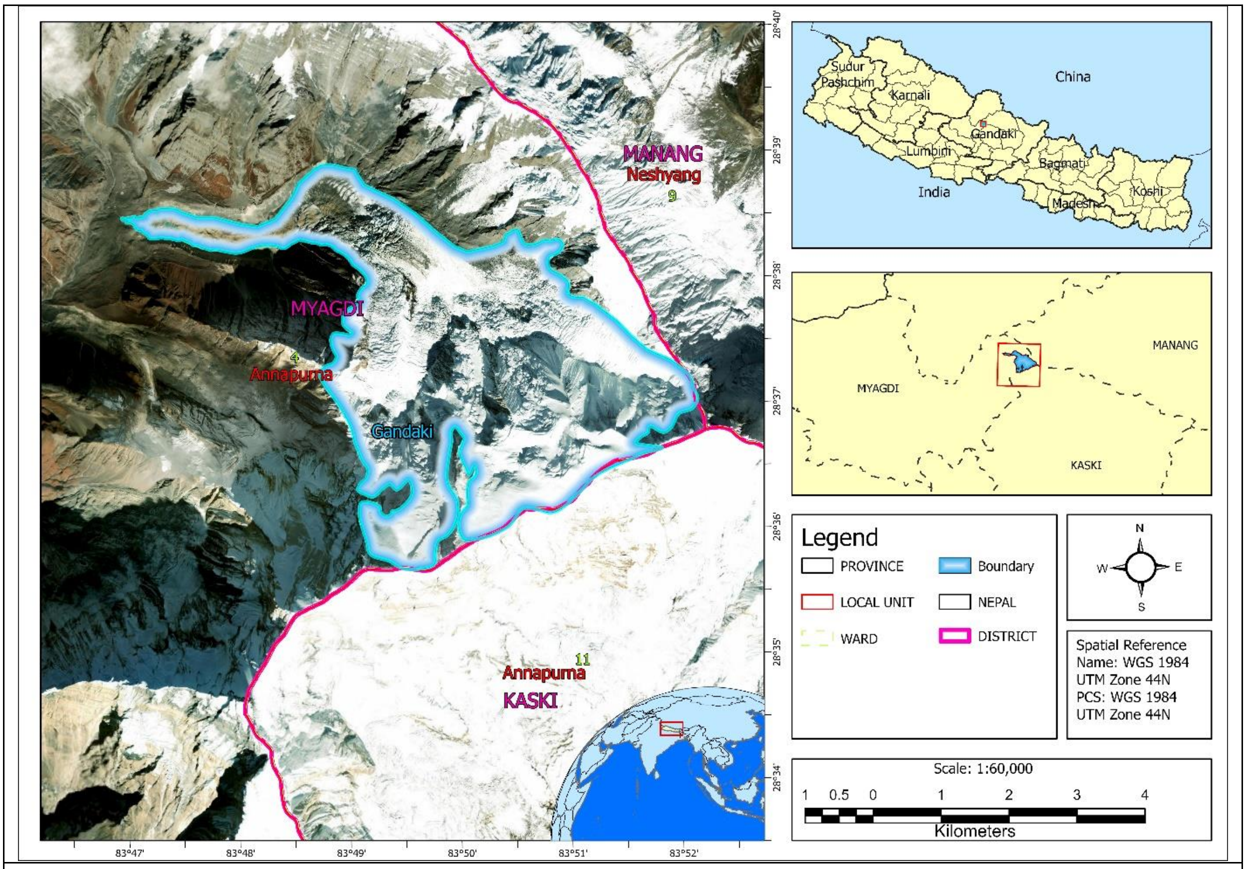

Figure 1: Study Area

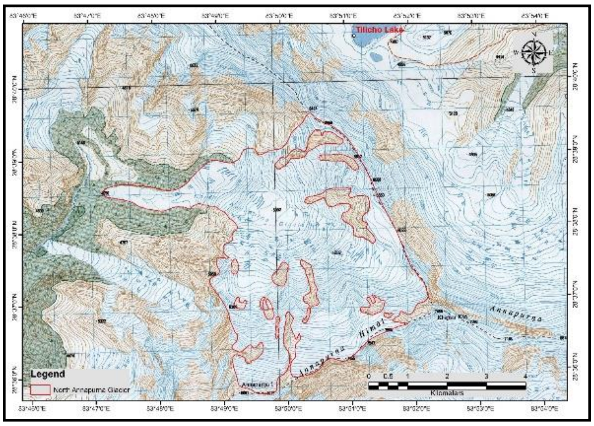

Figure 2: North Annapurna Glacier shown on Topographic map (2883 08 Tilicho) 1:50000 scale compiled from 1996 Aerial Photography

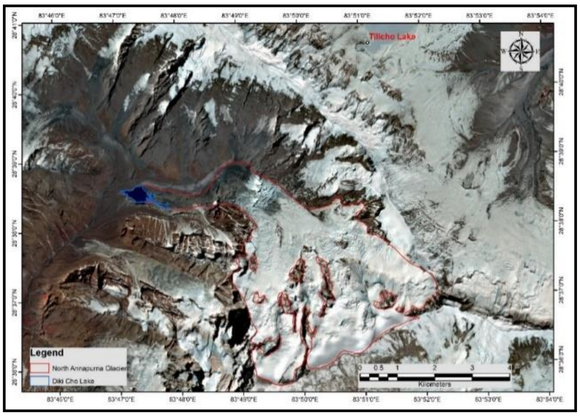

Figure 3: North Annapurna Glacier shown on false color composite (band 4,3,2) Sentinel 2 Multispectral Image of 2022 April

Sentinel images, DEM is used for the study. Images were used to delineate the lake boundary. Sentinel images from 2016 to 2023 were used in the study, Table . In total, we acquired eight images with no or low cloud cover. Spatial resolution of the images used is 10m. The images were already radiometrically and geometrically corrected and projected in UTM coordinate system. To avoid high cloud obscuration at other months and ensure minimal snow coverage the images from of April/May are used. PALSAR DEM was used to extract elevation and slope information of the lake surface. Slope information was used to differentiate lake