

Catastrophic Remobilization of Sediment During Extreme Rainfall Events

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ABSTRACT

Sediment production in mountainous areas occurs through a range of processes that operate at varying pace, from very slow, e.g., chemical transformation of bedrock to regolith, to very fast, e.g., mass wasting during earthquakes and storms. The latter are responsible for the production of vast amounts of sediment in a short period of time, that become available for transport downstream by fluvial processes. However, recent work has shown that only a small fraction of the sediment produced in mountainous areas is immediately evacuated downstream, with the remainder stabilizing on upland slopes and in valleys where it can remain stored for periods of time exceeding millennia. When the “right set” of conditions occurs, which usually involves extremely intense rainfall, this sediment can suddenly be remobilized in bulk and transported downstream, leading to extreme sediment transport and deposition with catastrophic consequences for communities downstream. Extreme rainfall events are becoming more frequent: events with precipitations exceeding 500 mm are being recorded all around the world every year. In this presentation, we will explore rainfall events that mobilized vast amounts of sediment in a series of locations and discuss the processes associated with such events, from their initiation to the bulking that makes them deadly. We will then discuss perspectives for mitigation of the risks associated with such events, including the identification of “sediment bombs” in mountainous areas, the prediction of extreme meteorological events with greater accuracy and resolution, and the identification of specific “points of failure” within river systems.

Sediment production versus sediment export

In most modern mountainous landscapes, there is excess sediment available for transport by rivers: the pace at which sediment is produced is far greater than the pace at which sediment is exported out of mountain ranges. This has been evidenced on a range of timescales: Blöthe and Korup (2013) showed that around 700 km³ of sediment are stored across the Himalayan Range, with sediment residence time in the order of 100 ky. In the Pokhara valley at the feet of the Annapurna range, Stolle et al. (2017) related an extensive 5 km³ valley fill to three great earthquakes that occurred between AD 1100 and AD 1344, while Lavé et al. (2023) documented a 23 km³ mega-landslide resulting from the collapse of an 8,000-m peak in AD

1190. A large part of the sediment associated with these events remains within the mountainous realm. On a shorter timescale, Francis et al. (2022) showed that less than 10 % of the total sediment produced during the 2008 Wenchuan earthquake in Sichuan has been exported to the main Min River in the decade that followed the earthquake. The retreat of glaciers is also exposing glacial sediment stores which, due to their poorly consolidated nature, can be easily remobilized. While the retreat of glaciers in itself is causing its own set of hazards, such as Glacial Lake Outburst Floods (GLOFs) (Richardson and Reynolds, 2000; Zhang et al., 2024), the exposure of glacial sediment that can be reworked by non-GLOF processes is important to consider. Reworking has been documented in many high-altitude and high-latitude landscapes, from the tectonically quiescent landscapes of Scotland to the steep, actively incising Sedungpu Gully in NE Himalaya (Ballantyne, 2002, 2019; Harries et al., 2021; Towers et al., 2025; Li et al., 2025). Permafrost degradation is also making new sediment stores available to erosion processes, as seen for example through increases in sediment flux to rivers on the Tibetan Plateau (Li et al., 2024).

Extreme rainfall events and the catastrophic remobilization of sediment

Over the last couple of decades, there has been an increase in extreme rainfall events around the world, in a wide range of environments and climates, with catastrophic consequences that now regularly make the news. While they take different names in the literature and the news, such as “Severe Convective Storms” (SCSs), “cloudbursts”, “Heavy-Precipitation Events” (HPEs), “atmospheric rivers” or “Mediterranean episodes”, these events always involve very large amounts of water falling in a short period of time, with the total rainfall during such events (lasting from one to three days) regularly reaching the incredible value of 500 mm. The sheer volumes of water involved can devastate cities, as exemplified by the Beijing floods on 21st July 2012 (<https://earthobservatory.nasa.gov/images/78626/heavy-rains-in-beijing>), during which rainfall reached 460 mm in the Fangshan District, and which caused around 80 casualties and ¥12 bn economic losses, or the Zhengzhou floods on 20th July 2021 during which the city received 617 mm of rainfall in three days. The latter event led to around 400 casualties and more than ¥130 bn economic losses, potentially aggravated by the human response (Guo et al., 2023). Among the four major flood disasters in Henan Province since 1949 (which had a probability ranging between 1-in-300 and 1-in-1000 years), three occurred in the past two decades in July 2007, July 2016 and July 2021 (Guo et al., 2023).

