



## Lahars, landslides and tsunami - the devastating impact of secondary hazards

Secondary hazards are processes triggered by an initial primary event and may occur:

- almost immediately, such as a landslide initiated by an earthquake.
- after a few hours, when a tsunami has crossed an ocean following a deep sea earthquake.
- a few years later, when rivers flood due to aggradation by landslide material. The economic and societal costs of these long term secondary hazards are often overlooked and frequently disregarded as being linked to the original hazard. This is critical because communities may not have access to disaster relief funding if the secondary hazard is not recognised as being part of the whole disaster, due to the long lag time.

Secondary hazards can make significant contributions to the total impacts of a hazard event and need to be identified so that appropriate responses and management plans can be put in place. Some impacts from secondary natural hazards are catastrophic, whilst the original primary hazard, albeit spectacular, may cause no impact at all, such as the 2004 Boxing Day tsunami.

Figure 1 is a classification identifying primary, secondary and tertiary hazards. This “multihazard” approach identifies all types of hazards following a primary event and their interrelationships. Single hazards rarely occur in isolation, and when primary hazards are understood in the context of other triggered hazards, it improves the mitigation and management of disaster risk. A primary hazard might not trigger secondary hazards but by weakening rock, may increase the probability of other hazards occurring in future.

A tsunami is always a secondary hazard because it requires an earthquake, volcano or landslide to displace a vast volume of water. Secondary hazards can trigger tertiary hazards - in the case of the Tohoku earthquake, the tertiary technological hazard was the destruction of the Fukushima nuclear power station. A landslide might occur as either a primary, secondary or tertiary hazard.

**Figure 1. Classification of primary, secondary and tertiary hazards**

Primary	Secondary	Tertiary	Example
Earthquake	Tsunami Landslides Soil liquefaction	Technological hazard Flooding Fires (burst gas pipes)	Tohoku 2011 (Fukushima) Sichuan 2008 San Francisco 1906
Volcanic eruption	Lahars Pyroclastic flow Tsunami	Flooding Volcanic winter	Nevado del Ruiz 1985 Montserrat 1997 Krakatoa 1883
Landslide	Tsunami		Lituya Bay, Alaska 1958
Hurricane	Landslide Flooding	Flooding Landslide	Typhoon Haiyan 2013 Katrina, New Orleans 2005
Drought	Wildfires	Landslide	California 2015

Work by researchers at Kings College London used a combination of space and time to analyse the relationships between primary and secondary hazards. Figure 2 shows, for example, that in the total area affected by an earthquake, aftershocks could occur in most of that area. The likelihood of aftershocks happening is high. Secondary landslides could occur in most of the areas affected by earthquakes, volcanoes and primary landslides, but they are most likely to occur in earthquake zones. Tsunami occur in some of the areas affected by earthquakes, volcanoes and landslides, but rarely do volcanic eruptions trigger tsunami.

**Figure 2. Spatial overlap and likelihood of secondary hazards (Adapted from Gill and Malamud, 2014)**

		Secondary hazards				
		Aftershocks & Tremors	Tsunami	Volcano	Landslide	Flood
Primary	Earthquake	H	M	L	H	L
	Volcano	H	L		M	M
	Landslide		M	L	M	L

Secondary hazard in **most** places  
 Secondary hazard in **some** places  
 Secondary hazard in **small % of** places  
 H = very common  
 M = occurs sometimes  
 L = occur rarely

This combination of space and time is important because once the primary hazard has occurred, the potential impact for each secondary hazard can be forecast in terms of location and likelihood, which can then be used for more effective disaster management.