surface from mountain shadows. GIS and Remote sensing software is used for vector as well as some raster operations like: Slope and aspect map preparation, Glacial lake boundary digitization. for creating vector(polygon) layer of glacial lake boundary, Meteorological data interpolation (by IDW method), etc. Remote sensing software was used in our project for NDWI calculation, layer stacking, sub-setting and visual interpretation.

Table 1 Sentinel images of different time periods used for the study

SN	Image Name	Date	Resolution
1	S2A_MSIL1C_20160804T045702_N0204_R119_T44RQS	2016-08-04	10m
2	S2A_MSIL1C_20170521T045701_N0205_R119_T44RQS	2017-05-21	10m
3	S2B_MSIL1C_20180521T045659_N0206_R119_T44RQS	2018-05-21	10m
4	S2A_MSIL1C_20190521T045701_N0207_R119_T44RQS	2019-05-21	10m
5	S2A_MSIL1C_20200624T045701_N0209_R119_T44RQS	2020-06-24	10m
6	S2A_MSIL1C_20210927T045701_N0301_R119_T44RQS	2024-09-27	10m
7	S2A_MSIL1C_20220415T045701_N0400_R119_T44RQS	2022-04-15	10m
8	S2A_MSIL1C_20230530T045701_N0509_R119_T44RQS	2023-05-30	10m

