REMOTE SENSING FOR NATURAL HAZARD STUDIES

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Lec 25 a: Introduction to Glacial Lake Outburst Floods Part A

Hello everyone, welcome to Lecture 25. So, today we will start the Glacial Lake Outburst Flood. This is part 1 of lecture 25, and this belongs to module 7. So, in this lecture, we will particularly see what glaciers are, what glacial lakes are, how they form, what the different types of glacial lakes are, and what we mean by GLOF, Glacial Lake Outburst Floods. So, let us start this from the beginning with what we mean by cryosphere so that in case you have missed the previous lecture, you will be able to follow all the contents of this lecture. So, the cryosphere encompasses all forms of frozen water on Earth, including snow, glaciers, ice sheets, icebergs, and permafrost.

A glacier is a large perennial mass of ice and snow that is constantly moving under the influence of its own weight and gravity. So, unless a glacier mass or the glacier ice moves, we do not call it a glacier. So, we will call it an ice sheet or ice or snow, but we never call them glaciers until they start their movement. So, the Indian Himalayas particularly contain the world's largest number of glaciers and snow outside the polar region and are aptly called the third pole of the world.

So, this is very, very important. The Indian Himalayan region is very important in terms of cryospheric studies. It consists of three major river systems. Indus, Ganga, and Brahmaputra stretch over five countries: India, China, Nepal, Pakistan, and Bhutan. We all have parts of this fluvial system that originated from the Indian Himalayas. This is the Hindu Kush Himalayas. So, here you can see we have Karakoram, Western Himalayas, Central Himalayas, Eastern Himalayas, and the Hindukush Himalayan region, which has about 8000 glacial lakes. The North Indian states of Uttarakhand, Himachal Pradesh, and Jammu and Kashmir have 200 lakes. So, you can see how important it is to study the glacial lakes, particularly in the Indian Himalayan region. So, let us understand the basic features of glaciers.

So, the accumulation zone, the area above the equilibrium where total snow accumulation exceeds ablation, is known as the accumulation zone. It is where the snowfall happens, and it accumulates, and slowly it gets thicker and denser and, then it takes the form of ice,

and subsequently, it forms a glacier. The equilibrium line is the boundary that divides the glacier surface into the accumulation and ablation zones. So, here you can see this red line. So, you can easily say that here in this particular area, melting is happening, and here you have the snowfall; this is the accumulation zone.

So, this will definitely be the higher altitude; this will be the lower altitude. The ablation zone is basically in this region. The zone below the equilibrium line where total ablation melting is higher than accumulation. So, it is not necessary, but the melting happens in this region only, and we call it the ablation zone; the snout, which is also very important, is the mouth of the glacier. So, if you see, this is a glacier boundary. And here, basically, it is ending. So, this is the lower altitude, and here it starts melting, feeding this particular lake. So, in this condition we have this snout here. So, the lowest point of a glacier is known as its terminus or toe, where the ice mass ends. So, here is the location. So, now let us try to understand the glacial lake in particular. So, here you can see this is one of our field photographs, and here you can see if this is clear to you that this is a glacier flowing from the top; it is coming from this region.

Now, this definitely is the snout of the glacier, and it is actually melting. Slowly, it is feeding this particular lake, and there is one more lake on this side. So, this is how they melt, and the meltwater accumulates in the snout of the glacier, where there is some depression and because of the depression, the water will accumulate and slowly take the form of a lake if it continues. So, this is another diagram to explain that if this is the glacier and this is the snout of the glacier, it is slowly melting and accumulating here. And then, subsequently, it takes years to develop this kind of lake. So, the glacier retreat plays a very important role. So, the retreat is a process in which the snout of a glacier moves back up. So, it will move up because of the melting. The valley, due to net ice loss indicating more ablation than accumulation, particularly in this region, will subsequently develop a glacial lake.

