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Global warming impacts on floods in high mountain regions

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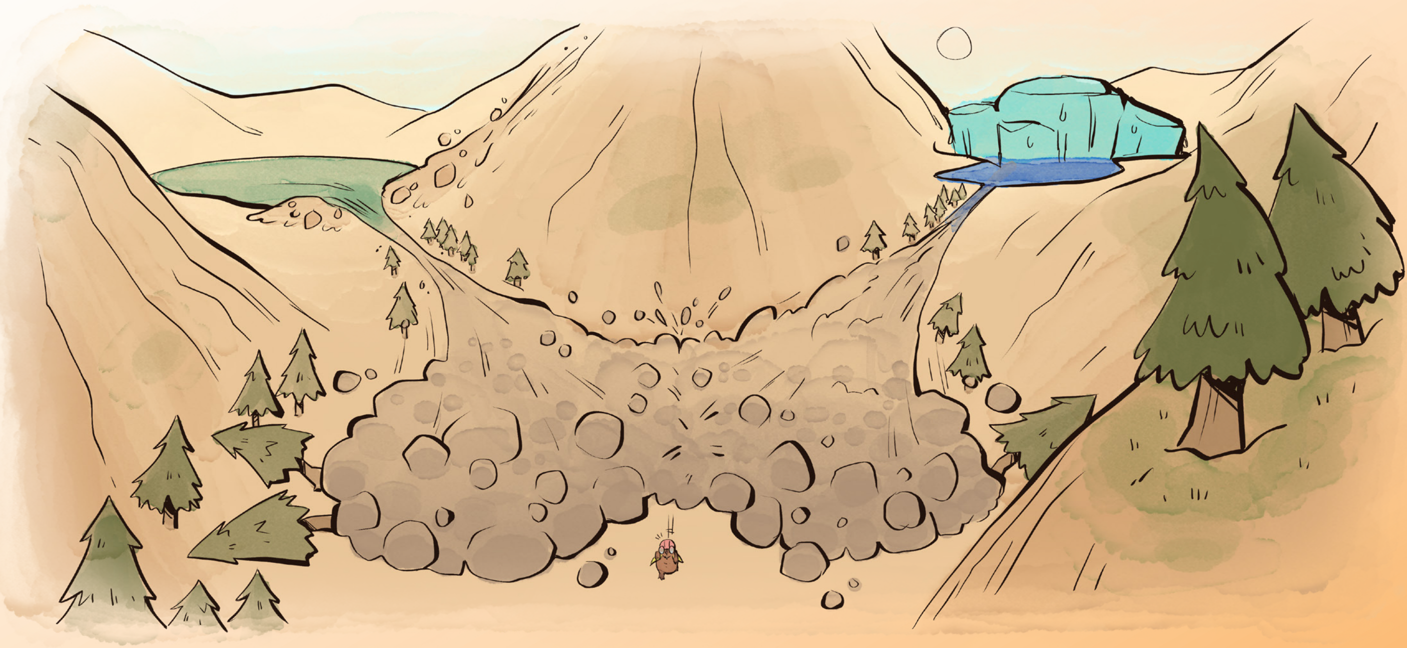
Mountains are formidable ecosystems that hold unique resources for human well-being. Climate change is more pronounced in mountain regions where high elevation amplifies the rate of warming, impacting glaciers and the cryosphere. Some mountain regions are even heating up twice as fast as the mean global temperature. At the same time, mountains are highly sensitive to direct human impacts, mainly in forest cover and land uses. The frequency and magnitude of extreme hydrological events could increase in response to these changes, jeopardizing the sustainable development of communities. We must understand how climate warming is affecting extreme floods impacting mountain communities to facilitate adaption and mitigation of future disasters.

Sustainable development in the face of climate change requires us to anticipate how the magnitude or timing of floods may change. Accurate prediction requires an understanding of what triggers a flood and what elements are involved. First, we need to know what the specific mechanisms are that generate a flood event with extreme discharges (how fast a volume of water moves) and whether these mechanisms change in a warmer climate. To identify a mechanism, we consider: 1) what the source of the water is, and 2) how it moves through a river system.

