Seismic monitoring may improve early warnings for glacial lake outburst floods

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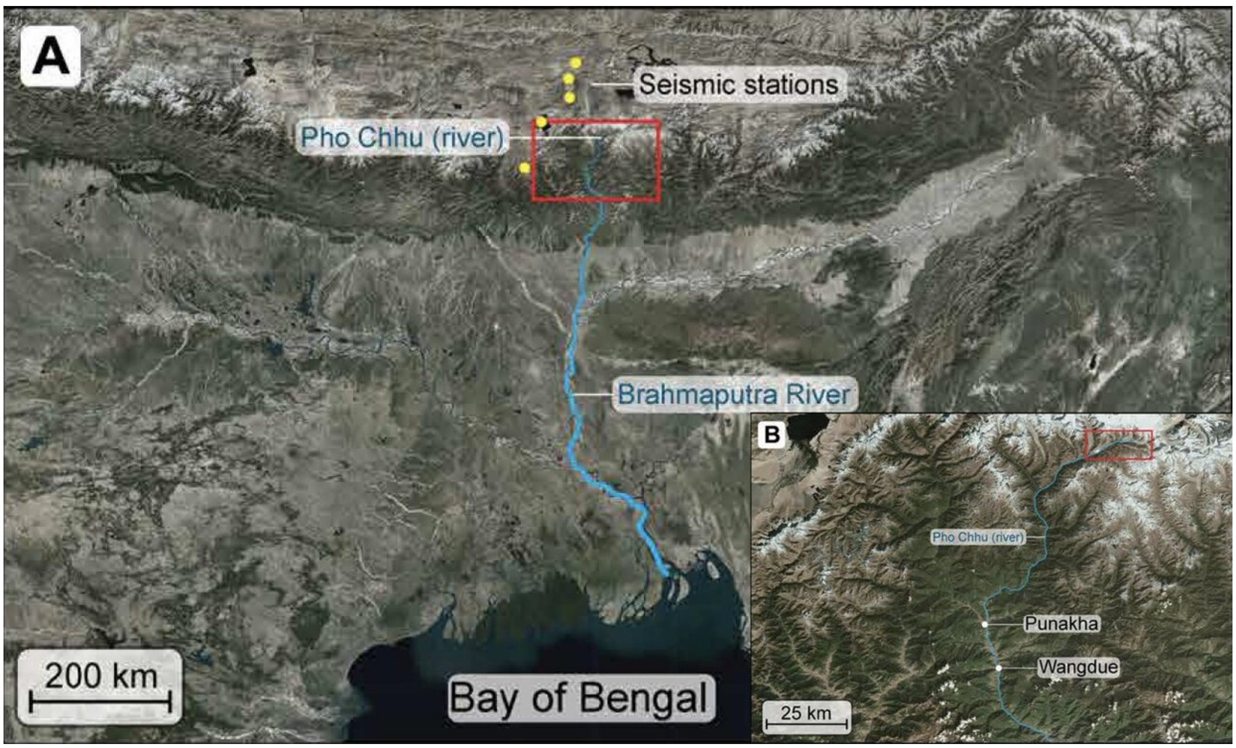


The larger map (A) shows the Pho Chhu river as it flows from the Himalayas into the Bay of Bengal. Seismometer locations are marked with yellow dots. The inset (B) zooms in on the area inside the red box in A, indicating the area where the glacial lake outburst flood began and the location of the village of Punakha 90 kilometers downstream. Credit: Maurer et al./*Science Advances* 2020

Vibrations in the ground may help to improve advanced warnings about sudden floods that result from glacial melting, according to a study published today in *Science Advances*.

On October 7, 1994, a natural dam that had been holding back a glacial lake burst, sending floodwaters crashing downstream into the Bhutanese village of Punakha. The sudden flood killed 21 people, destroyed 816 acres of crops and 6 tons of stored food, and washed away homes and other infrastructure. The new study, led by researchers at Columbia University's Lamont-Doherty Earth Observatory, discovered that local seismic devices unknowingly recorded this glacial lake outburst flood five hours before it reached the village.

Glacial lake outburst floods are becoming more frequent and more destructive in mountainous areas. As glaciers melt, the water pools into lakes trapped behind dams made of rocky glacial debris and ice jams. When the dam shifts or too much pressure builds behind it, the lake water rushes out in a catastrophic burst, posing a danger to downstream communities. As the planet warms, glacial lakes are becoming larger and more common, thus increasing the potential for glacial lake outburst floods (GLOFs).

