Hazard Modeling Using Sentinel Data for Risk Assessment and Management of Tsho Rolpa Glacier, Nepal

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Abstract: The accelerated melting of the Himalayan glaciers due to climate change has caused significant issues including Glacier Lake Outburst Floods (GLOFs), to the downstream communities and the infrastructure. This study focuses on the Tsho Rolpa Glacier in Nepal, utilizing Sentinel-1 Synthetic Aperture Radar (SAR) data to measure ice velocity and analyze the impacts of glacier melting on lake dynamics. A GLOF occurs when the volume and surface area of glacier lake water exceeds the capacity of the moraine dam. For hazard modeling, SAGA GIS 8.3.0 was used for the terrain modeling and hydrological analysis, which highlighted the flood-prone areas. ArcGIS 10.5 facilitated the integration of Sentinel-2 imagery with local topographic data to predict the flood scenarios. The integration of these tools enhanced the accuracy of flood paths predictions and provided much needed valuable insights into the impacts on the local infrastructure. The results highlights the growing risks associated with the climate-induced GLOFs, demonstrating the importance on real-time glacier monitoring and predictive hazard modeling. This study tries to be a helpful tool for decision-support framework for mitigating the socio-economic impacts of GLOFs in vulnerable regions such as the Himalayas.

1 INTRODUCTION

Glaciers are a very important component of the hydrological cycle of the earth system i.e. glaciers play a significant role as a fresh water reservoir in maintaining global sea level and regional water availability. Himalayan Glaciers acts as a freshwater reservoir to rivers downstream, which acts as a lifeline for millions of people living downstream. However, in the past few decade due to the ongoing impacts of the climate change, it has accelerated the rate at which the glaciers are melting, increasing the risk of Glacier Lake Outburst Flood (GLOF), landslides and other environmental disasters that threatens the local infrastructure, ecosystems and the daily livelihoods of the people living in those GLOFs prone areas.

In particular, the threat of GLOFs has raised a significant concern to the local demographic, as these events cause catastrophic flooding downstream when the moraine dam holding back glacier lake water fails due to excessive increase in the glacier lake due to melting of the glacier lake. The accurate and timely monitoring of glaciers and the hazards associated to it would play a critical factor for the risk assessment and disaster management in the event of GLOF incident. Thanks to the advancement in satellite technology, monitoring of glacier dynamics has become more precise and accessible. The Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 optical data, both provided by the European Space Agency (ESA), have proven to be indispensable tools for glacier monitoring and the development of hazard models. While Sentinel-1's radar capabilities enables the year-round monitoring (even in challenging weather conditions due to cloud penetrating radar capabilities) and are ideal for measuring ice velocity which is a key factor in understanding glacier dynamics (Copernicus Climate Sentinel-1, n.d.) but Sentinel-2's high-resolution optical imagery is particularly useful for assessing surface changes and developing detailed hazard models and predict the flood-path and the subsequent impacts of potential GLOFs.

Our approach to this study, was to generate awareness towards the potential disaster than could be caused by the GLOFs incidents in high impact areas such as Tsho Rolpa Glacial Lake in the Rolwaling Valley (Rounce, Watson, & McKinney, 2017). This

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study utilized the Sentinel-1 SAR data to measure the ice velocity of the Tsho Rolpa Glacier from 2020 to 2023, enabling the analysis of glacier dynamics. In addition to this, Sentinel-2 imagery was used to create an extensive hazard model. This study serves as a small yet significant step toward mitigating the impacts.

2 RELATED WORKS

2.1 Glacier Hazard Monitoring and Risk Assessment

Glacier hazard modeling is very important for the prediction of associated flood path in case of GLOF incident. Various studies have already been published on this topic, especially the effects of climate change in glaciers (Bolch et al., 2012).

Studied glacier retreat and thinning pattern in Himalayan glaciers. This study suggests the increase in potential risk of GLOFs as ice volume declines.