In colder climate periods, glaciers hold much of the water sources in mountain regions. But in recent decades, rising temperatures are responsible for melting glaciers. As glaciers recede, they form new lakes trapped behind unstable moraines (sedimentary mounds deposited at the front of the glacier) that act as dams. When these moraines are subject to certain conditions, the glacial lakes burst from their natural dams, causing a high volume of water to rapidly move through the river valley. This type of flood mechanism, called a glacial-lake outburst flood (GLOF), results in large disasters for human settlements and infrastructure in mountain river valleys. A comparable flooding process takes place when higher temperatures unsettle mountain slopes by reducing the coverage of frozen ground and intensifying rainfall. Landslides and destabilized rock glaciers fall down hillslopes and intercept rivers, causing a natural dam to capture streamflow. Like the moraine, these natural dams often fail and produce extreme floods in a mechanism called a landslide-lake outburst flood (LLOF).

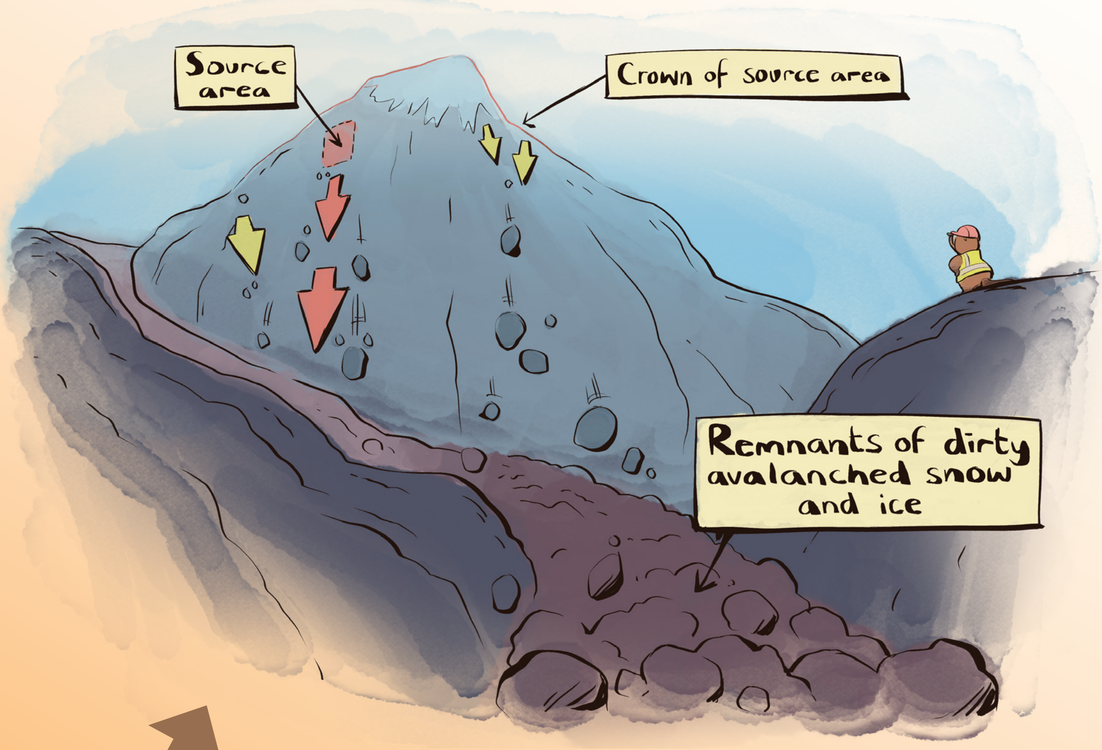
Other mechanisms for extreme flows include increased rainfall intensity and deforestation driven by people. Warmer air can hold more water, so mountains in our warming climate are experiencing bigger storms. Deforestation means less water is captured by soil. As a result, rainfall from larger storms runs off the slopes more quickly, generating larger flows in mountain streams. These mountain flood mechanisms illustrate the complex ways in which warmer temperatures create favorable conditions for extreme flows.



