REMOTE SENSING FOR NATURAL HAZARD STUDIES

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Lec 26 b: Glacial Lake Vulnerability Assessment Part B

Hello everyone, welcome back to Lecture 26. This is Part 2 of Lecture 26. So, we will continue our discussion on the glacial lake vulnerability assessment. So, when we talk about the lake assessment, we have to conduct the hazard assessment. This involves identifying and characterizing the potential for GLOFs, including factors like volume, dam type, and moraine ice. Potential triggering mechanisms include earthquakes, avalanches, or any other activities.
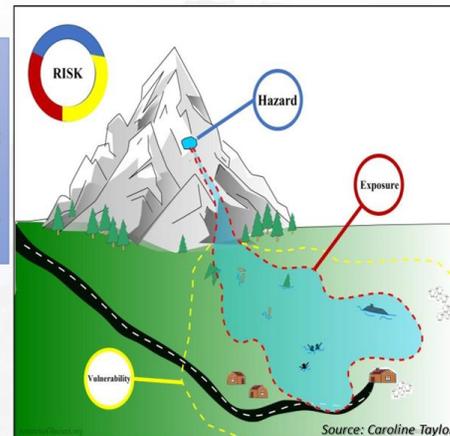

So, then we go for the vulnerability assessment; this evaluates the sensitivity of the exposed area to GLOF impacts, considering factors like the presence of critical infrastructure, population density, and adaptive capacity. Then comes the risk assessment. So, this combines hazard, exposure and vulnerability assessment. So, I will have a few more explanations to understand this risk, hazard, and vulnerability. Then comes the mitigation and adaptation strategies. So, based on the risk assessment, strategies are developed to reduce the likelihood and impacts of GLOF, including early warning

systems, infrastructure protection, and community preparedness. So, this particular slide is meant to explain the risk, hazard, exposure, and vulnerability. Now, you just try to listen to this and follow this image. So, the flood represents a hazard. So, here we have the flood. So, this represents the hazard, while exposure is shown as the area submerged by the water. So, this area that is submerged is the exposure. Vulnerability extends to the larger population that may be affected. Although the flood has a defined physical boundary, its consequences can reach well beyond that limit. So, I hope it is clear: risk, hazard, exposure, and vulnerability. The potential sources of harm, such as GLOF and avalanches, will be your hazards.

So, when we talk about risk, it is the probability of the hazard causing harm or damage that will affect the surroundings and environment. It can be people, or it can be the environment, or both. So, here you can see the risk; when we talk about risk, we have to go for the vulnerability assessment, exposure assessment, and hazard analysis and for the real-time observation, we have the remote sensing data, meteorological data, and hydrological data that are needed.

The susceptibility mapping includes the identification of high-risk zones. The modeling and simulation will determine the likelihood of the event and the severity of the event. So, let us take the risk. Risk is the probability of a loss that depends on hazards, vulnerability, and exposure. The most common definition of risk is the combination of flood hazard and flood vulnerability at a given location. So, risk will be the hazard multiplied by vulnerability. Risk assessment analysis aims to minimize the possibility of the GLOF event. When we talk about a hazard, it refers to a process or phenomenon that may cause disruption, damage, or loss of life. Whether something is a hazard or not depends on the probability that an event will occur and its expected magnitude. For

example, a dormant volcano has a very low hazard because the probability of eruption is near zero. Given that the same type of hazard can have different probabilities and magnitudes, we often scale our hazards, referring to them as low or high hazards.

Now, we have the vulnerability. In simple terms, it is the extent of harm that may occur to the elements exposed to the hazardous event. So, the vulnerability will be exposure plus susceptibility, and that will be subtracting resilience. It varies with the element under consideration; for example, physical vulnerability for physical elements such as houses, roads, infrastructure, etc. Other types of vulnerability are social and economic vulnerabilities related to society and the economy of that particular region or country. Vulnerability as a condition is influenced by various factors such as ecological, social, physical, and economic, and increases people's susceptibility to hazard impact. Now, let us talk about exposure. Exposure is the presence of vulnerable elements within the extent of flood inundation. It is assessed based on an inventory of anthropogenic elements such as villages, roads, bridges, hydropower stations, etc., that may be affected by the hazard. It refers to the likely economic, social, and cultural human impact of the hazard. For example, this can include people, livelihoods, services and resources, and infrastructure in that particular area.

