

Explain the causes of glacial lake outburst flood. 2025

A glacial lake outburst flood (GLOF) is a release of meltwater from a moraine- or ice-dam glacial lake due to dam failure. GLOFs often result in catastrophic flooding downstream, with major geomorphic and socioeconomic impacts.

GLOFs have three main features:

- They involve sudden (and sometimes cyclic) releases of water.
- They tend to be rapid events, lasting hours to days.
- They result in large downstream river discharges (which often increase by an order of magnitude).

Some of the largest floods in Earth's history have been GLOFs. They have caused large-scale landscape change, and even altered regional climate by releasing huge quantities of freshwater to the oceans.

Today, GLOFs pose a risk downstream communities and infrastructure. In Peru alone, GLOFs were responsible for ~32,000 deaths in the 20th century. They have killed hundreds to thousands of people in other mountain regions (e.g. the Himalayas), and destroyed roads, bridges, and hydroelectric developments.

An increasing hazard

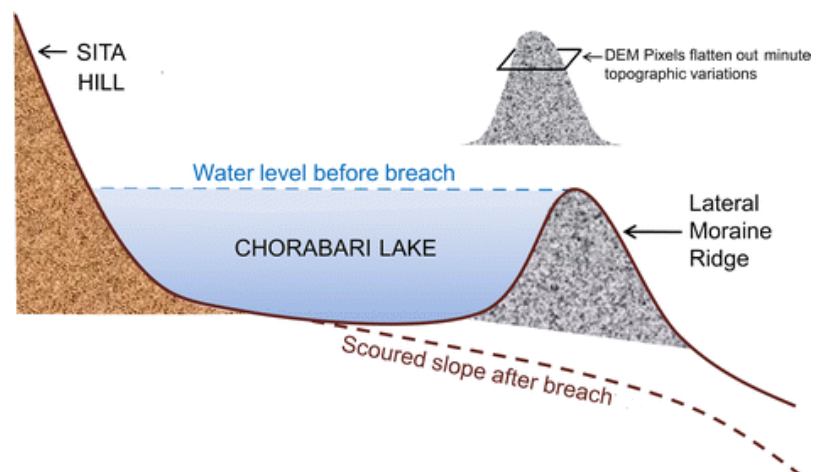
Importantly, the general global trend of glacier shrinkage through the 20th and 21st centuries has seen the number and size of glacial lakes increase, at the same time as human activities have expanded further into glaciated catchments. The study of how GLOFs occur and their impacts is therefore important for future hazard mitigation.

Glacial lake settings

There are two main settings in which glacial lakes form: (1) behind moraine dams, and (2) behind ice dams.

Moraine-dammed lakes

Moraine-dammed lakes form during periods of glacier retreat from a moraine. As a glacier margin retreats, water collects in the topographic low between the ice-front and the abandoned frontal and/or lateral moraine. Most existing moraine-

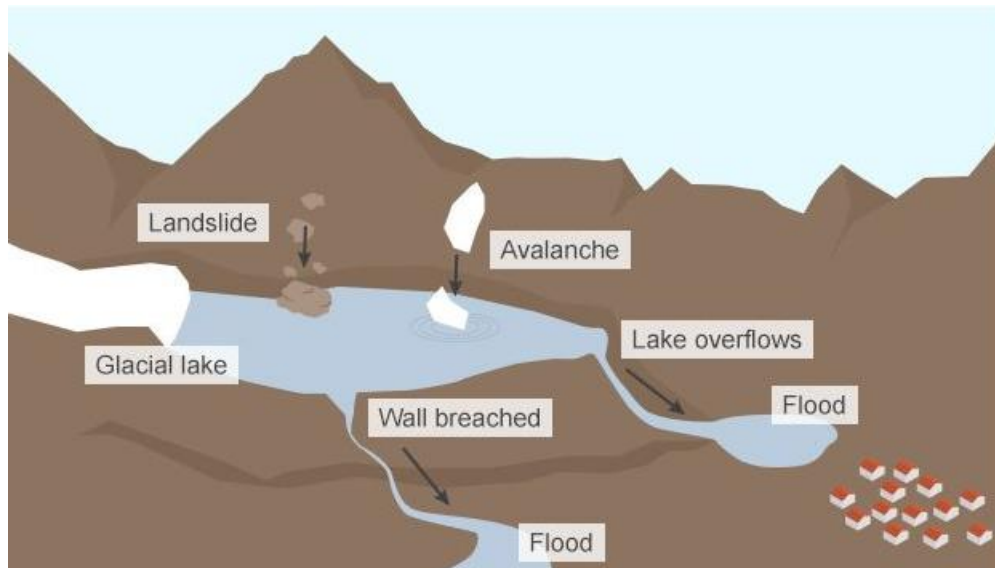


dammed lakes (such as the Imja Tsho glacial lake in Nepal formed when mountain glaciers began to retreat from large moraine ridges constructed during the Little Ice Age