Unprecedented disasters?

Once the flood mechanisms are known, we need to find out the biggest floods (discharges) to be prepared for, and how often they occur for a particular river or region. This is a challenging task in mountain regions. In general, mountains have been isolated regions where life, and processes, have gone unobserved. Moreover, it is very difficult and challenging to record hydrological events in these harsh environments. The recent development of remote sensing and satellite imagery has improved our knowledge of mountain processes, but it is limited to the last decades.

In 2013, a massive GLOF event in Kedarnath (north India) resulted in the loss of more than 6000 lives. It was caused by a combination of anomalous precipitation associated with the early onset of heavy monsoon rains and immediate snowmelt. The event was massive, causing extensive damage to populations and infrastructure.



Examples of recent massive floods linked to climate warming have occurred in the Indian state of Uttarakhand, including the events of Kedarnath in 2013 and Chamoli in 2021 (Shugar et al. 2021). Such events in recent decades appear to be unprecedented. But do these flows really represent the worst-case scenario for their river systems? If so, how often can we expect such floods in the future? We can't answer these questions with one or two observations. We need longer records with more observations of extreme flows to contextualize these events and prepare for future hazards.

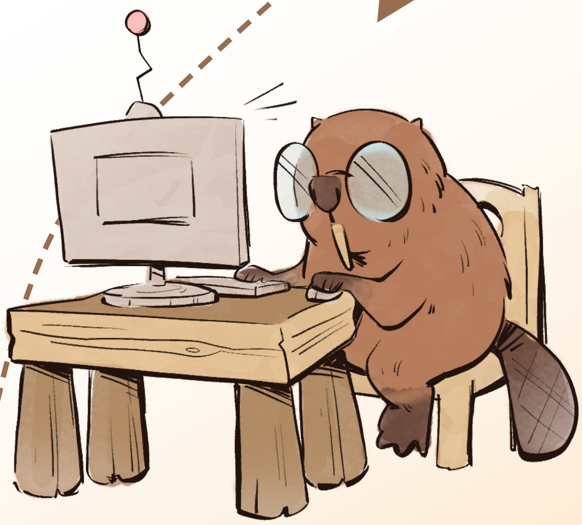
In 2021, in Chamoli (northern India), a large rockslide occurred in the upper part of the Rishiganga catchment, evolving into massive debris flow downstream. The event caused at least 200 deaths and extensive damage to road infrastructure. The slope instabilities associated with climate warming and long-term changes in cryospheric conditions appear to have played a role in triggering this disaster.

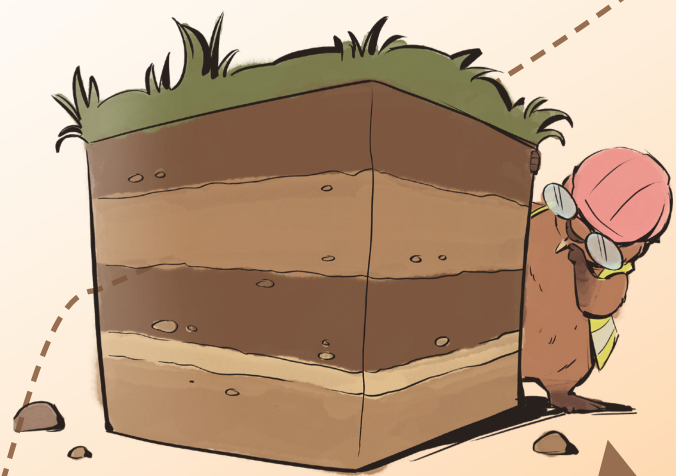
Searching for evidence of past flood disasters

Hello, I am Sandy, and I like to study the history of rivers. My job is to look for evidence of catastrophic events in the past.

There was a recent flood in a fantastic mountain valley, and the energy of the flood destroyed all the houses of a beaver community. The beavers are worried because they have never seen such an intense flood. Now, they have to build new houses, but they are afraid of experiencing similar disasters. Sandy is a geoscientist beaver who wants to help her friends. She decides to do research to find the best place for houses in the valley. First, Sandy examines the existing data and the entire aerial and satellite imagery to see what is happening in the headwaters. She sees a major glacier retreat and the formation of new lakes.

