# REMOTE SENSING FOR NATURAL HAZARD STUDIES

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Lec 25 b: Introduction to Glacial Lake Outburst Floods Part B

Hello everyone, welcome back to Lecture 25. So, we were discussing the glacial lake outburst flood. So, this is part 2 of this lecture. In the previous part, we completed the glacial lakes, how they form, what the different types of glacial lakes are, and what the different types of moraine-dammed lakes we have. So, now we will continue this discussion, and we will see the details of how we can map the glacial lakes. So, we have satellite imagery that is one of the sources; then we can also use a digital elevation model. Different indices can be used, classification techniques can be used, and microwave remote sensing data can be used because optical data has some limitations at high altitudes where cloud cover is more consistent. Then multi-temporal change detection can be used to identify this or to monitor these glacial lakes. Field investigation is the key to validating all these results. Then machine learning and deep learning approaches are now very popular and can be used.

And the GIS is basically where we can integrate all the datasets together and analyze the presence of glacial lakes or their increase in size. So, when we talk about glacial lake mapping, this is a very generic flowchart that explains the generic methodology. So, here when we have satellite images, they can be optical or microwave, and we have different types of methods; particularly for optical, we have different indices. Then, for microwave, the backscattering thresholding method can be used to identify the glacial lake. Here, manual digitization is also an option, and we can identify the glacial lake; this can also be used to validate or correct some of the lake's features that are coming from optical and microwave processing.
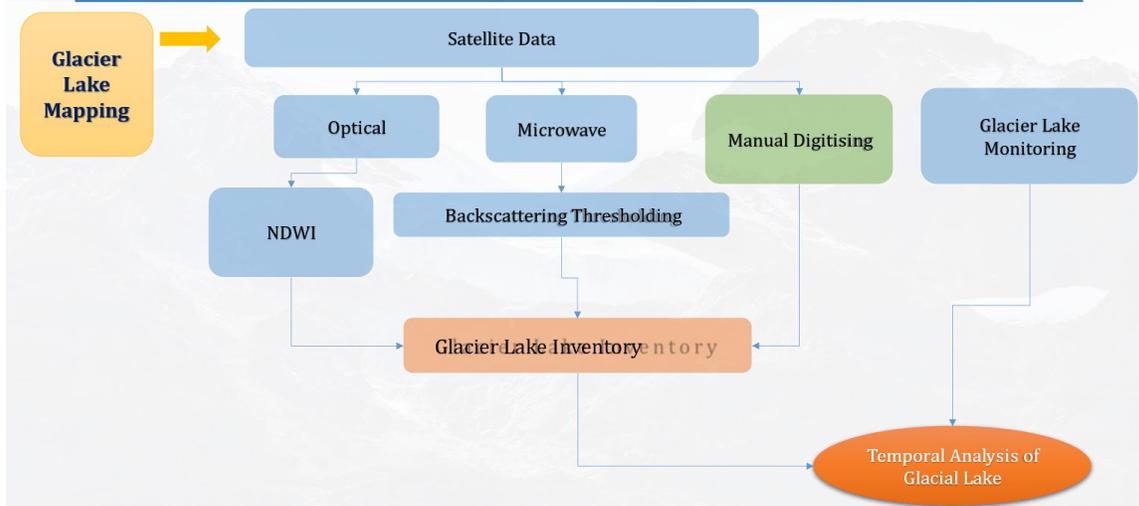
These are used for glacial lake monitoring, and temporal analysis of the glacial lake can be done. Mapping and monitoring of glacial lakes in India are essential. The CWC Central Water Commission, in collaboration with the National Remote Sensing Centre of ISRO, is responsible for the routine mapping and monitoring of the glacial lakes; thus, you can see that the different glacial lakes have been continuously monitored, and the satellite-derived long-term change analysis provides valuable insight for understanding glacial lake dynamics and their potential for GLOF. So, here you can see 1989, 1996, 2001, and how it is changing over time. Shisper Glacial Lake Outburst Flood in Karakoram (2022). So, here we have seen a major disaster that happened in 2022. The Karakoram Himalayas are vulnerable because of the changing climatic conditions, which are causing catastrophic floods in the surrounding areas, particularly in the downstream. The increasing natural and anthropogenic activities, especially in the Indo-Gangetic plains at the southern flank of the towering mountains, are a concern. So, we have analyzed the Shisper Lake breach that occurred on 7th May 2022 in detail using satellite remote sensing datasets. So, here you can see different maps that are from that publication. How these lakes have been formed over time and how they breached in 2022.