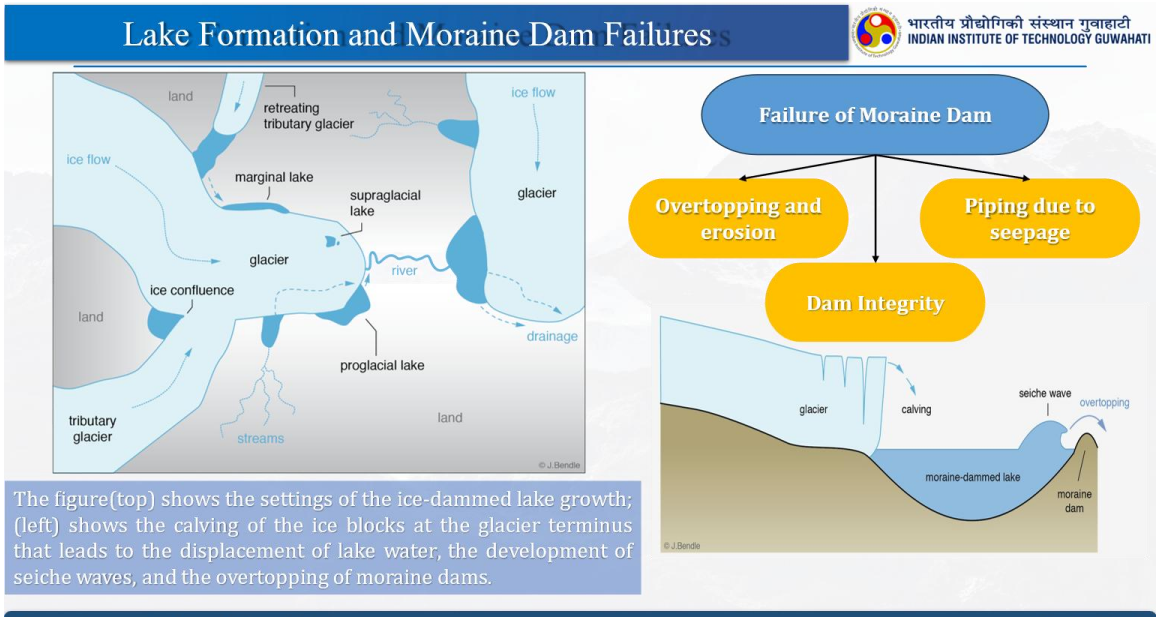
So, here you can see some of the real glacial lakes that are located here. So, the details are given here. So, this image I am using here explains how these lakes are formed and what the source of the water is. So, basically, here is the meltwater and this kind of depression that helps to develop the glacier lakes; earlier, this was the snout of the glacier, but because of the retreat, the snout has gone up, and now this area is available for lake formation, and these are the moraines. We will discuss this in detail in the moraine part.

So, let us try to understand the glacier lake. A glacial lake is a body of water that originates from glacier activity. They are formed when a glacier erodes the land and then melts, filling the depression created by the glaciers. The glacier lakes are often dammed by moraine or ice. So, as I said, this was the earlier snout of the glacier, but because of

the retreat, this snout has reached this level, and this area is available for glacial lake formation.