To quantify exposure, information such as population density, the count, number and types of houses, number of bridges, area of agriculture, land, and other infrastructure or activities of economic value must be collected within the likely hazard zones. So, the GLOF risk is usually defined as a function of hazard, exposure, and vulnerability. And here you can see this is the reason why we have the risk. So, the hazard exposure and vulnerability have been assessed. So, GLOF risk will be equal to hazard multiplied by exposure multiplied by vulnerability. So, this diagram shows the glacial lake outburst

flood risk. Risk is a combination of physical hazards, including the potential outburst magnitude, downstream exposure, and social vulnerability. So here are the different factors contributing to the glacial lake hazard. So, the first one is the volume of the lake. Then there are seismic activities, instability of moraine dams, glacial retreats, heavy rainfall or snowfall, human activities like mining, construction, road construction, bridge construction, avalanches, and stagnant glacier ice within dams. So, the importance can be understood here: the early warning system and the GLOF vulnerability analysis help to identify areas at high risk and develop an early warning system to provide timely alerts to populations. Infrastructure protection, which is another aspect, vulnerability analysis can inform the design and location of infrastructure to minimize GLOF impact. Then community preparedness will ensure that the people residing in that particular area know what to do and what not to do during a catastrophic event. Risk reduction strategies, so vulnerability analysis provides a basis for developing and implementing GLOF risk reduction strategies such as dam stabilization, drainage improvement, and climate change adaptation measures. So, here you can see the key aspects of glacial lake vulnerability analysis. So, here you have the identification of the potentially dangerous lake, GLOF simulation, impact assessment, risk mapping, and then mitigation strategies. Lakes are recognized by their size, depth, and dam stability.

The hydrodynamic model simulates the breach of lake dams. GLOF impacts on infrastructure, settlements, and populations that can be studied. Vulnerability assessment results are presented as a risk map. Risk map delineates an area that is more at risk. Based on the vulnerability assessment, mitigation strategies can be planned. So, the vulnerability assessment can be measured and quantified with the help of various indicators by estimating the exposure, sensitivity, and adaptive capacity, respectively. Quantifying the vulnerability of a system to specific natural hazards or climate change is known as the vulnerability assessment technique. So, here you have the exposure vulnerability index, sensitivity vulnerability index, adaptive capacity vulnerability index, and composite vulnerability index; these can be used to assess the vulnerability of a glacial lake. So, what are the different causes of glacial lake outburst floods? So, here we have a list of glaciers retreat due to climate change. Glacial moraine failure, avalanches, then glacial lake overtopping, landslides, human activities, glacial lake expansion, and glacial surging. Earthquakes, geothermal activities, extreme weather conditions, and then glacial calving. So, all of these can lead to glacial lake outburst floods. So, here you can see this is one example from the Sikkim Himalayas where we have conducted several field investigations. So, with the aim of identifying potential glacial lakes susceptible to future GLOF events. Lakes with an aerial coverage of more than 0.01 square kilometers have been considered for vulnerability assessment. So, to start with, we have used the remote sensing dataset, and then we did the change analysis for the glacial lake boundary, and we found that some of the lakes have vanished while some of the lakes are drastically increasing in size. Some of them are in their original condition. So, this analysis helps

you prioritize which glacial lake needs to be continuously monitored for any future hazards. The seismicity we have included in our analysis because this is one of the important aspects that can trigger the GLOF event. So, the northeastern Himalayan region experienced seismic tremors very frequently. The glacier bodies lie close to MCT and other tectonic features. There has been a record of 179 distributed earthquake events in the area with a magnitude greater than. So, here you can see the glacial lakes are represented in blue, and the star marks are basically the epicenters. So, this is the field investigation conducted in different parts of the Sikkim Himalayas. So, it is from one of the field investigations. where we have tracked for 96 kilometers to collect the in-situ datasets, and these are some of the photographs from the field that will help you understand how glacial lakes look in nature. So, this is the calving zone that you can see. This is from another location; it is from Rathong glacial snout.