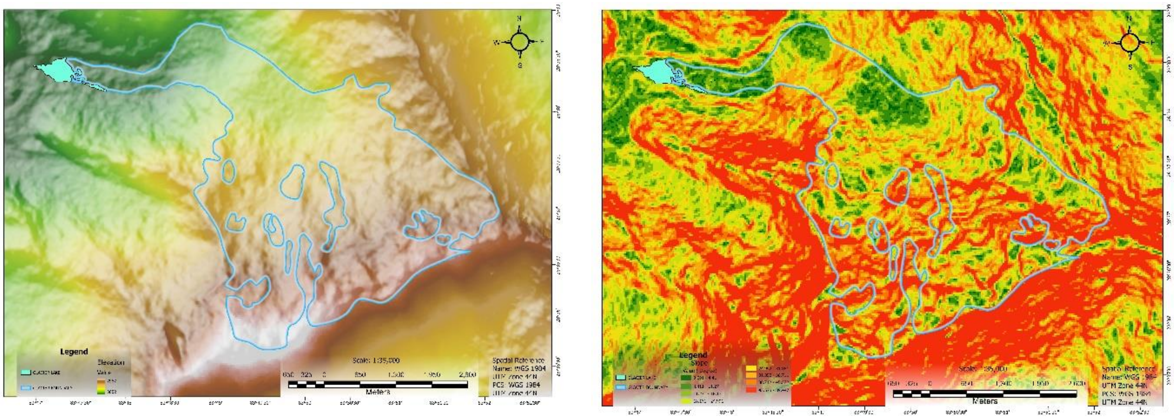

Figure 4 DEM (left) and Slope map (right) of study area

4. METHODOLOGY

Figure 5 shows the methodology followed for delineation of glacial lake boundary.

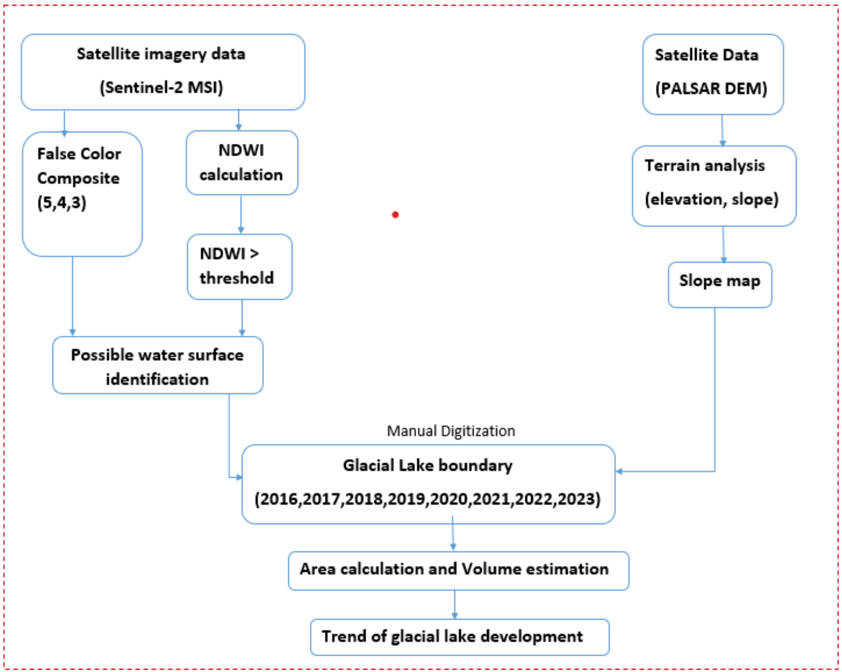

Figure 5 Flowchart of Glacial Lake Boundary Delineation

2.1.1 <u>Glacial lake boundary identification</u>

Initially, a preliminary study was done to identify the type of lake under study. We used high-resolution Google Earth images as auxiliary data for the purpose. Then sentinel images were downloaded. Each image acquired was then used for the delineation of glacial lake boundary. For that at first a subset of each image was created so that only necessary area could be seen in the view. For identifying glacial lake semi-automated method was used. We didn't used the classification technique (automatic process) because in automatic methods spectral signature algorithm is used. The minimum size of lakes detected by this method depends upon the spatial resolution of image; lakes are identified only if it composed of at least one pure pixel [11]. The resolution used in our study is 10m and some ponds around the lake to be studied is of very small size. Lake identification using automatic classification thus, would have been harder and erroneous. We used NDWI technique for extraction of glacial lake surface identification.