### Landslides as secondary hazards

Landslides occur due to earthquakes, volcanic eruptions, flood events eroding the slope toe or wildfires that make land more vulnerable to landslides in the future. The degree of devastation by landslides depends on a combination of factors, such as:

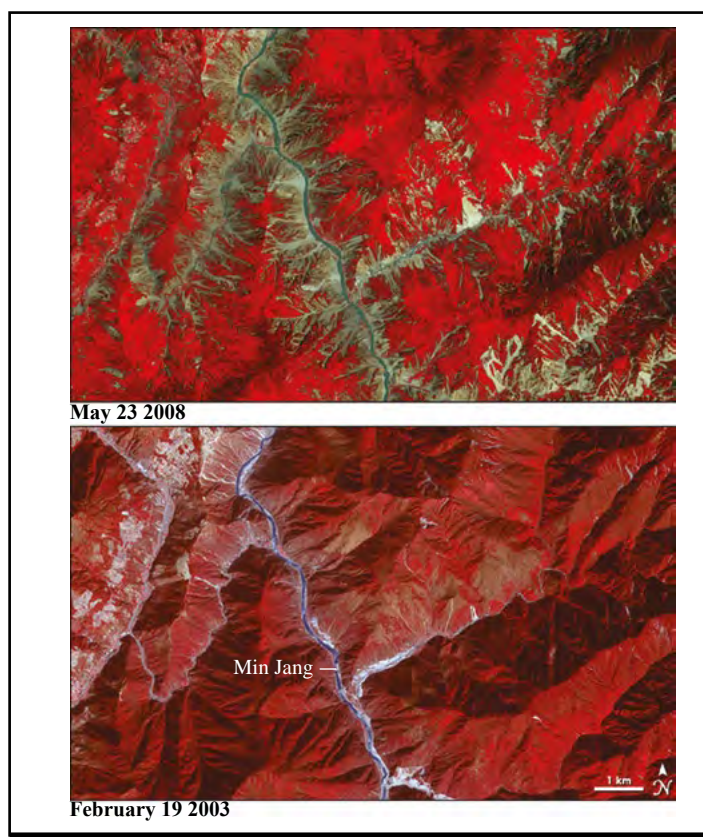
- speed of onset
- speed of movement
- slope angle
- ground saturation levels
- volume of material within the slide.

Earthquakes can lead to liquefaction if flat land has a high water content, as seen in city districts built on old lake beds, such as San Francisco. Water-saturated sediment temporarily loses strength and acts as a fluid, undermining foundations (liquefaction). When soil particles resettle, the ground is lowered. Mapping these sediments helps to predict or mitigate impact by informing preparedness planning.

### Case study – Sichuan 2008

In May 2008, an earthquake of M7.9 occurred where the eastern rim of Tibet overrides the Sichuan basin, creating the Longmen Shan mountain range. The compressional forces were so great that in places, the crust rose 9m up a shear face. The epicentre area was 300x10km and here, more than 15,000 secondary landslides, rock falls and debris flows resulted in about 20,000 deaths (out of a total of 85,000). Figure 3 shows the areal extent of secondary landslides – in 2003 some landslides can be seen (as brown patches), but the 2008 earthquake concentrated its energy at the top of slopes, maximising their impact as landslides pulled material down the whole slope. Tertiary flooding occurred as 33 lakes were created by landslide dams, causing flooding both upstream initially and then downstream flash flooding when the dams were breached.

**Figure 3. Extent of landslides in Sichuan province, seen from space (Source: NASA).**



The earthquake also caused more than 10,000 potential rock falls in deforested areas. The lag time may make it difficult to link the rock falls, when they happen, to the original earthquake and may prevent villages from claiming reconstruction funds if they cannot be proven to be connected to the primary earthquake.

**Figure 4. Impacts of the Sichuan earthquake**

#### Social impacts

85,000 deaths, approx. 1/3 from landslides  
5,300 children died in collapsed schools that were not built to building codes  
375,000 injured  
4.8 million homeless

#### Economic impacts

\$146 billion to rebuild/develop region

#### Environmental impacts

15,000 landslides  
10,000 potential rock falls  
33 lakes with debris dams >10m deep

### Lahars - volcanic secondary hazards

A lahar is an Indonesian word describing a hot or cold mix of water and volcanic debris, particularly ash, flowing down a volcano or river valley. Lahars appear as dark mudflows over snow and ice-capped volcanoes and spread out over the valley floor like a flood (Figure 5). They have the consistency, viscosity and density of wet concrete but can flow up to 70km/hr, spreading out for 100km, causing economic, social and environmental damage. Lahars travel along river valleys and destroy bridges and roads, making escape impossible, as well as being too hot, soft or deep to cross, so people get trapped.