Identification Of Vulnerable Glacial Lakes

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Factors/ Parameters	Symbol	Details	Critical value	Classes	Class index value (i)	References
Lake area/ Empirical volume/ depth	LA	Lakes with an area (A) of >0.02 Km^2 can store enough water to cause damage. Huggel's Volume : 0.14A$^{1.42}$ m^3 Huggel's Depth: 0.14A$^{0.42}$ m	>0.01 Km^2	0.01-0.05 Km^2 0.05-0.10 Km^2 0.10-0.50 Km^2 0.50-1.0 Km^2 >1.0 Km^2	0.20 0.40 0.60 0.80 1.00	ICIMOD, 2011; Huggel et al., 2002; Bolch et al., 2011; Aggarwal et al., 2017
Lake type	LT	Moraine- or ice- or combined dammed lakes are more critical to breach.		Snow-fed Glacial melt-fed Dammed Lake	0.25 0.50 1.00	ICIMOD, 2011
Increase in lake area	LI	>100% since 2007		<50% 50-100% >100%	0.25 0.50 1.00	Bolch et al., 2008; Bolch et al., 2011; Gardelle et al., 2011
Lake altitude	LE	Lakes at higher elevation have to cover longer and steeper path after breach due to which impact downstream increases due to more scouring and debris/sediment load.	>3500 m a.s.l	<3500 m a.s.l ≥3500 m a.s.l	0.50 1.00	ICIMOD, 2011
Slope between glacier and lake	SO	Steep slope between lake and glacier increases the risk of rockfall or icefall into the lake	>12°	<12° 12°-21° >21°	0.25 0.50 1.00	Wang et al., 2011; Prakash and Nagarajan, 2017
Discharge type	DT	Lakes with a perennial stream is comparatively safe than a closed lake.		Open Closed	0.50 1.00	Huggel et al., 2002
Slope of moraine boundary	MS	Topographic gradient of inner boundary of the lake	>10°	<10° >10°	0.50 1.00	Huggel et al., 2002

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So, here you can see he is standing on the glacial lake because we visited it during the winter, and the surface is frozen. Here you can see the metamorphosed glacial ice outcrops. We have also collected the moraine sample to analyze its stability. So, I have put a few more photographs here. So, I hope these photographs will help you understand the scale of glacial lakes that we are talking about and how they look in the field. So, you just see the photograph; this is the downstream of the glacial lake. So, this is the connection to the fluvial system. So, here you can see how the water flows. This is the glacial lake we are talking about. This is the inflow. So, this is where we are getting the water into this. So, it has a connection from here, and then there is another source that, in another photograph, you will be able to understand. So, this is another side of this lake from where we are, and here we have the glaciers. And we have also conducted a few

geophysical tests so that we will understand the stability of the glacier lakes. This is on top of that.

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Pairwise comparison matrix with weight (ώ) of factors