2.2 Sentinel-1 SAR Applications in Glacier Monitoring

Sentinel-1 SAR data provides all-weather year-round glacier monitoring, which acts as a great tool to monitor areas such as Himalayan region where cloud coverage is common. Several glaciers in previous studies such as (Rankl, Kienholz, & Braun, 2014) have utilized Sentinel- 1 data to monitor changes in Ice velocity and surface deformations.

2.3 Sentinel-2 Imagery Data for Hazard Modeling

Since Sentinel-2 provides a higher spatial resolution of 10 meters for visible and Near Infrared band (NIR), 20 meters for red-edge and SWIR band and 60 meters for atmospheric correction bound as compared to 5-20 meters of Sentinel-1 SAR (ChatGPT, Personal Communication, 2024). Hence, Sentinel-2 can be an important tool for monitoring small changes in glacier flood path making it more effective in Hazard modeling as compared to Sentinel-1 SAR (Paul et al., 2016).

2.4 Glacier Lake Area and Volume Change

The previous studies by (Maskey et al., 2013) provides insights on the significant expansion of Tsho Rolpa Glacier Lake, driven by impacts of climate change and accelerated melting of its parent glacier. The lake’s surface area, recorded at merely 0.23 km² in 1957, increased substantially to 1.65 km² by 1997, reflecting a dramatic growth of approximately 617% over four decades. This expansion of Tsho Rolpa Glacial Lake has heightened the threat of GLOFs.

3 METHODOLOGY

3.1 Study Area

Tsho Rolpa glacier, located in Rolwaling Valley of Himalayan region of Nepal is prone to GLOF incidents because of its large glacier lake that is actually growing because of melting glaciers (Damen, 1992) This study analyzes the spatial and temporal aspects of glaciers and glacier lakes.

3.2 Data Acquisition

Our study utilizes Sentinel-1 and Sentinel-2 data obtained from the open-access Copernicus Open

Figure 1: Google. (2021). [Map showing Tsho Rolpa Glacier] [Map]. Google Earth Pro (Version 7.3). Imagery date: March 25, 2021. Retrieved January 20, 2025, from https://earth.google.com/.

Access hub (Copernicus.eu). Since Sentinel-1 data were used for different purpose like monitoring natural disasters, environmental monitoring and different climatic analysis

(Copernicus Sentinel-1, n.d.). In our study, we have use Sentinel-1 as well as Sentinel-2 data for analyzing Ice velocity and Hazard modeling respectively provided by the European Space Agency (ESA). The datasets were taken in following ways:-

3.2.1 Sentinel-1 Data

Sentinel-1 uses a spatial resolution of 5m in range with 20m in azimuth (Du et al., 2021). The Twin polar-orbiting satellites i.e Sentinel-1A and Sentinel-1B are equipped with supply geographical data for environmental and security warranting for the expansion of the remote sensing, world economy and business which means the satellites function both during the day and at night and perform a synthetic aperture with radar imaging i.e. it process radar signal to create high-resolution image of Earth which is obtained by simulating a large synthetic aperture using the motion of the radar platform. We can obtain the imagery using Sentinel-1 bands in any weather. An active phased array antenna called C-SAR was developed to offer faster azimuth and elevation scanning which allows to cover bigger areas of incidence angle to support the SAR operation (Yulianto et al., 2021). In this research, High-resolution SAR images from the Sentinel-1 satellites were downloaded in Ground Range Detected High resolution (GRDH; Level-1).

Sentinel-1 is a sun- synchronous, near-polar orbit satellite with 175 orbits around the earth and 12 days repeat cycle. Both Sentinel-1A and Sentinal-1B share the same orbit plane with a 180- orbital phasing difference. The orbit altitude of Sentinel-1 Satellite is 693 km (Yulianto et al., 2021, September).

We have acquired the imageries in Interferometric Wide Swath (IW) Mode, which helps to monitor large area, and in Vertical-Horizontal (VH) Polarization i.e the signal is transmitted vertically and received horizontally. Also, all the images were downloaded in GRD.