In the study, led by Lamont-Doherty graduate student Josh Maurer, researchers discovered that a seismometer array located about 100 kilometers from the glacial lake had recorded a clear high-frequency signal at approximately 1:45am, around the time that the dam would have burst. They hypothesize that as the dam ruptured, the powerful and sudden outflow of water and/or sediments struck the riverbed, causing the vibrations that were picked up by the seismometers. The team was able to use the seismic data to reconstruct the flood as it made its way 90 kilometers downstream, reaching the village of Punakha at around 7am.

Currently, instruments monitor local water level in some glacial lakes and alert local communities if the lake level suddenly drops, indicating a

GLOF. However, such systems are known to be somewhat unreliable and have issued false alarms in the past. The study authors suggest that with some refinement, real-time seismic monitoring could be combined with water level monitoring systems to minimize false alarms and maximize warning times. In addition, a few strategically placed seismic sensors could potentially monitor for GLOFs over a large area, whereas water level monitors must be installed lake by lake.

The authors note that more research is needed before seismic GLOF monitors would be ready for deployment. The team hopes to find and explore other instances where seismometers have captured GLOF events, to better understand how to read and analyze the signals in real time. They also caution that the Punakha flood was very large, so the signal stood out clearly in the data; in the future, they hope to better understand whether the technique can reliably detect smaller glacial lake outburst floods, which can still cause severe damage.

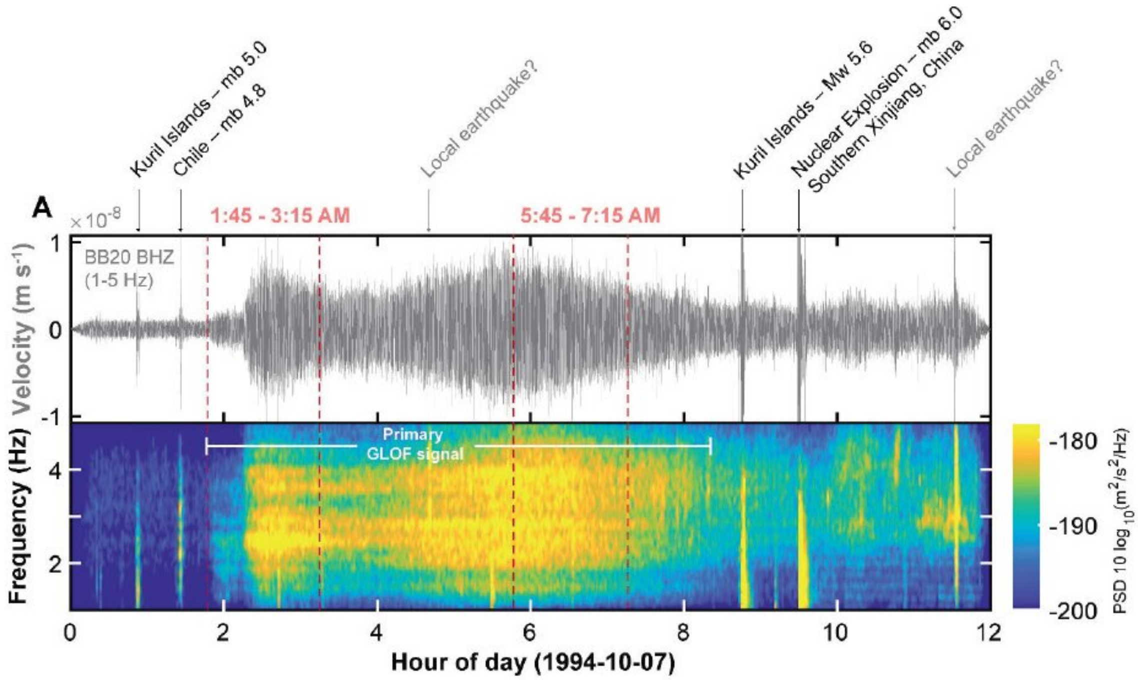
By reconstructing the Punakha flood, the researchers were also able to test various models of how flood waters would be expected to flow through the area, showing that seismic data could help to improve flood modeling. In addition, the paper used satellite imagery before and after the GLOF to assess its impacts on the area.