While water itself can cause considerable damage, many recent extreme rainfall events were compounded by the involvement of sediment. Some areas of the world are more prone to such disaster, such as the steep areas of the Uttarakhand State in northern India that sadly experienced a series of disasters in the past 12 years, all involving the transport and deposition of significant amounts of sediment. The Kedarnath disaster on 16-17th June 2013 was triggered by a cloudburst during which rainfall reached 325 mm in 24 hours (Dobhal et al., 2013), causing a lake outburst and tens of meters of erosion and deposition in the Kedarnath Valley (Devrani et al., 2015). More recently, the Dharali village (location: 31.040701099576886, 78.78129644598587) was entirely destroyed following a debris flow triggered by a cloudburst on the 5th August 2025. The village was built on a debris fan, like many villages in steep mountain ranges; embankments were built along the active channel to protect the village from debris flows. However, the magnitude of potential debris flows was underestimated, with the

2025 event leading to the entire debris fan being reoccupied, the buildings destroyed, and the village buried (https://www.isro.gov.in/indian_satellite_data_based_analysis_of_the_dharali_flash_flood.html).

Mass movement of hillslope sediment is sometimes generated by the heavy rainfall event itself, as was the case in the State of Vargas, a mountainous coastal region in Northern Venezuela, in December 1999. Extremely intense rainfall exceeding 900 mm in three days led to widespread landsliding, with many steep hillslopes being stripped of their soils during the event, and subsequent debris flows that devastated the coastal towns built on alluvial fans, causing around 15,000 casualties (Lopez and Courtel, 1999; Larsen and Wieczorek, 2006). While the extreme rainfall intensity is the main factor controlling the risks associated with such events, deficiencies in identifying potential sediment sources are leading to an underestimation of the risks. In the following, we describe a series of disasters during which the remobilization of overlooked sediment stores has led to consequences far worse than could have been anticipated.

The Melamchi disaster in Central Nepal began on 14th June 2021, leading to the erosion (and subsequent deposition) of a volume of 75 Mm³ of sediment within the Melamchi catchment (Chen et al., 2025). While the trigger of the disaster has been debated, the widespread mobilization of sediment in the headwaters of the catchment, far upstream of the locus of co-seismic landsliding associated with the 2015 Gorkha earthquake, suggests a hydrometeorological origin, even if river blockage by a landslide and subsequent lake outburst will have likely contributed to the severity of the event (Maharjan et al., 2021; Graf et al., 2024; Chen et al., 2025). Importantly, 64% of the total eroded sediment came from a valley fill in the headwaters of the catchment, at Bremathang. The fill is the result of an old landslide-dam or moraine-dam lake which filled up with sediment over time (Figure 1). The extreme hydrometeorological event which initiated further upstream caused incision into the old landslide dam, thereby exposing vast amounts of fine, poorly-consolidated lake sediment to erosion (Figure 1). Mobilization of large amounts of sediment has contributed to the devastating nature of the Melamchi flood: while the upper reaches of the catchment were dominated by erosion, the lower reaches experienced catastrophic deposition of sediment over thicknesses exceeding 10 m, including the destruction and burial of large parts of the town of Melamchi (including buildings, roads and bridges – location: 27.83045859598847, 85.57779104416024). While the Bremathang valley fill has likely remained stable for centuries to millennia, a threshold was overcome which allowed mobilization of the boulder-armored landslide dam and release of the sediment stored behind (Graf et al., 2024; Chen et al., 2025).