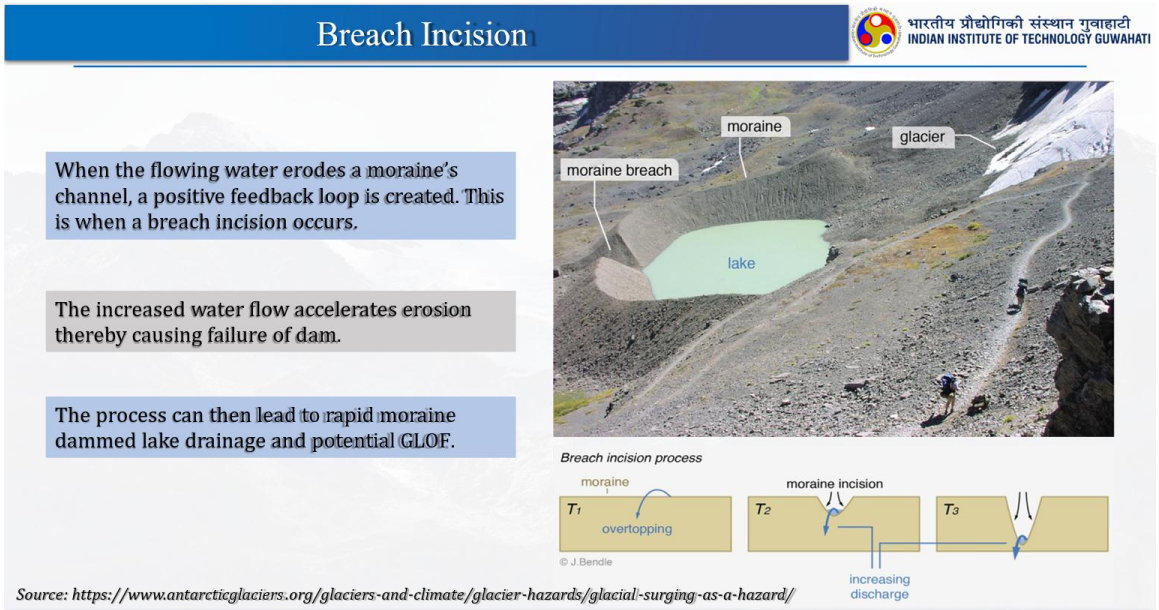
In the Indian Himalayan region, most glacial lakes are formed due to retreating glaciers as a result of climate change. Over 5,000 glacial lakes have been identified in the Indian Himalayan region, primarily in Sikkim, Himachal Pradesh, Uttarakhand, and Jammu and Kashmir. The majority are located in the upper reaches of river basins such as the Indus, Ganga, and Brahmaputra. This is from the ICIMOD report. So, here you can see the accumulation zone that is highlighted. So, these areas are receiving solid precipitation. So, here the accumulation actually happens, and these are the ridges. So, here you can see this kind of feature. So, these are the ridges, and here, since we have this snout, the melting happens. So, this water will start reaching this particular depression. So, this is called the ablation zone, and these are the glacial lakes. I hope this is clear. So, this is another image. So, these images have been generated using AI just to explain the features. So, here is the glacier that is flowing down, and this is the snout of the glacier; here you have the formation of glacier lakes. The formation of glacial lakes can be understood in this particular slide.

The accumulation of glacier melt water, unable to flow naturally due to barriers like ice dams, bedrock, or moraines, results in the creation of glacial lakes. This is what we saw in the previous slide. So, we have different types of lakes. Moraine-dammed lakes, where we have the moraines, are followed by ice-dammed lakes, and then we have glacial erosion lakes due to the erosion that generates depressions. Because of these depressions, which are available to accumulate water, we have the formation of new lakes called glacial erosion lakes and then we also have the other glacial lakes fed by the direct melting of glaciers within the glaciated valleys. So, here you can see that the failure of moraine dam can be understood. So, here the first one is overtopping and erosion. Piping due to seepage and dam integrity issues. So, these are the different causes of the moraine dam failure and here in this particular image, you can understand how the glacial lakes are formed. So, here you can see how beautifully they are explaining the retreating results in the formation of glacial lakes at several positions. So, these are called marginal lakes. And here you have the supraglacial, here you have another lake that is also connected to a river channel, and here we also have a glacial lake, and these are the fluvial channels that are connected to these glacial lakes. In lake formation and lake breaching, we need to understand the breach in the season.



So, when the flowing water erodes a moraine's channel, a positive feedback loop is created. This is when a breached incision occurs. So, here you can see that this is the glacier which is feeding this particular lake and there is a moraine breach here, and slowly the water will start flowing in that direction. Here, because of the moraine breach, the water will flow downstream. The increased water flow accelerates erosion, thereby causing the failure of the dam. The process can then lead to rapid moraine dam lake drainage and potential glacial lake outburst floods. This is the concept of glacial lake breach. We will have more details on the breaching, and here you can see how the Bishop Glacial Lake in Canada is increasing in size over the year. So, here you see how it is increasing and what is happening to the snow or the glacier present in this particular area.