3.2.2 Sentinel-2 Optical Imagery Data

Sentinel-2 provides a multispectral imaging that allows for high-resolution imagery data, useful for analyzing surface characteristics, glacier extent etc. For this study, Sentinel-2 imagery data was assessed from Copernicus Open Access hub/Copernicus browser, which is a platform for Sentinel data. A processing level of 2A was used, which provides atmospherically correct surface reflectance (Copernicus Open Access Hub, n.d.)

3.3 Methods of Hazard Modeling

Hazard Modeling is crucial for predicting the potential flood paths in case of GLOF incidents. Knowing the potential flood path/flow paths would prepare local governmental bodies and demography to be more prepared in such incidents. Along with that it is also crucial for the planning infrastructural development around such GLOF prone areas.

For hazard modeling Sentinel-2 imagery data was utilized which was taken from the Copernicus hub and then pre-processed using SAGA GIS 8.3.0 software's "Filled sink (Wang & Liu)" pre-processing tool to correct the elevation layer in Digital Elevation Model (DEM) map and from DEM map, channel network vector was created using the Hydrology tool in Terrain analysis of SAGA GIS 8.3.0. Then the original DEM map and channel network was imported into ARCGIS 10.5 and merged into a single layer. The channel of order greater than 0.1 in terms of width and length was specified and connected creating the hazard modeling layer in 2D. Now the map was converted into a KML file and 3D visualization was done in Google earth. Both the DEM model and TIN visualization layers in Google Earth Pro are taken as final results as 2D and 3D hazard models. Both DEM layer and TIN layer were used as results as they both could high light the aspect of elevation to present the actual terrain features.

3.4 Ice Velocity

Glacier ice velocity plays a crucial role in understanding

Table 1: Parameter of images.

Acquisition date	Acquisition date	Acquisition date	Acquisition date
2020-01-04	2021-01-10	2022-01-05	2023-01-12
2020-02-09	2021-02-15	2022-02-10	2023-02-17

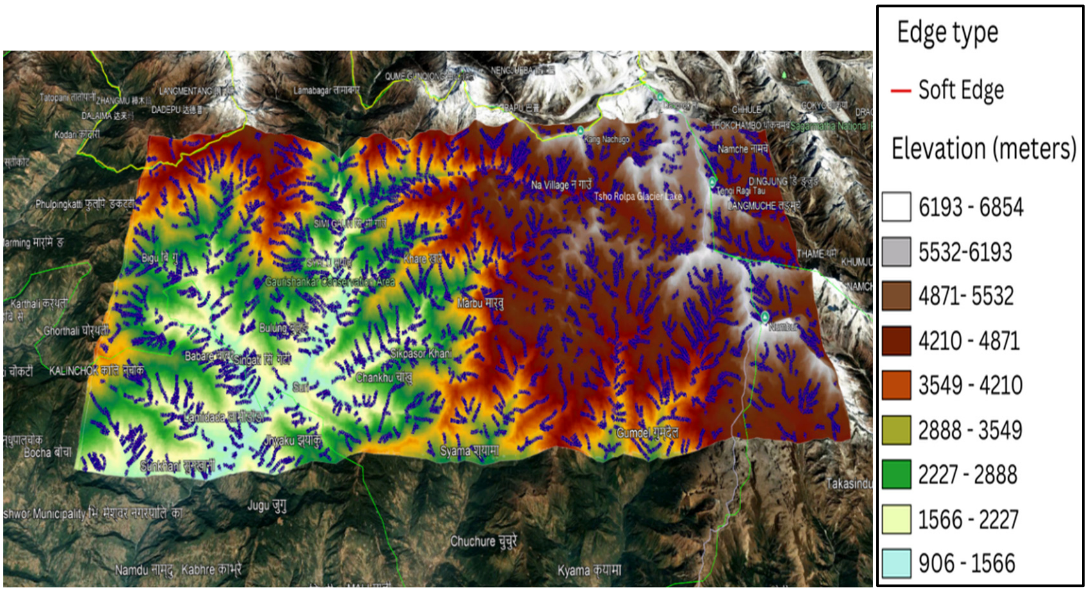

Figure 2: 2D DEM layer Hazard Model.