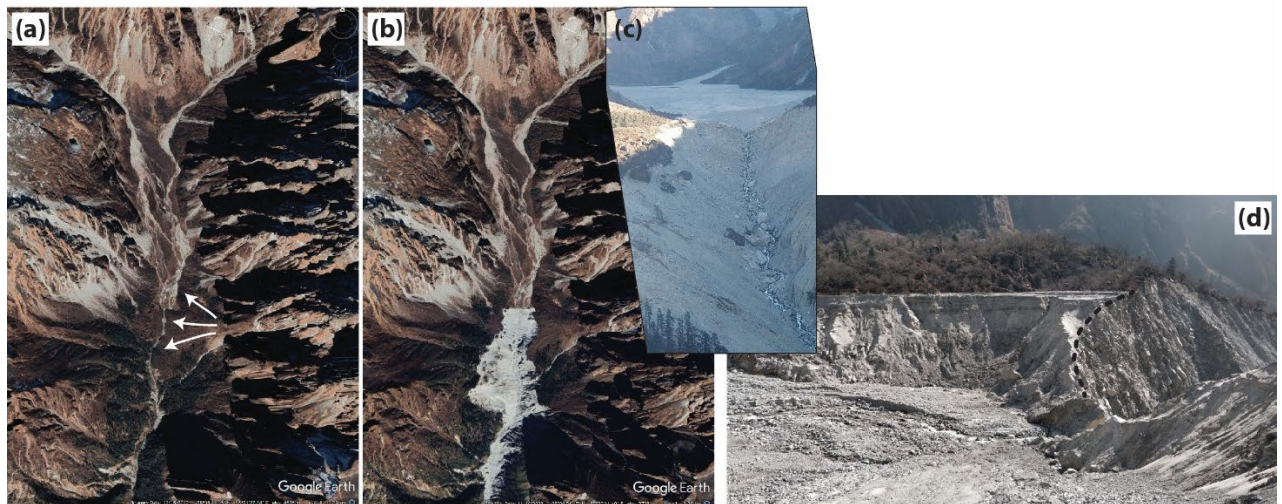


Figure 1. the Bremathang valley fill (location: 28.087918468136046, 85.54569419230117), major source of sediment for the Melamchi disaster. (a, b) satellite images of the valley fill before and after the disaster (source Google Earth, © 2025 CNES / Airbus); images are 3 km wide. (a) from December 2017, showing low-gradient wide valley fill in an otherwise steep landscape with narrow gorge; arrows show location of inferred palaeo-landslide dam that caused the valley fill. (b) from November 2023, showing incision into valley fill, most of which occurred in the month after the disaster. (c, d) photos of the incised valley fill post-disaster (source B. Raj Adhikari). (c) is view upstream (north) while (d) shows the contact between the horizontally-bedded valley fill (north, left) and the boulder-rich landslide dam (right, south) at the breach point (dashed line).

A similar event occurred in the French Maritime Alps during a Mediterranean episode associated with Storm Alex on the 2nd-3rd October 2020. Water levels in the Roya, Tinée and Vésubie, three mountain catchments with drainage area ranging from 400 to 750 km², rose from less than a meter to more than 8 meters in a few hours, with discharges exceeding 800 m³/s, breaking all historical records (Arbizzi et al., 2021). More than 500 mm of rainfall fell on the town of St-Martin-Vésubie in 24 hours, leading to widespread devastation along what would have been considered a “small perennial mountain stream” before the event (Figure 2). The event caused 18 casualties and around €1 bn worth of damages (Arbizzi et al., 2021). Liebault et al. (2024) estimated that more than 4 Mm³ of sediment were mobilized during the event in the Vésubie valley, leading to the valley floor rising by 2.4 m on average, but with very large spatial variations: while deposition was dominant in the downstream reaches, the upper reaches experienced widespread erosion, with erosion and aggradation both exceeding 10 meters in places. Satellite imagery shows sediment mobilization in the form of debris flows on the hillslopes in the headwaters, but a significant fraction of the sediment came from the valley floor (Figure 2): the flood was powerful enough to mobilize the glacial and fluvio-glacial sediment that occupied the valley bottom and on which infrastructure and houses were built. Today, the devastation remains visible. Sediment is regularly remobilized during storms, as large amounts of unconsolidated sediment have been exposed both on the valley floor and on the now undermined hillslopes (Figure 2), complicating the task of the authorities in terms of managing the new valley planform. Morche and Schmidt (2012) demonstrated that elevated bedload sediment flux persisted for years following a dam break event on the Partnach River in the Bavarian Alps, due to the reactivation and destabilization of hillslopes and debris fans that were undermined by the flood.