Appropriate NDWI thresholds were manually chosen for different images to obtain binary images from which we could initially distinguish water and non-water information. The threshold values used for NDWI were 0.28 for 2016-2021 and 0.12 for 2022 and 2023. Various articles suggested that manual interpretation technique is most efficient and accurate method for delineation of glacial lakes [23, 36, 20]. Therefore, in our study also we used manual interpretation even though it was labour intensive and time consuming than other techniques. Manual examination and modification was used to outline glacial lakes based on the produced binary images and False colour composite images. The boundary was represented in vector format. A slope map was prepared using PALSAR DEM. On the basis of slope map and elevation information any other misidentified features (e.g. mountain shadows) were then distinguished easily and the boundary was then edited manually. Hence, final boundary of lakes for each time point was obtained. Area of lake for a year was the sum of area of all polygons in the boundary vector files prepared in GIS software.

2.1.2 Validation

The high-resolution satellite image from google earth that was used for validation purpose is shown in figure 6. The image is of 2nd November 2017. The figure also shows glacial Lake Boundary obtained from the image by manual digitization process.

The area of glacial lake from google earth image was found to be 116800 m^2 (11.6 ha) and that from Sentinel image on date 21st May 2017 was found to be 111650 m^2 and on May 2018 was found to be 117270 m^2. Date of high resolution satellite image from google earth is in between the sentinel images that we have used for the NDWI extraction.

Figure 6. Validation of Glacial lake boundary using google earth

5. RESULTS AND ANALYSIS

Glacial lake boundary identification

Sentinel-2 images in false color composite and binary images of different years that were created and used for the glacial lake boundary delineation are shown below in figure. Similarly, Final layer of glacial lake boundary delineated for each year is also shown in figure.