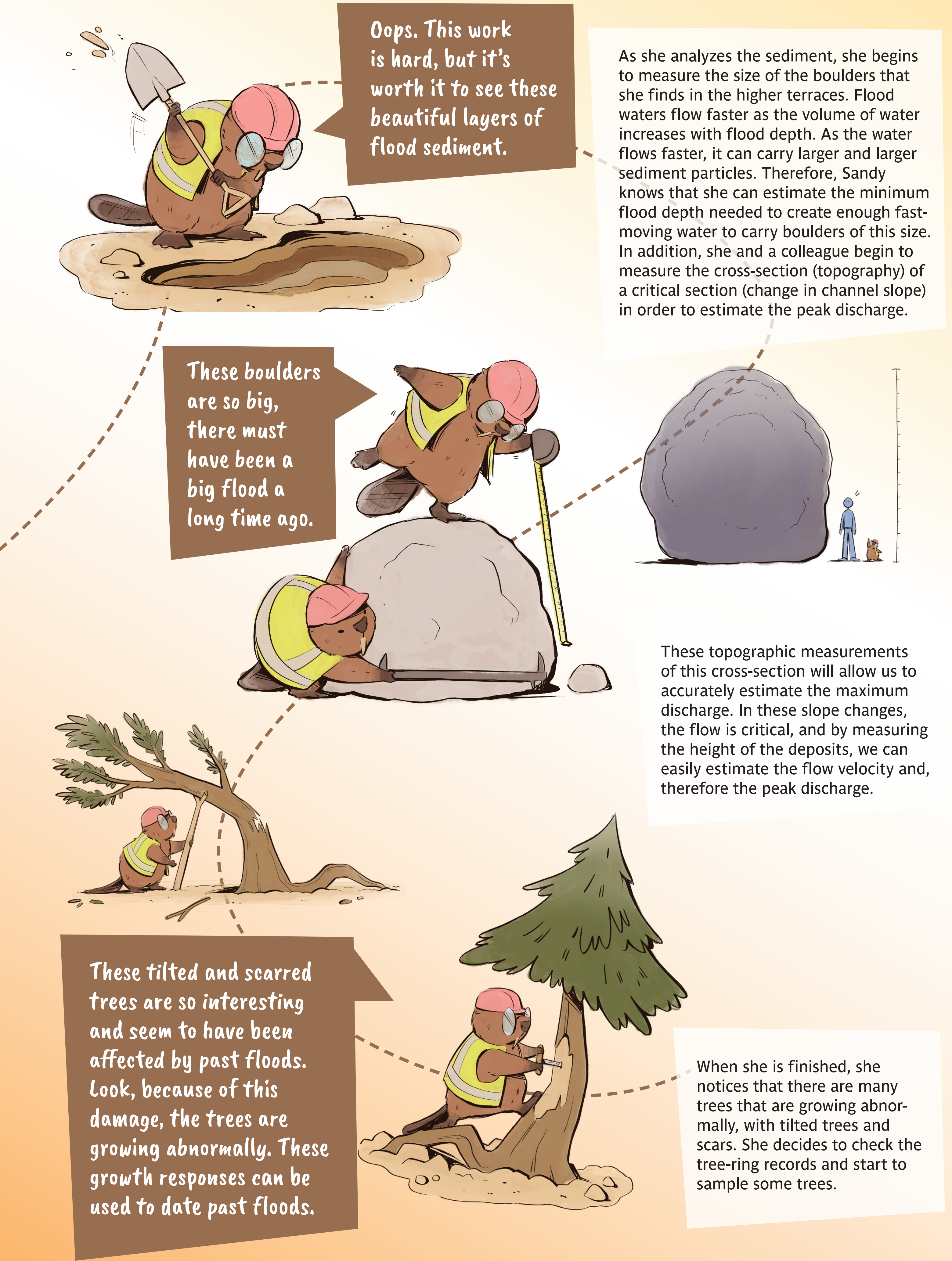
Um, this is interesting... The glacier has retreated 253 meters in the last 10 years and a new lake has formed on the glacier front...