**Figure 5. Lahars flowing down Mt St Helens (Source: USGS)**

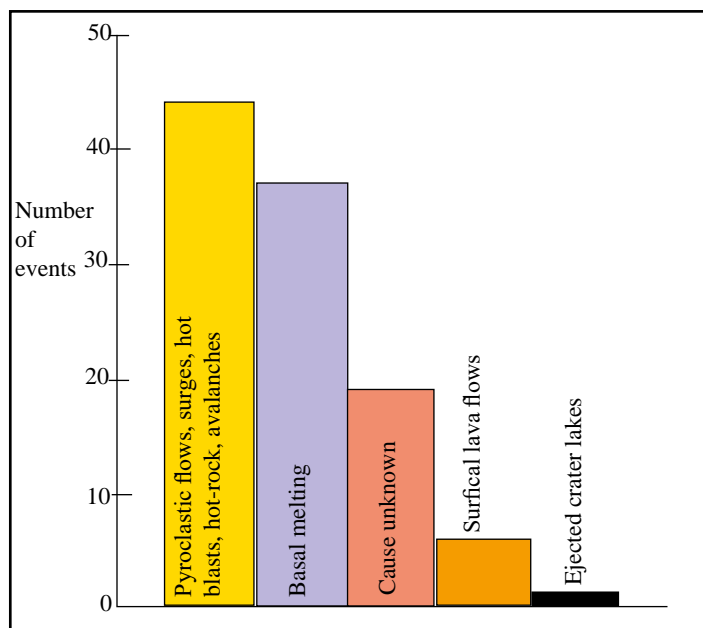


### Causes of lahars

Many of the largest and most destructive lahars are associated with volcanoes with substantial cover of snow and ice. Pyroclastic flows are the most common volcanic events that generate lahars - even relatively small events quickly melt large quantities of snow and ice (Figure 6). The eruption of lava beneath a glacier can result in substantial ponding of water, which may lead to enormous outpourings of water. The largest historic lahars in terms of discharge (volume of material per second) have occurred in Iceland, where these glacial outburst floods are called jökulhlaups. They are not typical lahars because they lack a high ash content and so appear to be "diluted" and some people regard them as flood events. Lava flows moving slowly across snow usually do not melt snow and ice rapidly enough to form large lahars.

Crater lakes rarely burst but when they do, they release huge volumes of water that mixes with ash to form lahars.

**Figure 6. Causes of lahars (Source: USGS)**

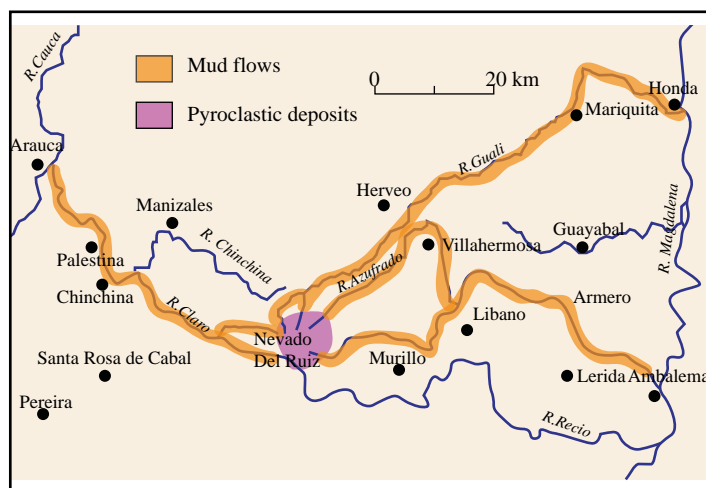


It is not always the case that larger eruptions create more devastating lahars. In 1991 Mt Pinatubo erupted with a VEI=7 but only 800 people were killed by lahars. Three years later, the lahars were reactivated by monsoon rains, representing a significant time lag and raising the question “To which primary hazard should it be ascribed – the 1991 Pinatubo eruption or the 1994 monsoon?”