Moraine-dam failures

The failure of glacier and moraine dams depends on two main factors: (1) the integrity of the dam, and (2) the nature of trigger mechanisms

Moraine dams tend to be narrow and sharp-crested. As such, they are more likely to fail than broader dam types, such as ice-contact fans or landslides. Most moraines are made up of loose, poorly sorted, permeable sediment, and some contain ice cores. Unconsolidated sediments are susceptible to failure, especially if saturated, while the melting of ice cores may cause moraines to subside over time. Despite these weaknesses, where a moraine is low, wide, and armoured by large rock material it may survive intact for hundreds or even thousands of years.



Displacement waves

Outburst floods in moraine-dammed settings are often caused by the sudden input of material into a lake causing displacement of water and overtopping of the dam. Displacement (or seiche) waves are commonly triggered by avalanches or rockfalls, or calving of a lake-terminating glacier.

Other triggers include, the rapid input of meltwater from an glacier upstream, heavy rainfall or snowmelt events that rapidly raise the lake level, or earthquakes that destabilise the moraine dam

Breach incision

Once overtopped, a process called breach incision can occur. This occurs as water flowing across the dam surface erodes a channel into the moraine, starting a positive feedback process where channel incision allows more water to escape, and the higher discharges leaving the outlet encourage greater rates of erosion. This process allows a moraine dammed lake to drain very rapidly. It also adds large volumes of unconsolidated sediment to the flood waters, which may then develop into highly destructive debris flows.

Ice-dammed lakes

In contrast to moraine-dammed lakes, ice-dammed lakes form when drainage is blocked by a glacier that advances or becomes thicker. Consequently, ice-dammed lake growth is closely related to glacier mass balance and climate. Ice-dammed lakes form wherever a glacier blocks the drainage of meltwater.

The main settings for ice-dammed lakes- include: where a tributary valley is blocked by a trunk glacier; where a glacier from a tributary valley advances across the main trunk valley; in openings between the lateral glacier margin and ice-free valley sides; and at the point where two glaciers join.

Ice-dam failures

Unlike moraine dam failures, the drainage of an ice-dammed lake does not necessarily end in dam destruction. This is because water can drain through subglacial channels that close up when water discharge drops, or because an ice-margin may temporarily float before regaining contact with the bed

Ice dam flotation

Ice-dam flotation occurs due to the difference in density between ice ($\sim 0.9 \text{ g/cm}^3$) and water ($\sim 1.0 \text{ g/cm}^3$). when lake level reaches 90% of the glacier dam height the ice will lift from the bed, and water can escape through subglacial conduits. However, as a lake empties, and its level falls below 90% of dam height, the glacier drops to the bed and subglacial conduits close up. This stops lake drainage and allows a lake to refill.

Overspilling

Lake drainage can also occur by simple overspilling, for example, during a large rainfall or snowmelt event that causes lake level to rise. This is most common at cold-based glaciers, which are frozen to the bed and less permeable than warm-based glaciers.

2024 : Discuss the variations in nature of glaciers in India and the emerging issues due to climate change

India is home to some of the largest reserves of ice and freshwater outside the polar regions, often referred to as the "Third Pole." Almost all Indian glaciers are alpine or valley glaciers, concentrated exclusively in the Himalayan and Karakoram mountain ranges.

However, because the Himalayan arc stretches over 2,500 kilometers across diverse climatic zones, the nature, size, and behavior of these glaciers vary dramatically from west to east.

1. Regional Variations in Glaciers

The Indian glaciated region can be broadly divided into three distinct zones, each governed by different climatic systems.