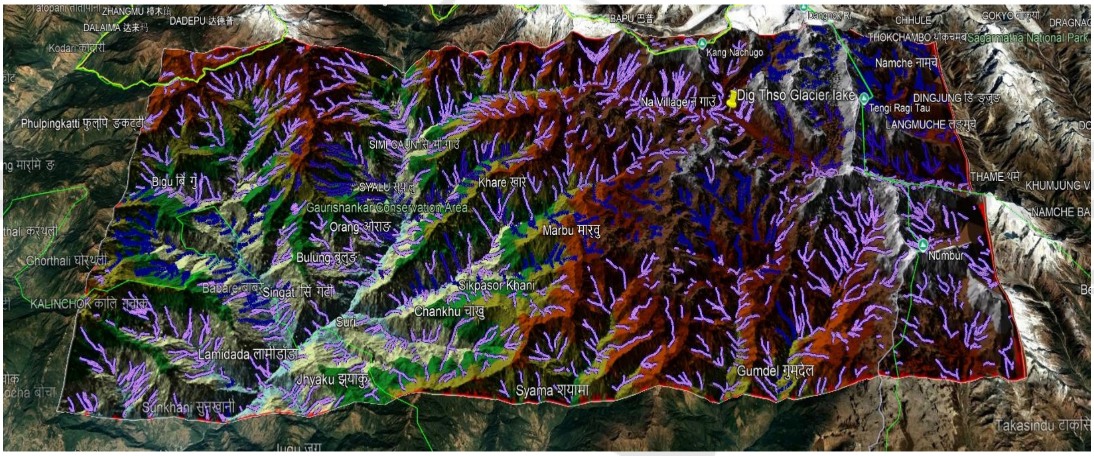

Figure 3: 3D Hazard Model.

the overall glacier dynamics influenced due to climate change. The velocity of glaciers caused by different factors including geographical location, ice thickness, and environmental conditions (Hyde, 2024). In regions like Himalayans the glacier dynamics affects the availability of fresh drinking water highlighting socio-economic effect to the country and measurement of glacier's ice velocity are essential for modeling future glacier changes and potential natural calamities like flood and landslide (Millan et al., 2023). Ice Velocity of glaciers can be measured using different techniques but in this study we have used optical and SAR imageries to analyze the glacier ice velocity since high resolution optical imageries provides high accurate measurement (Gu et al., 2024). In this research study, we have use offset tracking analysis calculated by Sentinel Application Platform (SNAP) to analyze image intensity information for identifying and matching points between image (Gu et al., 2024). In offset tracking random points are generated and compared between two points which allows to analyze glacier movement with high accuracy and calculated by

$$\text{Offset} = \sqrt{(A^2 + D^2)} \qquad (1)$$

Where, Offset is the offset of the drifted glacier area, A is the average value of offset drifted glacier area, D is the standard deviation of the drifted glacier area (Gu et al., 2024).

We have used the following technique for the analysis of the Ice velocity:

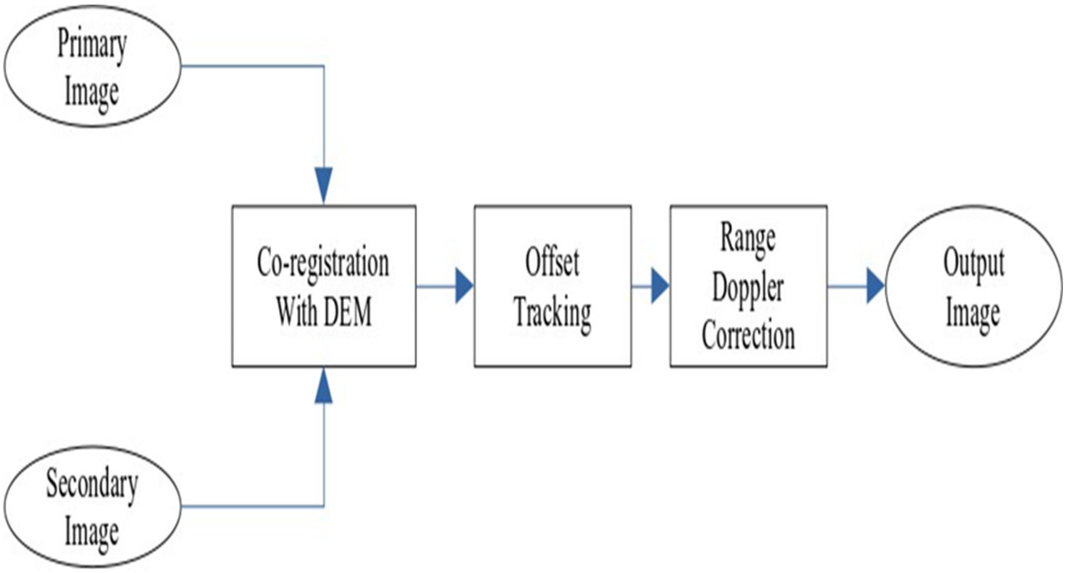

Figure 5: Flowchart of Ice Velocity Processing.

4 RESULTS AND DISCUSSION

4.1 Results from Hazard Modeling

The Hazard Modeling of Tsho Rolpa glacier lake reveals detailed potential flood paths and hazard zones in case of a GLOFs event. This model shows flood paths (purple and blue lines as in figure 2 and figure 3) where water could flow as a direct result of an outburst event of the Tsho Rolpa glacier lake. From this model, it was clearly shown that rural communities such as Na Village (as seen in map) are at a high risk which serves as a critical tool for identifying vulnerable areas and guiding mitigation strategies.

4.2 Results from Ice Velocity Measurement

From the figure 5(a), (b), (c), (d) it was found that the ice velocity in the area in the year 2020 January-February was a maximum of 0.129m/day and minimum of 0.016m/day indicated by Red color and White color respectively similarly in the year 2021 January-February there was a slightly fluctuation in the velocity with a maximum velocity of 0.056m/day and minimum of 0.002m/day indicated by Red color and White color respectively. In the year 2022, we can observe that the ice velocity became twice as of 2021 with a maximum velocity of 0.106m/day and minimum of 0.006m/day indicated by the red and white color. In the year 2023, we observed a decrease in the velocity of ice with maximum of 0.058m/day and minimum of 0.002m/day.

5 DISCUSSION

5.1 Interpretation of Hazard Modeling Results

The Hazard Modeling of Tsho Rolpa glacial lake highlights the GOLF risks of the region. The flood paths visualized in the Figure 2 and Figure 3 shows those rural communities such as Na Village which are in a direct hazard zone. The visualized flood paths demonstrate the utility of integrating remote sensing data with the hazard assessment tools. The accuracy of the flood paths can be further refined which was discussed in the future works.

5.2 Interpretation of Ice Velocity of Measurement

From the above result, we can conclude that the Ice velocity in the area has fluctuation over time and can lead to moraine dam collapse due to continuous flow of water in the Tsho Rolpa lake and with fluctuation in ice velocity the possibility of GLOF can be occurred anytime. With Global temperature rising (Copernicus Climate Change Service, n.d.), the possibility of glacier melting with numerous amount of water flowing into the lake can lead to a possible GLOF

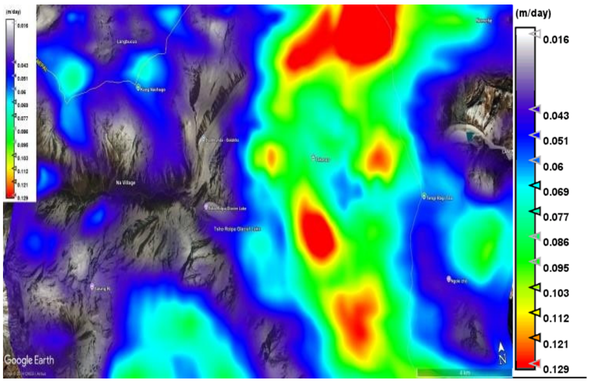

Figure 5(a): Ice velocity of 2020.