### Case study – Nevado del Ruiz

The Nevado del Ruiz volcano is in the Andes, where the Nazca plate is subducting under the South American plate. It is a stratovolcano, capable of explosive eruptions although in 1985 its VEI=3, so other factors must have played a part in the destruction. 20% of its snow and ice cover was melted by pyroclastic flows and channels 100m wide and 2-4m deep were eroded into the icecap. Lahars 50m thick travelled at 60km/hr down existing river valleys (Figure 7), carrying a heavy debris load that crushed, abraded and eroded all in its path.

**Figure 7. The destructive path of lahars from Nevado del Ruiz in Colombia. (Source: USGS)**



It took the authorities two hours to realise that an evacuation was necessary but although attempts were made to tell people to leave, most did not. There were several reasons for this:

- By 7.30pm, it was dark.
- A thunderstorm was in progress.
- There had been no education and evacuation drills.
- Many people did not have the means to leave the town.

At 9.05pm part of icecap of the 5,400m volcano melted, causing rivers to overflow. A natural dam burst, releasing a torrent flowing at 45mph (70kph) and a massive mudflow over Armero. People tried to outrun or drive away from the roaring mudstones and water but died in the chaos as they jumped on vehicles.

Armero was inundated with several pulses of flowing material. At 11:25 p.m. a small flood of cold, relatively clean water overflowed from the Río Lagunillas, sweeping into downtown Armero. This water was from an upstream lake that was displaced by lahars entering the lake. Ten minutes later the main pulse of lahars overran Armero, causing 23,800 deaths, with 2000 deaths also in Chinchilla, Mariquita and Honda.

**Figure 8. Timeline of the Nevado del Ruiz disaster**

3.15pm:	First eruption.
5.15pm:	People in Armero (29,000) noticed fine dust.
5.30pm:	National Geology and Mining Institute advised evacuation.
7.30pm:	Civil Defence attempted an evacuation by going door to door, but few agreed to leave.
9.05pm:	Strong tremor on volcano followed by hot pumice and ash. 45mph (70kph) lahar developed in Lagunillas valley.
11:25pm:	A flood of cold relatively clean water (lake burst) flooded downtown Armero to a few cms.
11:35pm:	The largest pulse arrived and within 10-20 minutes, destroyed most of the buildings and swept away most of the people in Armero. Flow depths of the lahar were 2-5 m.
1:00am:	Last pulse struck Armero.

In 1988 a group of lawyers invited survivors in Manizales, Guayabal and Lerida to sue the government for gross negligence in not developing effective preparedness plans for known hazards and not giving warnings or evacuating in time. In total, 1,000 people claimed for 20,000M Colombian pesos (£40M).

It was anticipated that government lawyers would argue that people took their own risk in occupying a fertile, yet hazardous area. Instead, they argued that “enforcing evacuation” was not one of the designated functions of the Ministry of Mines and Energy. As proof of government concern, evidence was produced that the Civil Defence had gone door to door to warn people in the early stages of the eruption.

Three expert volcanologists were questioned as to whether the scale, timing and location could be accurately forecast. They said this was not possible and so the government was cleared of responsibility. However, the disaster was a catalyst for dramatic improvement in disaster protection in Colombia and an effective Governmental Preparedness System at central and provincial level was made.



## Tsunami – a secondary hazard

Tsunami are always a secondary hazard, created by a displacement of water caused by:

- submarine earthquakes
- submarine or island-based volcanoes
- submarine or land-based landslides.