So, the details are available in this paper. Now, the Imja Tsho Lake. So, here we have one lake from Nepal. So, this lake is situated in the Mount Everest region at an altitude of 5,010 MSL. Lake is fed by the glaciers; its average highest altitude is 7,590 meters, and this is the fastest-growing lake in the Himalayas.

It is one of the potentially dangerous lakes in the Nepal Himalayas. So, you can see the location is given; then this is another example. So, this is a false color composite (FCC) that I hope you remember from the remote sensing portion. So, this is captured by the LIS

IV MX sensor onboard the Resourcesat-2 satellite on November 27, 2016. This is the mountainous terrain labeled as the feature ridge and hill shadow that helps to illustrate the area's relief. The glacier formation located in the Manas sub-basin belongs to the broader Brahmaputra basin. The image clearly highlights the glacial lake positioned at the glacier snout. The lake is visible in bright blue tones representing the presence of water. The glacier appears with a lighter texture. So, you can see it here. You all must have heard about South Lhonak Glacier Lake. So, the South Lonak Glacier Lake has witnessed a substantial increase in its area over time. So, this example I have already quoted in the previous few lectures in 1967 and 2022 shows how the area is changing. So, now let us talk about the identification and mapping of these glacial lakes.

So, for the glacial lake mapping or identification, we know that these are located at a higher altitude. So, the satellite images are preferred. Let us try to understand the identification and mapping of glacial lakes. So, we all know these glacial lakes are situated at a higher altitude. Where field investigation is very difficult. That is why satellite remote sensing datasets or UAV-based measurements are one of the important sources of information. So, utilizing these satellite images or aerial images, we can have different types of indices that can be used to identify or map the glacial lakes located at higher altitudes. So, let us talk about GLOF risk factors. So, the size of the glacier, the melt rate, and the size of the glacier lakes. The strength of moraines is one of the key parameters that may trigger the GLOF risk. The population along the valley, infrastructure, and livelihood are getting affected because of such a GLOF event.

So, what should we do? To establish a risk model, lake inventory should be conducted, a field survey of the most at-risk lakes should be performed, lakes should be monitored regularly, mitigation strategies for extreme conditions should be developed, and we should have an early warning system for susceptible glacial lakes. Which is located at a higher altitude. So, the glacier and glacial lakes are found in remote, difficult-to-reach areas, making field-based inventories time-consuming and difficult; satellite imagery and aerial photos proved to be more efficient in the accurate mapping and monitoring of the glacial lakes. When we say regular monitoring of the glacier and glacier lake, it is remote sensing that can help to map these on a regular basis by enabling the observation of lake dynamics, surface area change, and surrounding terrain using satellite remote sensing, aerial photography, and thermal sensors. So, all of these can be a very good source of information.

So, here we will have the steps involved in generating the inventory of glacial lakes in the Himalayan region. So, first what we will do is go for the basin boundary delineation. Then we will have the digital database, then we should have ortho-rectified satellite images, and then identification and digitization of the glacial lakes. So, this will help you have a very high-precision digital database of the glacial lakes. I hope you have understood the basics of glacial lakes: how they form, the different types of glacial lakes,

the different types of glacial lake boundaries, moraine-dammed lakes, ice-dammed lakes, and why we are giving importance to these glacial lakes and why they are important.

> For glacial lake identification from satellite images, it is preferable to have images with least snow cover and cloud free.

> The least snow cover occurs in the period between May and September in the Himalayas.

> If snow precipitation is late in the year, winter images are also suitable except for the problem of long relief shadows in the high mountain regions.

(Ministry of Water Resources & NRSC (2013)

The Normalized Difference Water Index (NDWI) is commonly used for
- Identifying the extent of glacial lakes,
- Monitoring changes over time,
- Differentiating water bodies from ice, snow, and surrounding terrain.

Normalised Difference Water Index (NDWI):

{Green (BAND 2)- NIR (Band 4)} / {Green (Band 2)+ NIR (Band 4)}

NDVI ranges from 0.25 to 0.9 for water

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So, that part we have already covered in the lecture. Now, let us try to understand what we mean by glacial lake outburst flood, and we will see the details on this. So, this particular video beautifully explains GLOF. So, there is one lake, and there is calving. and because of this calving, you have the release of the water. So, here the breach in the season happens, and then this excess water will flow, causing GLOF downstream. So, let us start with the basics: what is a GLOF? A glacial lake outburst flood, or GLOF, is a sudden release of water from a lake fed by glacier melt that has formed at the side, in front of, beneath, or on the surface of the glacier. So, any kind of release of water from these lakes will be GLOF. A sudden release of meltwater from a glacier or glacier dam lakes sometimes results in a catastrophic flood formed by the melting of a channel or by subglacial volcanic activities termed as GLOF. Glacier meltwater is often dammed by moraines, ice, or bedrock, but its failure through breaching or overtopping can cause a devastating impact on the mountain communities and infrastructure. So, I have covered all the different types and details of why and how we call it GLOF.