Factors↓→	LA	LT	LI	LE	SO	DT	MS	GP	CL	RP	SP	FO	WH	L	E
LA	1	1	1/5	4	8	5	6	3	4	8	8	1/3	1/3	4	4
LT	1	1	1/5	4	4	6	2	5	3	8	8	1	1	7	7
LI	5	5	1	6	7	4	4	3	8	9	9	2	2	8	8
LE	1/4	1/4	1/6	1	1/2	1/3	1/3	1/4	1/3	4	4	1/5	1/5	1	1
SO	1/8	1/4	1/7	2	1	1	1/5	1/4	1/4	3	3	1/6	1/6	3	3
DT	1/5	1/6	1/4	3	1	1	1	1/2	1	3	3	1/5	1/5	1/3	1/3
MS	1/6	1/2	1/4	3	5	1	1	1	1	3	4	1	1	1	1
GP	1/3	1/5	1/3	4	4	2	1	1	5	5	7	1	1	3	3
CL	1/4	1/3	1/8	3	4	1	1	1/5	1	5	6	1/5	1/7	2	2
RP	1/8	1/8	1/9	1/4	1/3	1/3	1/3	1/5	1/5	1	1	1/4	1/5	1/2	1/3
SP	1/8	1/8	1/9	1/4	1/3	1/3	1/4	1/7	1/6	1	1	1/4	1/5	1/3	1/3
FO	3	1	1/2	5	6	5	1	1	5	4	4	1	1/2	4	3
WH	3	1	1/2	5	6	5	1	1	7	5	5	2	1	3	2
L	1/4	1/7	1/8	1	1/3	3	1	1/3	1/2	2	3	1/4	1/3	1	1/2
E	1/4	1/7	1/8	1	1/3	3	1	1/3	1/2	3	3	1/3	1/2	2	1

Rank and weights of factors

Factors	Rank	Weight
Increase in lake area	1	0.216
Lake type	2	0.121
Width/height ratio	3	0.116
Lake area	4	0.113
Freeboard offset	5	0.104
Parent glacier proximity	6	0.074
Slope of moraine boundary	7	0.053
Connected Lakes	8	0.041
Earthquakes and tectonic factors	9	0.031
Stream order	10	0.029
Discharge type	11	0.028
Landslides	12	0.026
Lake altitude	13	0.023
Proximity to road network	14	0.013

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So, here you can see this is the glacier, the main body, and here the water is flowing through it. So, the meltwater is entering this lake. And this is the moraine, the glacial moraine. This is from another location; this is Gurudongmar Lake. So, based on our field investigation, the literature review, and the remote sensing data products, we have formalized this analysis. So, to identify the vulnerable glacier lakes, we have considered different parameters that are listed here. You can see why we have listed that, which is also explained in this. Then, based on the pairwise comparison matrix with the weight of factors, we ranked the different parameters and identified their weightage in our analysis. Based on that, we have identified different types of glacier lakes: highly vulnerable, moderately vulnerable, and safe. So, here you can see one of the lakes; just see this one, it is classified as moderately vulnerable, and I will try to show you the field photograph of it. So, since we visited during the winter, this looks dry, but in the summer season, this will be completely filled with water. So, it has been observed that 8 glacial lakes are highly vulnerable to future events. These lakes are moraine-dammed lakes, and their aerial coverage, as well as the volumetric capacity, has increased rapidly in the last few decades. 11 glacial lakes are classified as moderately vulnerable and should also be checked for a glow event as they might become vulnerable in the near future due to glacier melting. So, here you can see the results.

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For moraine-dammed lakes, Mean Depth (D_m) is given by (Cook and Quincey, 2015)

$$D_m = 3 \times 10^{-5}A + 12.64$$

Hydrographs for different scenarios
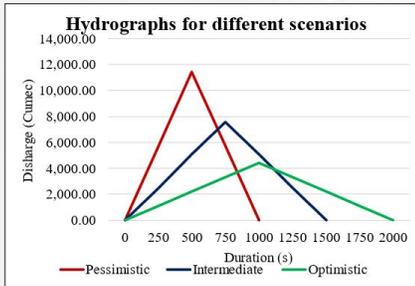
For moraine-dammed lakes, Peak Discharge (Q_{max}) is given by (Evans, 1986),

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

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Then comes the GLOF modeling. So, here you can see this specific video. This video is from the GLOF modeling, where we have simulated how the lower reaches or the low-lying areas will receive the water after a GLOF event, what the impact will be, and how much area will be covered by the GLOF or the catastrophic event. Using this same hydrodynamic modeling, we have also identified the depth map and velocity map that will help you understand what the impact of a GLOF event will be in the downstream. So, these are the two papers that you can refer to, and it is an extensive paper where we have explained the different processes and methods associated with glacial lake outburst floods, and we have also explained the vulnerability risk part. So, these are the references that we have used in this lecture.

Thank you. Thank you very much.