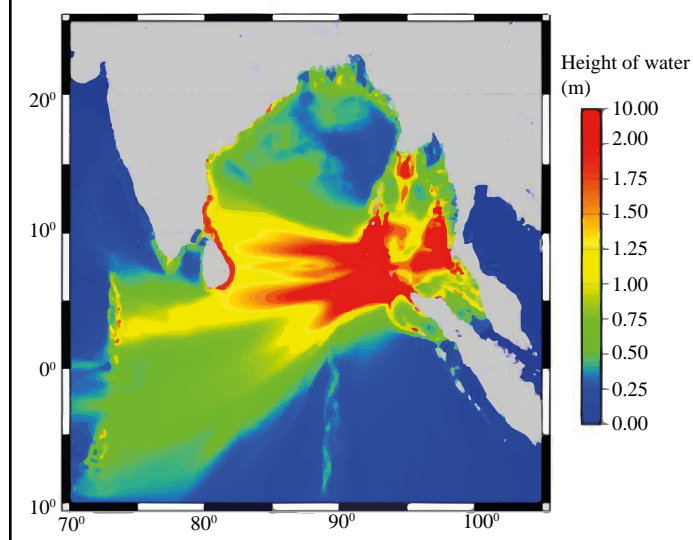
### Case study - Boxing Day 2004 (Indian Ocean) tsunami

The tsunami followed one of the four largest earthquakes ever recorded (M9.2), with the Indian plate being subducted under the Burma plate, causing a 1,600km fault rupture in a nearly north-south orientation, with the majority of slip concentrated in the southernmost 400km of the rupture. This primary hazard caused no deaths or damage but the subsequent tsunami was one of the most catastrophic disasters ever recorded, with 238,000 deaths in the following five hours.

There was significant spatial variation in its impacts. The greatest release of energy was in an east-west direction (Figure 10), meaning that Sumatra and Sri Lanka were hardest-hit. Banda Aceh suffered 31,000 deaths in the first hour. On a regional scale Bangladesh, with its low-lying coast, benefited from the fact that the earthquake proceeded more slowly in the northern rupture zone, greatly reducing the energy of water displacement.

At a local scale, there were also huge contrasts in destruction. One of the few coastal areas to evacuate ahead of the tsunami was on the Indonesian island of Simeulue, as close to the epicentre as Banda Aceh. Island folklore told of an earthquake and tsunami in 1907, and so the islanders fled to inland hills after the initial shaking and before the tsunami struck. From a population of 78,000, there were only 7 deaths.

**Figure 10. Energy released by the 2004 tsunami, as measured by wave height**

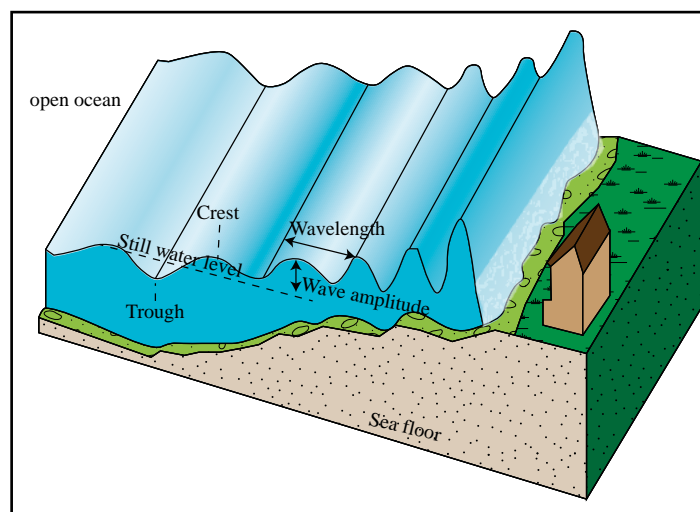


### Factors determining the destructiveness of tsunami

#### 1. Wave energy:

When a tsunami is generated out to sea, the water displacement can form waves with wavelengths greater than 100km. The longer the wavelength, the greater the volume of water and more energy is conserved. In deep water no energy is lost to frictional drag with the seabed. As it approaches the shore, the water becomes shallower, forcing the circular wave motion into an elliptical form, which heightens until it can no longer be maintained and breaks. This is called shoaling, and causes destructive flooding.