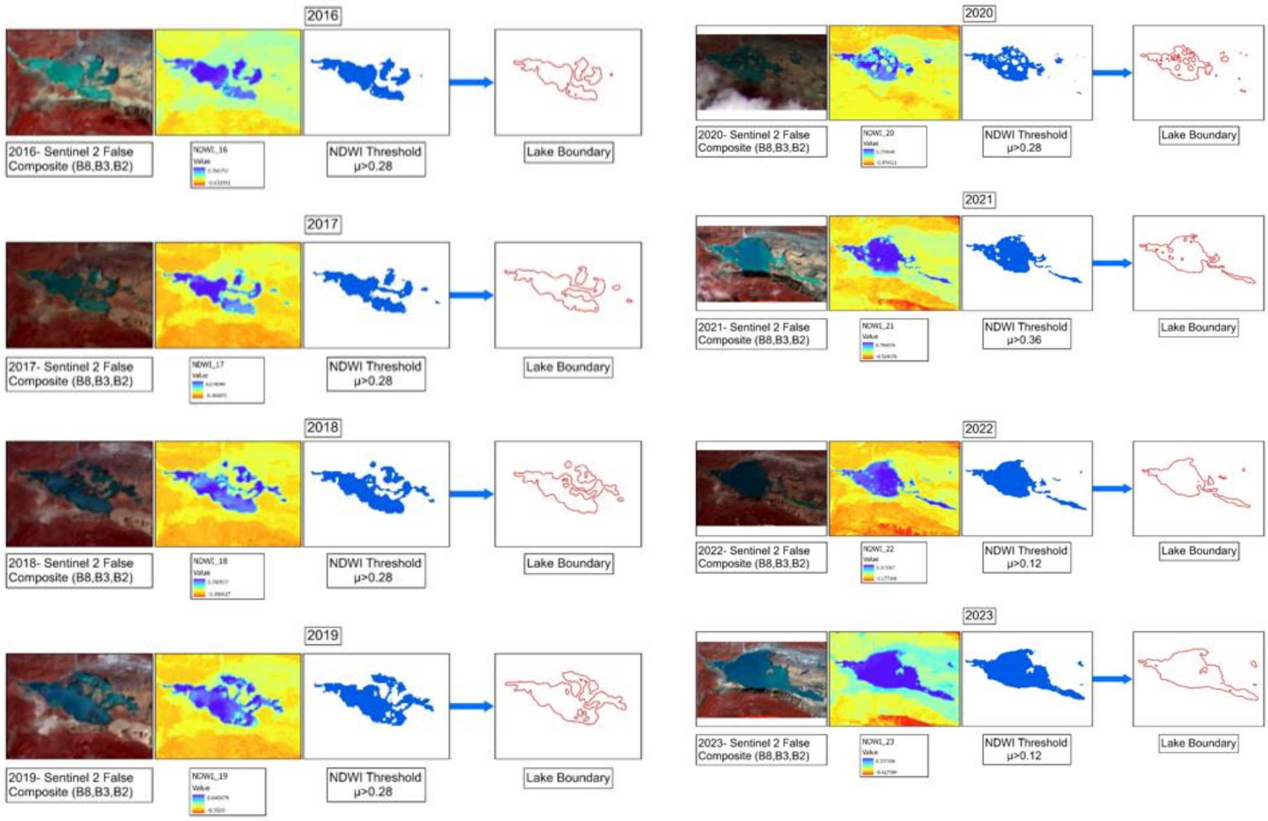

Figure 7 False color images, NDWI and glacial lake boundary identified in the overall study period

Trend of Area change of glacial lake

The area of glacial lake in year 2016 to 2023 are given in table in Figure 8.

As shown from the figure and table, through Sentinel-2 imagery spanning 2016 to 2023 years we can see that, the glacial lake has exhibited a consistent and notable increase in area, expanding from 10.027 hectares in 2016 to 28.781 hectares by 2023. This represents an average annual growth rate of approximately 2.64 hectares, roughly equivalent to four football fields per year. The steady increase in lake size over this period underscores a significant and continuous expansion trend, highlighting a dramatic threefold growth in just seven years. This consistent expansion contrasts with previous fluctuations observed in earlier data and suggests a clear and ongoing impact on the lake’s size, likely driven by environmental changes.

Year	Area (Ha)
2016	10.027
2017	11.165
2018	11.727
2019	13.260
2020	15.775
2021	19.714
2022	21.827
2023	28.781
2016	10.027
2017	11.165

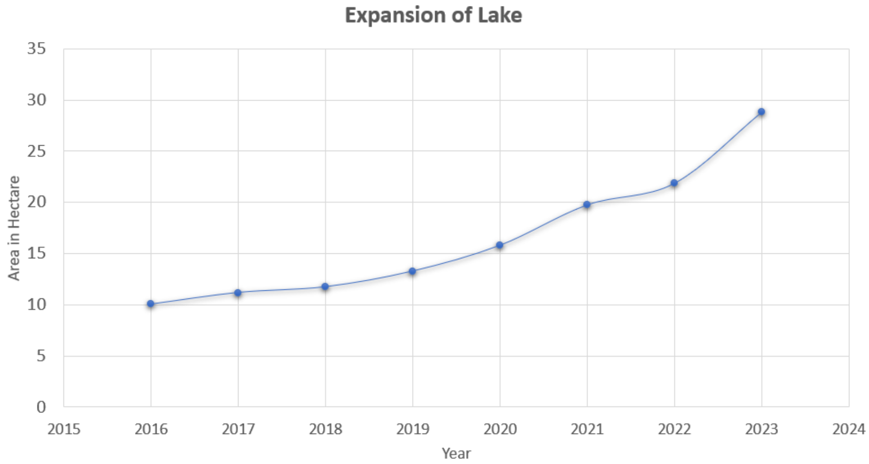

Figure 8 Lake Area Expansion rate from 2016-202

Glacier Retreat

Taking the Sentinel-2 images from 2016-2023, as shown in the figure below we can see that glacier has been retreating every year. The total retreat of glacier is almost 350m in seven years. The retreat is calculated by averaging the movement of glacier in different years, whose position is clearly visible in sentinel image of 10m resolution.