Region	Key Glaciers	Climatic Driver & Snow Accumulation	General Characteristics
Karakoram & Trans-Himalayas (Ladakh)	Siachen, Nubra, Chong Kumdan	Winter Westerlies: Accumulation happens primarily in winter due to Western Disturbances.	Home to the largest and longest glaciers (Siachen is ~76 km long). High altitude, cold-arid climate, and massive ice volume.
Western & Central Himalayas (J&K, Himachal, Uttarakhand)	Gangotri, Milam, Bara Shigri, Pindari	Transitional: Influenced by both Winter Westerlies and the Southwest Summer Monsoon.	Medium to large valley glaciers. They are heavily debris-covered and form the critical source of major North Indian rivers like the Ganga and Yamuna.
Eastern Himalayas (Sikkim, Arunachal Pradesh)	Zemu, Rathong	Summer Monsoon: Accumulation heavily dependent on the Southwest Monsoon (summer precipitation).	Smaller in size and shorter in length. Because they are located at lower latitudes, the climate is warmer and wetter, making them highly sensitive to temperature changes.

2. Variations in Glacial Characteristics

Beyond their geographical location, Indian glaciers vary significantly in their physical nature and behavior:

- **The Altitude of the Snowline:** The snowline (the lowest elevation where snow remains year-round) varies based on latitude and moisture.

In the **Western Himalayas/Karakoram**, the snowline is lower (around 4,500 to 5,000 meters) because of the higher latitude and colder climate.

In the **Eastern Himalayas**, despite heavy precipitation, the snowline is much higher (around 5,000 to 5,500 meters) because it is closer to the equator, resulting in warmer ambient temperatures.

- **Debris Cover (Supraglacial Debris):** Unlike polar glaciers, which are mostly "clean ice," many Himalayan glaciers are heavily covered by rock debris, boulders, and dust.

Thin debris actually accelerates melting because the dark rocks absorb solar radiation. (often found in the lower snouts of Western Himalayan glaciers like Gangotri)

Thick debris (often found in the lower snouts of Trans Himalayan glaciers like Siachen) acts as an insulating blanket, slowing down the melting process.

- **Surging vs. Retreating Glaciers:**

Most glaciers in the Indian Himalayas (like Gangotri and Zemu) are **retreating** rapidly due to global warming.

The **Gangotri glacier**, the primary source of the river Ganga (originating at Gomukh), is retreating at an alarming rate of approximately 10 to 30 meters per year. This retreat is not just about rising air temperatures; it is driven by a complex interplay of atmospheric and structural mechanics.

- **Negative Mass Balance:** A glacier's health is dictated by its mass balance—the difference between *accumulation* (snowfall at the top) and *ablation* (melting at the bottom/snout). For decades, Gangotri has experienced a severe negative mass balance. Warmer, shorter winters mean less snow accumulation, while hotter, longer summers accelerate ablation.
- **The Albedo Effect and Black Carbon:** Albedo is the measure of a surface's reflectivity. Fresh white snow has a high albedo, reflecting most solar radiation back into space. However, prevailing winds carry "black carbon" (soot from industrial pollution, vehicular emissions, and stubble burning in the plains) up to the Himalayas. When this dark soot settles on the Gangotri glacier, it drastically lowers its albedo, causing the ice to absorb heat and melt faster.
- **Supraglacial Lakes:** As the surface ice melts, it forms large pools of water on top of the glacier known as supraglacial lakes. Water absorbs more solar heat than ice. These lakes act like thermal drills, melting the ice downward and creating deep crevices (moulins).

When this water reaches the bedrock, it lubricates the base of the glacier, causing it to slide faster and fracture at the snout.

- **Thinning vs. Retreating:** Retreating (the snout moving backward) is only half the story. The Gangotri glacier is also actively *thinning* (losing vertical volume). Even if the snout appears to pause its retreat in a given year, the sheer loss of ice volume makes the glacier structurally weaker and more prone to fragmentation.

However, some glaciers in the Karakoram range are exhibiting a rare phenomenon known as the the **"Karakoram Anomaly,"** where they are either stable or actively advancing (surging) despite global temperature rises.