So, any kind of release of excess water, which is causing a catastrophic impact downstream, will be GLOF. In the Himalayas, particularly, the melting of glaciers leads to the creation of proglacial lakes. The expansion of these glacial lakes poses a significant risk of glacial lake outburst floods, a serious geomorphological hazard involving the sudden release of water from these glacial lakes, called GLOF. GLOF is a specialized case; particularly here in this image, you can see that it is a moraine-dammed lake, and it will breach, causing the catastrophic discharge of water from the lake downstream. Generally, there are two types of breach: over-topping breach and piping breach.

And it will cause the rapid movement of water sediment and other mixtures in the downstream area, leading to huge losses. So, it will carry everything whatever comes in the way. During the South Lhonak Glacial Lake Outburst, it washed away a 60-meter-high dam that was part of Sikkim's largest hydropower project. So, the estimated loss you can see is huge. So, these lakes are located at a higher altitude, but their catastrophic impacts can be seen downstream. So, why are GLOFs important? I hope you understand the basics. Threats to human settlements, destruction of infrastructure, evidence of climate change. This is one of the indicators of economic disruption and environmental impact. And, which calls for the early warning system. So, the causes of glacial lake outburst floods.

So, here you can see the glacier retreat because of climate change, then glacial moraine failure due to overtopping or maybe calving effects, avalanches in that particular region, glacial lake overtopping, landslides, and human activities. Glacial lake expansion, glacial surging, earthquakes or any other seismic events, geothermal activities, extreme weather events like rainfall or snowfall, and glacier calving. These are the causes of the glacial lake outburst floods. Why do glacial lake outburst floods occur more frequently in the Himalayas? Due to high glacial activity, glacier melting has increased, indicating glacial lake formation; avalanches are very common, climate change is significant, the slope of the steep terrain is very high, population density is also increasing, and landslides occur due to earthquakes because these are high seismic zone areas. The effects of GLOFs can be seen as infrastructure loss, loss of life, agricultural damage, environmental damage, and this particular figure explains how devastating a GLOF can be. So, here you can see the bridge and what has happened in this particular area. Now, we have understood what GLOF is and how devastating it could be, but how to mitigate it and how to solve this problem. When you think about solving this GLOF problem, one can immediately say to reduce the water by using artificial drainage. Here, high-density polyethylene pipes can be used to reduce the water level. An early warning system should be established so that any such event can be forecasted and people can save their lives and property.

The scientific approach is needed, and the risk assessment should be done. Glacial lake cascades, so the cascading lakes and outburst floods from an upstream lake can overwhelm a downstream lake. So, we have seen another example in which three lakes were connected. Now, here you see this is one lake, this is another lake; we have one small one here and one here. Now, suppose this particular lake is very stable; it is safe and not vulnerable to glacial lake outburst.

But because of some activity here, this glacial lake may release some water, and this will enter here. This may also trigger these lakes, or this will lead to this, and then this lake will be vulnerable to glacial lake outburst floods. This is a Landsat image representing the lake's cascading effects. Causes of triggering GLOF events include seismic activities, which are very important. Earthquakes can destabilize the moraine dam directly or trigger

landslide avalanches in the area. Heavy rainfall or rapid snowmelt will also trigger. Volcanic or geothermal activity and ice avalanches will also increase the vulnerability of the glacier lake. Cascading events that we have understood in the previous slide, such as human activities like mining, construction, and deforestation in high mountain areas, can destabilize slopes, increase the risk of landslides or altering drainage patterns, potentially contributing to GLOF risk. So, the primary triggers for a GLOF are the collapse or breach of a moraine dam or ice dam water in a glacial lake. This is due to the glacier meltwater, avalanches or volcanic activities, and the underlying factors leading to a potentially unstable lake.

The glacier is melting and retreating, forming unstable dams. Ice dams formed by the glacier itself, increase water volume in the glacial lakes. So, these will cause or trigger the GLOF, the dam failure, and the moraine dam failure. Ice dam failure. So, these dam failure mechanisms have direct impact on the GLOF.

Then displacement waves, the large waves generated by a sudden event, can overtop the dam, ice, or snow avalanche falling into the lake. Rockfalls or landslides enter the lake because the surrounding area can experience a landslide event. Large blocks of glacial ice are calving into the lake. So, the Chamoli disaster was one of these examples. The implications of GLOF, the possible implications of GLOF, and what can be done to reduce the risk.