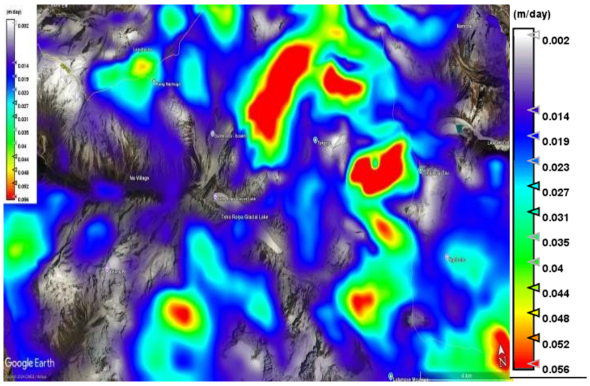

Figure 5(b): Ice velocity of 2021.

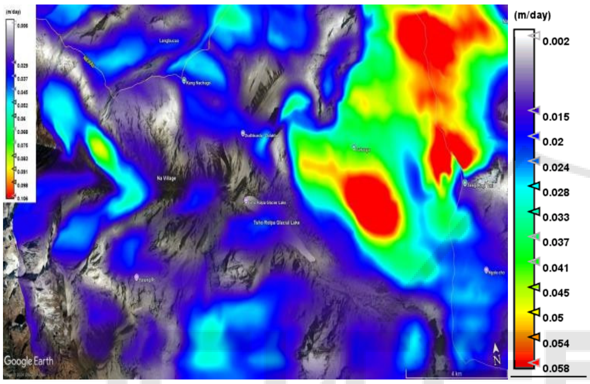

Figure 5(c): Ice velocity of 2022.

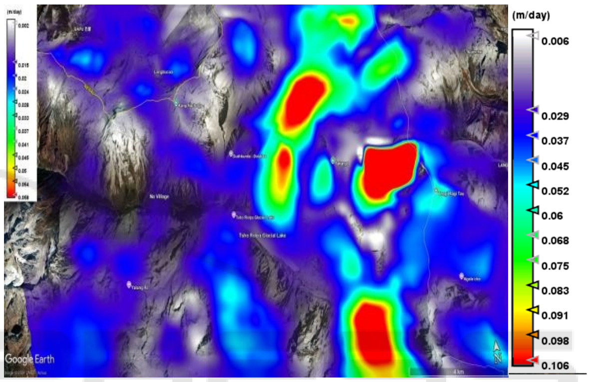

Figure 5(d): Ice velocity if 2023.

condition in the area which can badly affect the country's economic as well as long-term effect can be seen.

6 CONCLUSION AND FUTURE WORKS

GLOFs are natural disasters that will happen eventually. The only viable method of risk reduction are the early warning systems. The study of glacier ice velocity provides us an insight about the dynamics of glaciers, sea-level rise and response to climate change. With the help of ice velocity integrated with hydrology, we can design an early warning system. The hazard modeling provides crucial insights on the nature of flood paths and high-risk zones, where the early warning can effectively reduce the risk on life and properties. The rapid expansion of glacial lake and the resulting potential flood path emphasizes the urgent need for intervention for the mitigation of GLOFs.

One of the major challenges many countries that has direct access to the ocean or sea are facing is continuous sea-level rise and one of the major cause for sea level rise is melting of glaciers, which add tons and tons of water continuously in the ocean resulting in rise of sea level. Future work should focus on refining the accuracy of flood paths generated by hazard models by incorporating real-time data. Further works can be done analyzing different parameters like ice thickness, surface displacement using satellite data as well high precision GPS stations and InSAR to get high accuracy results. Similarly more sophisticated modes can be developed that can simulate ice velocity in different weather and climate variables taking in note about the surface as well as internal glacier melting and deformation. The current hazard model relies on the geospatial data and the assumption of the lake stability which might not full capture the dynamic nature of GLOF events so direct field-based data collections and validation of observations along with advanced hydrodynamic modeling could address these gaps and provide a more refined hazard model.

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