Similarly, you can see an example from South Lhonak Glacial Lake. This image is from 1967, and this is the size of the lake. Now, here you can see this is from 2022, and here we have also marked the earlier traces of the boundary of the glacial lake and how it has increased over the years. So, we have to be very careful, and we have to continuously monitor these glacial lakes which are susceptible to GLOF. So, in this particular video, we will try to explain how it is changing over time.

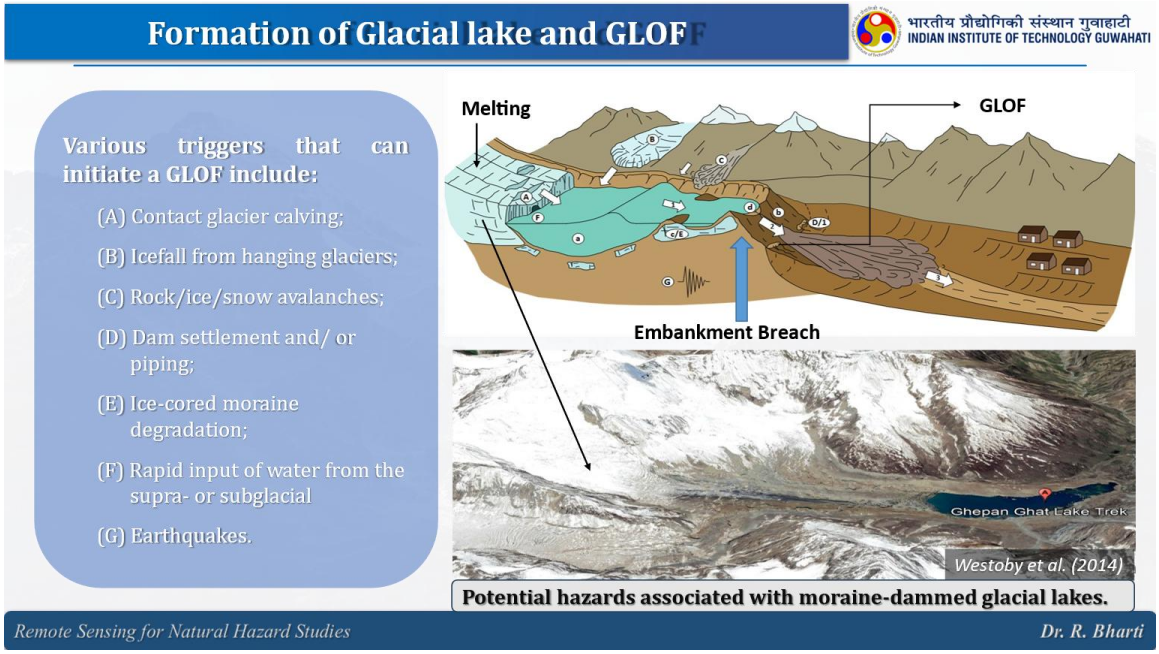


So, you just carefully watch the video here. In 2023, this particular lake failed, and we had a glacial lake outburst flood, and the reason was calving. So, there was one moraine that calved, and it fell into this particular lake in South Lhonak because of the overtopping that happened, and this particularly breached the moraine that was available here, which then caused the glacial lake outburst and here you can see the importance of the glacial lake and why we need to study it. So, these are freshwater resources for us, and they are a very good climate change indicator because of the new formation of the glacial lake.

Then retreating is happening if some of the lakes have vanished; that means more glaciation is occurring or accumulation is taking place. Tourism and livelihood are also present because it helps attract people and improve the local people's livelihoods. Ecological importance: naturally, the ecology of that particular area will be maintained, and it also has the potential for hydropower generation. The most important thing is that we need to be very careful and monitor these glacial lakes for any potential hazards. The formation of the glacial lake can be understood here. The glacial lakes are typically formed by the accumulation of meltwater from glaciers. The lake is held back by moraine, the accumulation of glacial debris or ice dams. This image shows a high-altitude, snow-covered mountainous region. Several glacial lakes are located near the ends or along the courses of glaciers.