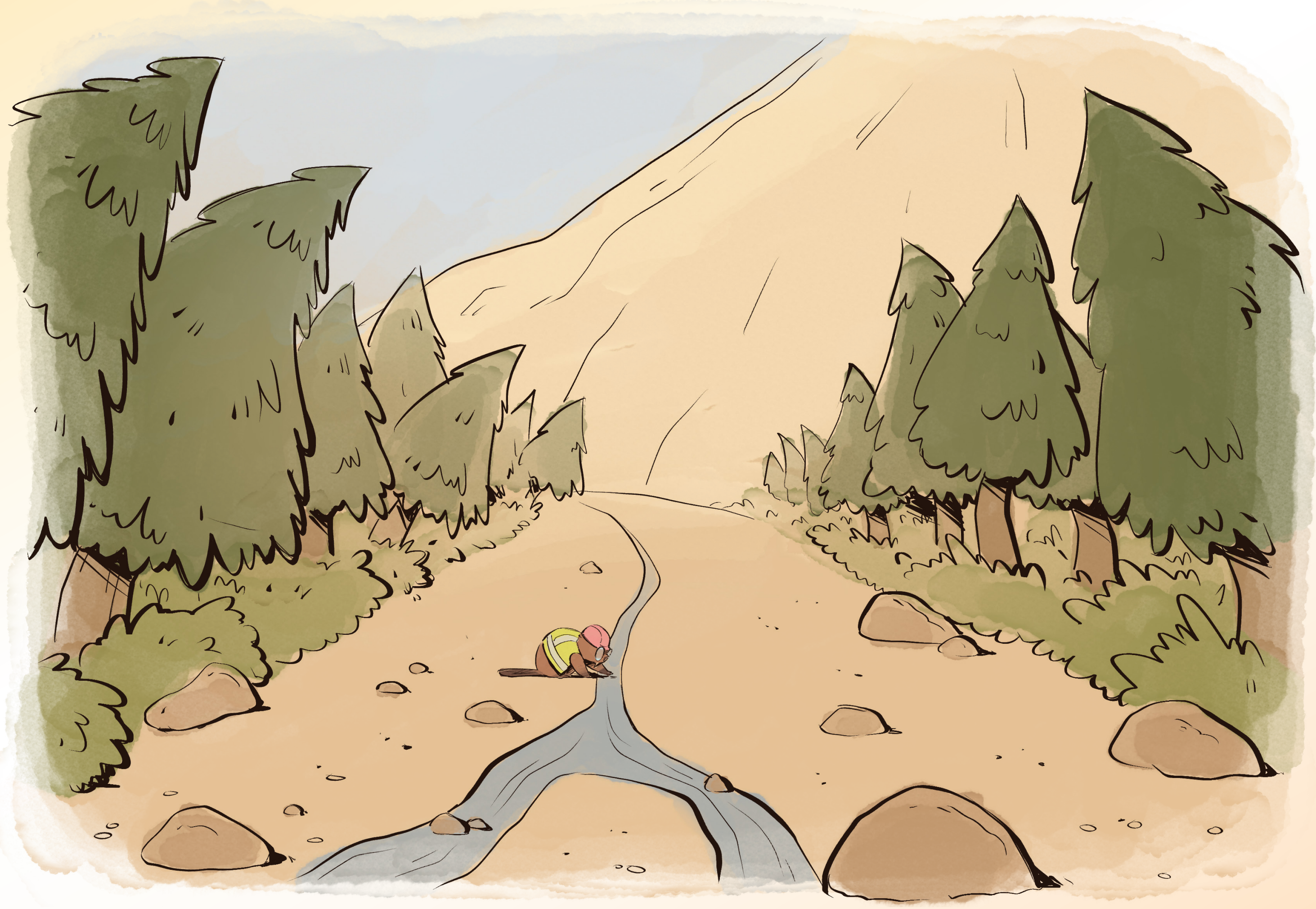


Sandy starts looking for paleoflood deposits along the river channel below the lake and finds a nice outcrop with nice layers of fine sand. She explains to her friends what a slack-water flood deposit (SWD) means.