**Figure 11. Generation of a tsunami (Source: Waikato Regional Council)**



#### 2. Shape of coastline:

Indented coastlines with long, narrow bays concentrate energy on the bay head due to a funneling effect as the wave travels up the bay, as happened at Anchorage in 1964. Irregular coastlines and offshore islands can set up interference patterns in the waves which, when they coincide perfectly, can accentuate the waveform.

#### 3. Relief of coastline:

Cliffs present a natural barrier to a tsunami, but low-lying land allows seawater to incur for several kilometres, such as in Sendai, Japan in 2011.

#### 4. Presence of natural defences:

Coral and mangroves act as natural defences by dissipating wave energy through their large surface areas. Tourist developments have removed much mangrove vegetation and this exacerbated the impact in the Indian Ocean 2004 disaster.

#### 5. Demography:

In all natural disasters, the old and young are most vulnerable due to their lack of mobility and strength. In the Tohoku 2011 disaster, 65% of deaths were those aged over 60 and in the 2004 tsunami, >30% of deaths were children. Also significant in 2004 was the gender count – 80% of deaths were female, explained by traditional lifestyles. Men were fishing at sea, the safest place to be in a tsunami, whilst women were performing their domestic roles and looking after children at home on the coast.

#### 6. Lack of experience:

The 2004 tsunami occurred at holiday time when there were many foreign visitors to the region. 2,500 tourists lost their lives, 50% of these being German and Swedish. Also, globalisation and emigration have led to local communities losing their history of past events.

#### 7. Lack of, or inadequate, warning systems and evacuation plans:

The Japanese have long protected their coastline against tsunami but in 2011, the walls were not high enough and 20,000 lives were lost, together with the destruction of the Fukushima nuclear power station. The latter had global implications because other countries reviewed their nuclear energy policies and Germany brought forward the phasing out of nuclear power from 2036 to 2022.

The Indian Ocean did not have a tsunami warning system because it was thought that the region could not produce such a powerful earthquake. In 2005 the Indian Ocean Tsunami Warning System (IOTWS) began to be constructed, and whilst a tsunami cannot be predicted, modeling scenarios is a vital preparation tool for communities.

### The importance of secondary hazards in preparedness planning

Technology alone is not sufficient in defending against both primary and secondary hazards. Development of resilient communities is essential, which are educated in hazard risk and develop their social and physical environments in ways that mitigate that risk. When major disasters happen, it is understandable that there is a focus on immediate relief and repairing infrastructure. But allocating scarce redevelopment resources very rapidly after an event may be wasteful if it is done before the extent and severity of secondary phenomena are recorded and understood. At worst, redevelopment may be overrun by secondary hazards that have still to occur. For example, a river disturbed by landslide debris may flood many times in future. Risk assessment needs to take into account secondary events that have not yet occurred, but this is a very difficult concept when communities are desperate for immediate relief.

### Summary

1. If the linkages between primary and secondary hazards are better understood, post-disaster response can be improved.
2. An interdisciplinary approach will enable flood managers, civil engineers, social planners, finance officers, local government officers etc. to interact and enable them to do their own jobs more effectively.
3. A holistic approach will ensure a better allocation of post-event resources in space and time, and improve future risk reduction measures.
4. A better understanding of the role of secondary hazards will assist in restoring resilience and independence to affected communities, by ensuring that efforts to rebuild infrastructure and economic capacity are not frustrated by secondary hazards.

### Further Research

Reviewing and visualizing the interactions of natural hazards. Gill and Malamud  
<http://onlinelibrary.wiley.com/doi/10.1002/2013RG000445/abstract>

Summary of Nevado del Ruiz

[http://www.geology.sdsu.edu/how\\_volcanoes\\_work/Nevado.html](http://www.geology.sdsu.edu/how_volcanoes_work/Nevado.html)

Sichuan landslides

[https://en.wikipedia.org/wiki/2008\\_Sichuan\\_earthquake](https://en.wikipedia.org/wiki/2008_Sichuan_earthquake)

Tsunami

<http://www.noaa.gov/factsheets/new%20version/tsunamis.pdf>

Light relief but thought-provoking!

<http://xkcd.com/1611/>

### Acknowledgements;

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