So, these are highlighted with circles. The image emphasizes how melting glaciers contribute to the development of these lakes in an ever-changing icy environment. So, here you can see they are slowly getting generated and slowly increasing their size. So, some of them will have the potential to GLOF. So, we have to keep on monitoring the status of the glacier in that particular area, how the mass is changing the mass balance,

and how the glacial lakes are increasing in size. The formation of glacier lakes has these major components. So, the first one is the melting process, as a vertical thinning of the glacier happens; then we have global warming, which causes rising temperatures that accelerate the rate of glacier melting, leading to glacier retreat. Accelerated glacier retreat has led to a significant enlargement of glacier lakes. As a result, the horizontal expansion of the lake increases across the Himalayas. On average, glacier retreat in the Himalayan region is 10 to 14 meters per year.

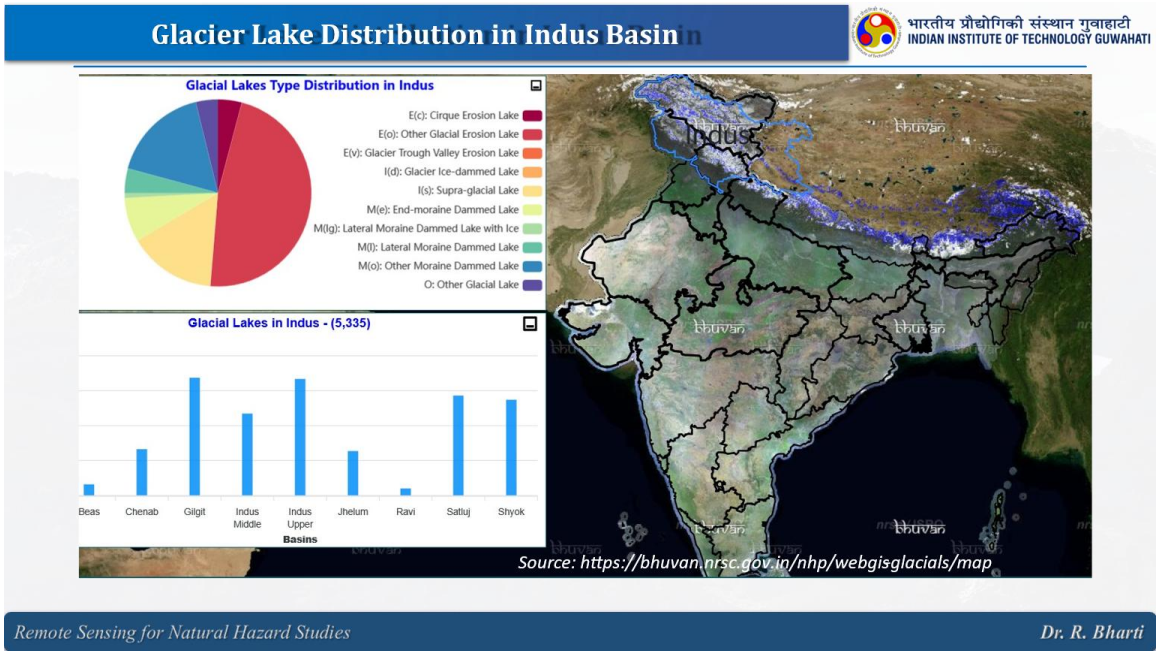


So, this is a very general statement. Now, let us understand the various triggers that can initiate a GLOF. So, the contact glacier calving is what we have seen in the previous few slides. Ice falls from hanging glaciers. So, this Rishi Ganga valley was one of the examples. Then rock, ice, or snow avalanches, dam settlement and or piping, ice-cored moraine degradation, rapid input of water from the supra- or sub-glacier, and any other earthquake can also trigger this GLOF event. So, here you can see that this particular conceptual diagram beautifully explains the process. So, what is happening here? This is the melting zone. So, it is melting, and slowly it is feeding this particular glacial lake, and then it is coming to the fluvial channel. Now, if there is a breach at this particular point, what will happen? The GLOF can be seen here. So, here is the zone where we can have the embankment breach, and here you can see that this is linked to a real image.