These sand and silt sediments have been transported in suspension by flood waters, and are later deposited on high areas of valley sides, and upstream of tributaries. The height of the flood sediment layer tells us that the flood reached that location, so we can infer the depth of the flow. And multiple flood deposition layers represent different flood events whose ages can be determined in the laboratory by isotope and luminescence analysis.


Oops. This work is hard, but it's worth it to see these beautiful layers of flood sediment.
As she analyzes the sediment, she begins to measure the size of the boulders that she finds in the higher terraces. Flood waters flow faster as the volume of water increases with flood depth. As the water flows faster, it can carry larger and larger sediment particles. Therefore, Sandy knows that she can estimate the minimum flood depth needed to create enough fast-moving water to carry boulders of this size. In addition, she and a colleague begin to measure the cross-section (topography) of a critical section (change in channel slope) in order to estimate the peak discharge.
These boulders are so big, there must have been a big flood a long time ago.
These topographic measurements of this cross-section will allow us to accurately estimate the maximum discharge. In these slope changes, the flow is critical, and by measuring the height of the deposits, we can easily estimate the flow velocity and, therefore the peak discharge.
These tilted and scarred trees are so interesting and seem to have been affected by past floods. Look, because of this damage, the trees are growing abnormally. These growth responses can be used to date past floods.
When she is finished, she notices that there are many trees that are growing abnormally, with tilted trees and scars. She decides to check the tree-ring records and start to sample some trees.

How do we reconstruct past floods?



We can model the event by quantifying the age and discharge of past floods using evidence preserved in the river landscape for centuries. Dating past floods requires an exhaustive field survey to find evidence of past floods. We need to determine the age of each flood event. There are several age-dating techniques, depending on the nature of the evidence. Relative methods only allow us to determine whether a particular flood is older or younger than another. Therefore, relative dating provides the sequence of events that occurred, but not their dates or the number of years between events. Absolute dating allows us to define the time of the event in a calendar, which helps to determine the rate of occurrence, or the relationship to climatic conditions.

On the other hand, estimating the magnitude of a flood requires a combination of information from the field and the use of numerical equations. In general, these equations require knowledge of the topography of the channels and moraines and bathymetry (underwater topography) or lakes, which is often difficult to obtain. Depending on the availability of data, researchers use empirical equations to estimate the magnitude (peak discharge or volume) based on parameters that can be easily obtained (moraine geometry, lake area, etc.). Or, they use complex numerical models able to simulate the process chain, including the generation of a wave caused by the impact of a landslide into the lake, and how this wave erodes the terminal moraine and generates the outburst flood downstream.

How can we prevent future flood disasters?

A recent study suggests that the occurrence of GLOFs may increase in the future, especially in vulnerable countries (Zheng et al. 2021). Preventing future disasters will be challenging, but necessary to ensure a sustainable and more equitable world. Researchers around the world agree that quality urban planning with reliable hazard maps is the most cost-effective option for adapting to, and mitigating, future disasters. In areas where vulnerable elements (i.e. population and infrastructure) are located, the implementation of an Early Warning System (EWS) has become an alternative. However, this option has some problems related to: 1) the need to rely on measurements that could fail in harsh mountain environments, 2) the need to implement exhaustive maintenance of the systems, and 3) the problems, or false alarms, that could lead to misperception of the population i.e. "crying wolves". In addition, some EWS' have been designed to adapt to rapid socioeconomic development in the mountains, without a proper understanding of the flood processes. Therefore, EWS' should be a complement to hazard zoning and, in any case, an exclusive element for mitigation and adaptation.

Further reading

Shugar DH et al. (2021) Science 373(6552): 300-306

Benito G, Thorndycraft VR (2020) Earth-Sci Rev 200: 102996

Zaginaev V et al. (2019) Glob Planet Change 176: 50-59

Zheng G et al. (2021) Nat Clim Change 11(5): 411-417

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