So, different management techniques that can basically reduce the risk. One thing we can do is reduce the lake level. If we lower the lake level, then the volume of the water will be smaller, which will reduce the vulnerability of that particular lake to GLOF. The major GLOF occurrence in India, so this is a list.

So you can just go through it. You can see these are the glacial lake outburst events in India. The Kedarnath disaster in 2013, we all know how devastating it was. Then South Lhonak Glacial Lake; this is the impact you can see. Then, let us understand the role of geospatial technology in GLOF studies. The snow line in the Himalayan glaciers generally lies at an elevation of 3,800 meters above mean sea level.

Due to their remote and inaccessible location, studying glacial lakes through field investigations and inventories is very tough. Remote sensing and GIS are effective tools that help us map and monitor these lakes. So, with remote sensing datasets, you can identify the surface features, geometric properties, slope, and elevation that can be identified, and the time series data will help you study how a glacial lake is being formed and how it is changing its shape and size over time and, the GIS will allow you to integrate all your satellite images and field investigation information into a particular model, and you can see how a particular lake is vulnerable to a GLOF event.

So, the space input is listed here. So, you can read the volume and depth estimation of the glacial lake; it is very, very important. So, in the absence of bathymetry data for a lake, an area-based empirical scaling approach was adopted to estimate its volume. Various empirical models exist that approximate the volume of the glacial lake using their surface area; among these is the equation proposed by Huggel et al. It is one of the most widely referenced and has been utilized in numerous prior studies related to GLOF studies. So, this is the equation you can see for the hydrodynamic modeling of a glacial lake.

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➢ In the absence of bathymetric data for the lake, an area-based empirical scaling approach was adopted to estimate its total volume.

➢ Various empirical models exist that approximate the volume of glacial lakes using their surface area. Among these, the equation proposed by Huggel et al. is one of the most widely referenced and has been utilized in numerous prior studies related to GLOF studies.
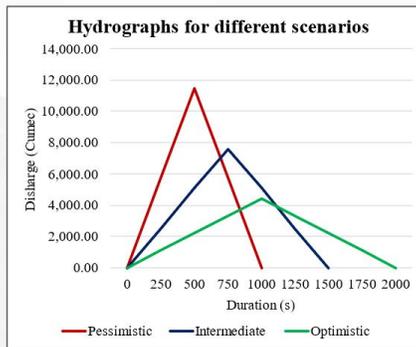
$$V = 0.104 \times A^{1.42}$$

➢ Formula for calculating average depth has been estimated by (Huggel et.al).

$$D = 4 \times 10^{-5} \times A + 5.0564.$$

These Huggel's equations are used to identify the volume of the lake. These models solve the basic flow equations of continuity and momentum, and mainly produce the outburst hydrograph due to dam breach, maximum flood level, and discharge, including time of travel at defined cross sections. Glacial lake outburst floods have been simulated through various analytical, numerical, empirical, parametric, and physical modeling techniques highlighting the complexities involved in such events. These models are designed to represent impact wave generation, dam breach mechanisms, and the propagation of flood water downstream. So, here you can see that different models are available.

To understand the flood propagation after breaching for estimating peak discharge, inundation boundary, time to peak, and travel time are used. The modeling approach is very good for early warning system mitigation planning and emergency responses. So, here you can see the GLOF modeling data requirements. So, this is a generic list; when you go for specific glacial lake modeling, you will, or you may need to modify this list. The structural geometry and boundary conditions will be required in your GLOF modeling.

GLOF Modeling

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Hydrographs for different scenarios

For moraine-dammed lakes, Mean Depth (D_m) is given by (Cook and Quincey, 2015)
$$D_m = 3 \times 10^{-5}A + 12.64$$

For moraine-dammed lakes, Peak Discharge (Q_{max}) is given by (Evans, 1986),
$$Q_{max} = 0.72\ V^{0.53}$$

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This is one example I am showing you of how it looks when you have GLOF modeling. So, this is just to help you understand what exactly I mean by GLOF modeling. So, because of the breach. How the water is flowing and how much area will be covered during this peak flood time will determine our mitigation policy. So, with this modeling, you can have the depth map and the velocity map.

At what location and at what velocity can we expect this because we have the topographic information? So, this kind of modeling will help us save lives and property. So, what are the final recommendations? To enhance the monitoring policy, we must again adopt new policies and encourage coordination among scientific institutions, disaster management authorities, and local government. An early warning system should be in place for any potential glacial lakes that are susceptible to GLOF. Then future research suggests modeling potential breach scenarios and downstream impact mapping. So, these are the references that I have been referring to in this lecture.

So, you can go through it if you are interested; you can go into detail.

Thank you very much.