So, here is the snout of the glacier, and here it is melting, and this lake is fed by this meltwater and here, if something happens to this particular embankment, then downstream you can see the GLOF event. The Himalayas are called the third pole due to their vast snow and glacier coverage, and they are extremely vulnerable to global climate change. The rising temperature of the earth accelerated the retreat and thinning of

glaciers, leading to the formation of new glacial lakes and the expansion of existing ones that we have seen in the Sikkim Himalayas.

So, we have one paper that is provided in the link. There, we have seen that many of the new lakes have formed and that they are slowly increasing in size. Glacial lakes formed by the melting of glaciers are an important source of fresh water for Himalayan rivers, but they also pose a serious hazard in the form of glacial lake outburst floods. Analysis of satellite data from 1984 to 2023 reveals that 676 glacial lakes out of 2431, which are more than 10 hectares, have significantly expanded; among them, 130 are in India within the Indus, 7 in the Ganga, and 58 in the Brahmaputra. So, here you can see the glacial lakes in the Himalayas; the number is 28,000, including all sizes, and it is also classified into different types. Similarly, in the Indus basin, what are the different types of lakes we have, and what is their distribution? Then we have glacial lakes in the Ganga.



So, here you can see 4707 different types of lakes, including glacial lakes in the Brahmaputra basin, where the number is very high at 18001. Different types are listed. So, if you want to know more and explore this information, you can visit the Bhuvan website to see the details. So, let us try to understand what the different types of glacial lakes are.

So, glacial lakes are divided into four major types. So, we have referred to the NRSC inventory for this. First is the Moraine-Dammed Lake, then we have the Ice-Dammed Lake then Glacier Erosion lakes and the other glacial lakes. So, here are some examples so that you will be able to understand what we mean by that. So, glacial erosion lakes are like this: it is because of the erosion activity of the glaciers.

This depression has formed, and it acts as the dome where the water can accumulate and this is the ice-dammed lake where ice is acting as a moraine. Then we have a moraine-dammed lake. Here, the moraines are actually making these embankments.

Let us try to understand the moraine-dammed lake. When glaciers melt, the water in these glacial lakes accumulates behind loose naturally formed glacial moraine dams made of ice, sand, pebbles, and ice residues. So, here are the glaciers. So, it is flowing downstream and this is the zone and let us say this is the snout of the glacier. Here, some depression is formed, and the accumulation happened, resulting in the Moraine Dam Lake. They are unstable and potentially lead to glacial lake outburst floods because these are loose grains. And, slowly over time, they get compacted and have very good strength. If the moraine dam is impermeable, the lake continues to fill until it reaches a balance through seepage or overflow. Outbursts can be triggered by factors such as heavy inflow, increased melting, and flood surges due to calving. Internal seepage because of the seepage in these moraines, high hydraulic pressure due to the amount of water, or the thawing of permafrost caused by rising temperatures because ice is also present here.

If there is too much change in the temperature, this will melt, and then the strength of this moraine will be lost. Now, we have the ice dam lake. Ice dam lakes commonly form in areas where a tributary valley is obstructed by a main glacier. So, here you can see it.

This is the tributary glacier, and this is the main glacier. They may also develop when a glacier forms as a side valley advances into and blocks the main valley. Other typical locations include the gap between a glacier's lateral margin and the adjacent ice-free valley wall. Ice dam lakes can also emerge at a junction where two glaciers converge.

Now, we have subglacial lakes. So, this is basically the location. So, you can easily understand that "subglacial" means it is beneath the glacier. So, subglacial lakes form beneath glacier ice where there is no gradient for fluid potential. Water is routed from the glacier surface glacially to the base, where it collects to form these lakes. Although subglacial lakes cannot be directly identified using satellite imagery, their presence is often inferred from the occurrence of "Jokulhlaups." Now, we have supra-glacial lakes; supra-glacial lakes form on the surface of the glacier.