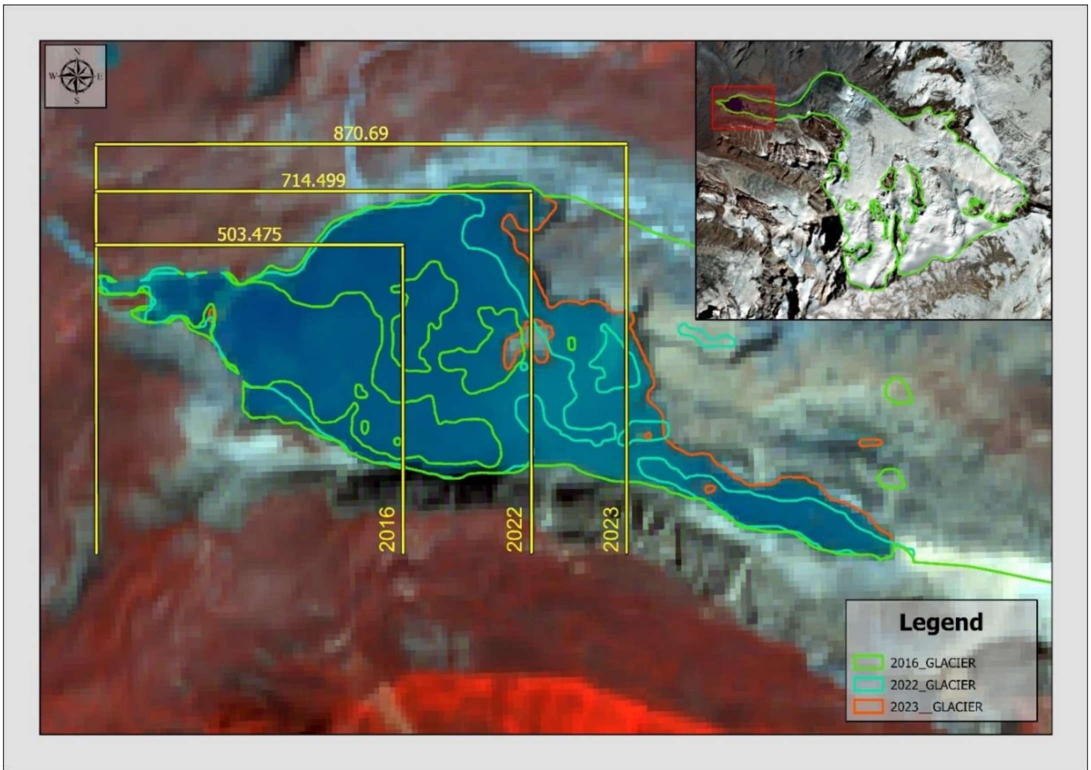

Figure 9 Glacier Retreat

6. CONCLUSION AND RECOMMENDATION

The expansion of Glacier Lakes, as evidenced by the increase from 10.027 hectares in 2016 to 28.781 hectares in 2023, highlights a concerning trend in the context of glacial retreat and climate change. The rate of expansion, calculated at 16% annually, signifies a rapid and significant growth in the size of these lakes over a relatively short timeframe. Glacier Lakes form as glaciers retreat and melt, creating depressions in the landscape that fill with water. The accelerated melting of glaciers due to global warming has led to the formation and growth of these lakes. However, while the creation of Glacier Lakes is a natural process, the rapid expansion observed in this case raises several concerns. One of the primary concerns associated with the rapid expansion of Glacier Lakes is the increased risk of glacial lake outburst floods (GLOFs). GLOFs occur when the natural dam containing a glacier lake fails, releasing large volumes of water downstream. The increased size of Glacier Lakes means that the potential volume of water released during a GLOF event could be significantly higher, posing a greater risk to downstream communities, infrastructure, and ecosystems.

Furthermore, the expansion of Glacier Lakes can have broader environmental impacts. Changes in the size and location of these lakes can affect local ecosystems, including freshwater habitats and biodiversity. The influx of glacial meltwater into these lakes can also alter water quality and nutrient levels, further impacting the surrounding environment. The rapid expansion of Glacier Lakes underscores the importance of monitoring and managing these water bodies. Implementing early warning systems for GLOFs, conducting regular assessments of glacier lake dynamics, and developing sustainable water management strategies are essential steps in mitigating the risks associated with Glacier Lake expansion. Additionally, efforts to reduce greenhouse gas emissions and mitigate climate change are crucial in addressing the underlying factors driving glacial retreat and the formation of Glacier Lakes.

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