The mechanics behind this anomaly are fundamentally tied to the region's unique geography and localized weather systems:

- **The Winter Westerly Dominance:** Unlike the Central Himalayas (Gangotri), which rely on the summer Southwest Monsoon, the Karakoram is an arid, high-altitude desert that receives its moisture almost exclusively from **Western Disturbances** during the winter. Climate change has paradoxically intensified these winter storm systems over the Karakoram, dumping massive amounts of fresh snow on the glaciers.
 - **Localized Summer Cooling:** Because the Karakoram receives heavier winter snowfall, the thick, fresh white snow cover persists well into the summer. This extended high-albedo cover reflects intense summer sunlight. Consequently, the ambient summer temperatures over the Karakoram have actually shown a localized *cooling* trend, which heavily suppresses the summer melting (ablation) phase.
 - **Avalanche-Fed Accumulation:** Many Karakoram glaciers sit in steep, sheer-walled valleys. They do not just grow from direct snowfall; they are heavily fed by avalanches from the surrounding peaks. This constant dumping of ice and snow protects the main glacial bodies from shrinking.
 - **The Thick Debris Shield:** While thin dust accelerates melting (as seen in Gangotri), the Karakoram glaciers are covered by an extraordinarily thick layer of heavy rock debris and boulders caused by constant rockfalls. This thick layer acts as a highly effective thermal blanket, insulating the ice below from warming atmospheric temperatures.
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- **Glacial Lake Outburst Floods (GLOFs):** Because the Indian Himalayan Region (IHR) houses over 28,000 glacial lakes, it is highly prone to these sudden disasters. The nature of the terrain means variations in hazard levels. Glaciers in Sikkim and Uttarakhand frequently form moraine-dammed meltwater lakes at their snouts. When these unstable natural dams break, they cause catastrophic flash floods downstream, a risk that is currently escalating across the Central and Eastern Himalayas.

1. The South Lhonak Lake GLOF, Sikkim (October 2023)

This is the most critical recent example of a "multi-hazard cascade" and is highly relevant for contemporary disaster management case studies.

- **The Trigger:** A massive landslide of a waterlogged lateral moraine (frozen rock and debris) collapsed into the **South Lhonak Lake**, a high-altitude glacial lake in North Sikkim. This created a 20-meter-high tsunami-like wave within the lake that breached its natural boundary, releasing nearly 50 million cubic meters of water within minutes.
- **The Impact:** The downstream surge destroyed the **1,200 MW Teesta-III (Chungthang) Hydropower Dam**, a major engineering installation worth over \$2 billion. The flood washed away more than 30 major bridges, raised the Teesta riverbed by several meters, killed over 80 people (including army personnel), and severely disrupted life all the way into Bangladesh.

2. The Kedarnath / Chorabari Tal Disaster, Uttarakhand (June 2013)

This stands as one of the deadliest climate-induced disasters in India's history, highlighting how meteorological extremes can trigger a GLOF.

- **The Trigger:** The region witnessed unprecedented, multi-day cloudbursts and heavy rainfall. This sudden water influx, combined with rapid snowmelt, filled the **Chorabari Tal (Lake)**, which sits just 2 km upstream of the Kedarnath temple town. The fragile moraine dam of the lake gave way under the immense hydrostatic pressure.
- **The Impact:** A colossal wall of water, boulders, and thick sludge slammed directly into Kedarnath town. It caused widespread destruction down the Mandakini and Alaknanda river valleys, resulting in the loss of nearly 5,000 lives and destroying vast swathes of tourism and civic infrastructure.

Highly Vulnerable "Lakes to Watch" (Future Risks)

Indian scientific agencies (like ISRO and the National Disaster Management Authority) have classified **195 glacial lakes in India as high-risk**. Two prominent examples actively being monitored include:

- **Ghepang Ghat Lake (Himachal Pradesh):** Located in the Lahaul and Spiti district, satellite data shows this lake has expanded by over 170% in recent decades due to rapid glacial retreat, posing a severe downstream threat to the Chenab river valley.
- **Safed Lake (Uttarakhand):** Studies indicate this moraine-dammed lake's area has doubled in size. Hydrodynamic modeling shows that a breach here would completely inundate downstream settlements like Milam village within an hour.

UPSC Mains Value Addition: The Government Response

India's shift from *reactive relief* to *proactive risk mitigation*:

1. **National GLOF Risk Mitigation Project (NGRMP):** A ₹150 crore targeted project focusing heavily on structural interventions in four states: Arunachal Pradesh, Himachal Pradesh, Sikkim, and Uttarakhand.
2. **Technical Interventions:** Conducting **Bathymetry scans** (measuring lake volume/depth) and installing **Automated Weather & Water Stations (AWWS)** at high-risk lakes (like South Lhonak) to establish real-time Early Warning Systems (EWS) via mobile cell broadcasts.

The health of these varied glacial systems directly dictates the water, food, and energy security of the entire Indo-Gangetic plain.