Experts who were not involved in the study, including geographer Simon Allen and glaciologist Holger Frey (both from the University of Zurich), said the study represents a promising first step toward a seismology-based early warning system. Allen said that more research is needed, since the technique has only been tested on one lake so far, and cautioned that maintaining a real-time seismic monitoring network in the Himalayas or elsewhere would present financial and technical challenges.

"The algorithms need to be extremely reliable," said Frey. "All events must be detected, but at the same time false alarms need to be avoided by all means." He also emphasized that including people from the affected communities in the design and implementation of such systems is critical in determining whether or not they are ultimately successful.

"This study is a great demonstration of the potential for long-range seismic detection of large outburst floods," said Kristen Cook, a geologist at the GFZ German Research Centre for Geosciences who was not involved in the study. "This seismic detection could have important implications looking both back in time to validate flood models and better understand the processes of outburst floods, and potentially forwards in time if a seismic early warning system can be developed. Outburst floods are a big concern in the Himalaya, especially as development along river corridors increases and lakes are growing, so both more robust early warning and better modeling would have significant societal benefits."

Other authors of the study include: Joerg Schaefer, Joshua Russell, and Nicolas Young from Columbia University; Summer Burton Rupper from the University of Utah; Norbu Wangdi from the Center for Water, Climate, and Environmental Policy in Bhutan; and Aaron Putnam from the University of Maine.



The tremors triggered by the GLOF and detected by far away seismometers: the initial outburst at 1:45 a.m., flood getting stronger at 2:15 a.m., and slowly tapering off after 7:15 a.m. Credit: Maurer et al./*Science Advances* 2020

Learn more about the study in a brief Q&A with study co-author Joerg Schaefer, below.

How did the idea for this study first develop?

This all started when we were working on the well-preserved and nearly complete moraine sequences in front of the GLOF lakes. They were in the pathway of the 1994 GLOF, and beryllium dating shows that they are old, like 4,000 years old. I was puzzled as to how such a devastating GLOF could pass these old glacial landforms without destroying them, washing them out. I asked graduate student Josh Maurer to check the spy satellite imagery and the subsequent remote sensing images for pictures of the lakes and moraines just before and just after the flood. He did that, and we documented the outburst and early phase of the 1994 GLOF. We learned that the flood was just not super dramatic right at the start, and only took out a small part of the terminal moraine section. This is a striking and scary reminder that GLOFs starting at these high altitudes pick up their devastating energy by gravity on their way downhill.

Josh realized the potential, and we started to wonder if the GLOF signal should not be visible in the seismometer record. Josh got in touch with Josh Russell, a Ph.D. student in seismology at Lamont, and together they went to work and applied a technique called 'cross-correlation based seismic analyses,' with which they could track the evolution of the GLOF with seismometers as far as 100 km away from the actual flood. They found the flood signal in stunning clarity and synthesized the seismic data with eyewitness reports and a downstream gauge station within a numerical flood model.

We also used the remote imagery before and after the flood to estimate the sediment deposition in the valley downstream to assess the damage, and traced the speed of vegetation recovery.

This is probably the most innovative earth science paper I have had the pleasure to be part of. My main role in it has been to support the work of these brilliant grad students.

Did you encounter any obstacles in the development of this project? If so, what were they? How did you overcome them?

Josh and Josh encountered a variety of problems during their cross-correlation analyses, but they worked brilliantly and effectively as a team. Once all the results were on the table, it took us a while to organize the pieces from many different disciplines to form a coherent earth science manuscript, and to realize and formulate the potential of this technique for a new generation of GLOF early warning systems.

How do you think other glacial lakes could be prioritized for future research along these lines?

One of the biggest strengths of this approach is the regional applicability. We can use this toolkit, for example, to ask the seismometer record whether or not there are similar 'GLOF- type signals' in the system. And, using Josh's satellite image processing techniques, we can search the region for the source of similar floods that might have occurred in the area over the last 40 years.

Being able to track the formation, growth and in particular increase in lake level over time is the key to evaluate and identify the most hazardous lakes in the region. Topography and sediment availability are probably similar across different GLOF-prone valleys in the region, but we should absolutely produce a map highlighting human settlements and areas that are key to their livelihoods in relation to the GLOF hazard from higher up in the Himalayas.

More information: "Seismic observations, numerical modeling, and geomorphic analysis of a glacier lake outburst flood in the Himalayas" *Science Advances* (2020). advances.sciencemag.org/lookup … .1126/sciadv.aba3645

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