So, here you can see that this is a glacier that is flowing. And here these lakes are on top of the glaciers. So, the base of these glaciers will be the ice or glacier ice. Meltwater accumulates in depressions or hollows of these ice surfaces. So, you can see this image. Supraglacial lakes typically form due to melting processes and are commonly found in the lower ablation zone of glaciers covered by debris.

This is an example of a supraglacial lake on the surface of the glacier in Bhutan. So, these lakes are from Bhutan. So, here is another example from this particular paper, and you

can see how these lakes are formed on top of glaciers. So, these are called supraglacial lakes.

Glacial Lake cascade; this is from Changbaxia GLOF. The new glacial lakes are formed at higher elevations above existing lakes. It will increase the risk of a cascade outburst event. So, this is the aerial view depicting the position of three interconnected glacial lakes. So, here is one, this is the second one, and this is the third one.

Now you see the connection. So, these three are connected. So, if there is a breach of one of the glacial lakes located at a higher altitude, then the lower altitude lakes will have a greater potential for GLOF. In this scenario, even a small outflow from an upper lake can potentially trigger a major release from the lower lake. So, we have the example from Changbaxia. So, a cascading flood event occurred in the eastern Himalayas in 2001, initiated by an ice avalanche into Changbaxia.

Which triggers the initial event. This outburst subsequently propagated downstream, impacting the low-lying lakes. In this particular slide, we will try to understand the glacial erosion of lakes. These lakes are formed by glacial erosion where the glacier calves out depressions and fills them with water. Cirque Lake, formed in the rounded depression of glaciers, and valley lakes formed in the border of U-shaped valleys carved by glaciers are examples of erosion-based lakes. The other glacial lakes that we have discussed earlier are also glacial lakes formed by glacier erosion, which are difficult to identify by morphological features and do not belong to the other type described below.

Can be classified as another glacial erosion lake, these other lakes can exist beneath, within, or on top of the glacier. So, it can be subglacial, englacial, or supraglacial. So, for the glacial type and their identification keys, a two-character coding system is used to classify glacial lakes, where the first character is an uppercase letter indicating the main type of the lake. The second character is the lowercase letter enclosed in parentheses that denotes the specific subtype.

For instance, the symbol M(e) identifies an end moraine-dammed lake. A comprehensive list of glacial lake types is presented in the next slide. So, there you will be able to understand how we are using these identification keys. So, here we have M(e), M(I), M(Ig), and the details are given in this table. So, I hope this will help you read, or in your work, you can also name the glacial lakes. The types of moraine-dammed lakes include end moraine dammed lakes and lateral moraine dammed lakes, depending upon the position and morphology of the dammed condition.

The moraine material may be ice-cored or ice-free. Before the ice body of the glacier completely melts away, glacier ice exists in the moraine and beneath the lake bottom. The ice bodies stored in the moraine and beneath the lakes are sometimes called dead ice or fossilized ice. As glacier ice continues to melt, the lake becomes deeper and wider.

Finally, when the ice contained in the moraines and beneath the lake completely melts away because of the high temperature, the composition of the lake water consists of only the bedrock and the moraines.

So, here you can see an example of a moraine. Here is the glacier. Please provide a sentence for correction. This is the snout of the glacier at present day. But you can see this particular ridge. So, it shows that the snout was maybe here earlier. Because of the retreat of this glacier, this feature is still present, and this is what we call the lateral moraine, and this is the middle moraine in between.

I hope this is clear. Here, we have another example to explain the lateral moraine and how it forms. So, here you see how these glaciers are connected and flow downward and here, in between, you have moraines. So, I will just mark the moraine. So, you see, this is the boundary of the glaciers. So, these are basically the moraines. Here, we also have moraines. So, in this particular image, you can see that this is the ridge.

This is basically your moraine. So, with this, I will end part 1 of this lecture. We will continue this discussion in the next part. Thank you. Thank you very much.