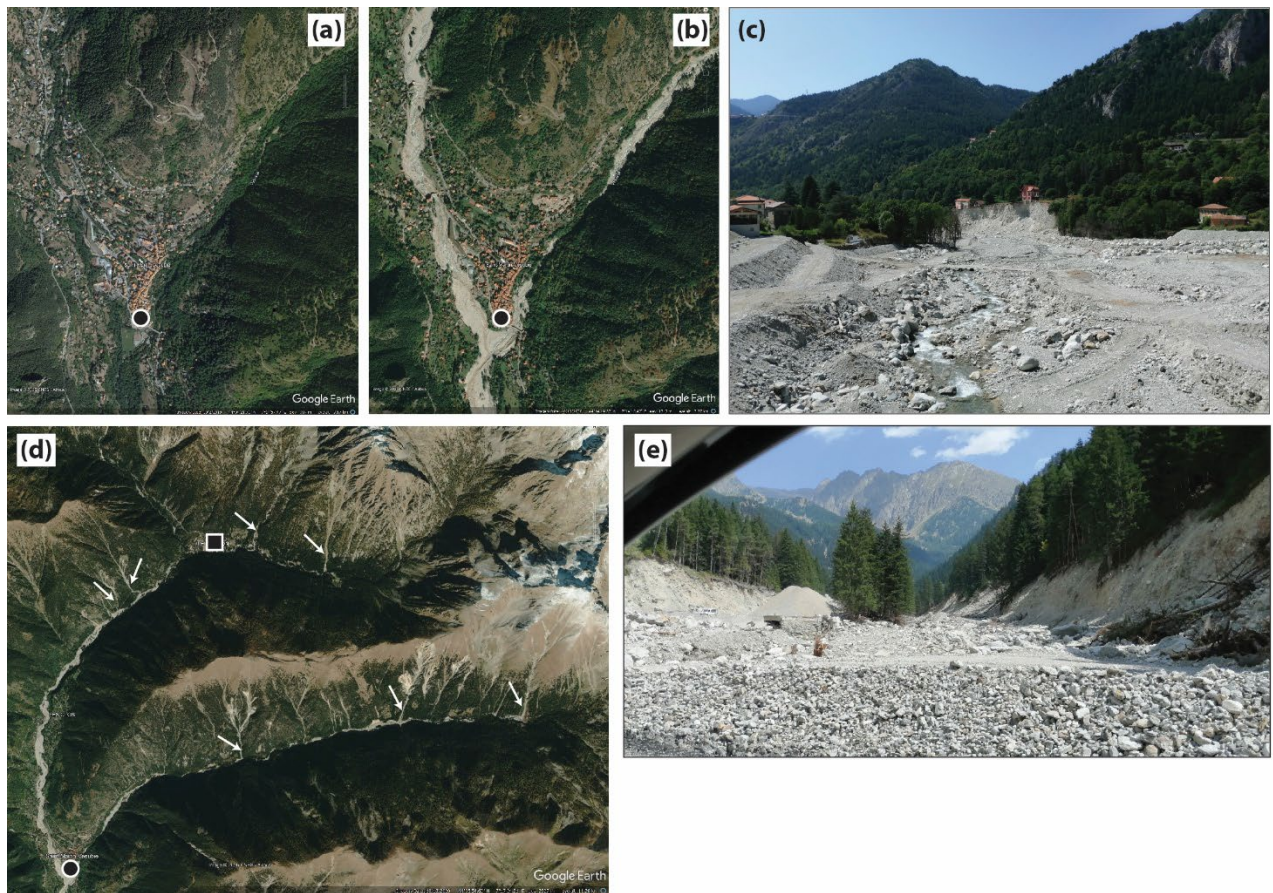


Figure 2: the picturesque town of St-Martin-Vésubie in the French Maritime Alps (location: 44.06847838205745, 7.255973985023541). (a, b) satellite images before and after Storm Alex, taken in Nov. 2017 and on the 13th Oct. 2020, respectively; images are 1.7 km wide. Images show catastrophic widening of the active channel during the event. Dot shows the southern tip of the village from where picture (c) was taken. (c) picture taken in Aug. 2021, looking downstream (south) of the village, showing the amount of incision into fluvio-glacial valley fill. (d) satellite image showing upper part of the catchment, with arrows indicating debris flow channels likely reactivated during the event; image is 9 km wide. Most of the sediment mobilized came from the valley bottoms and adjacent hillslopes in the area, with deposition becoming dominant kilometres downstream of St-Martin-Vésubie. Square is “Le Boréon”. (e) picture taken in Aug. 2021 on the way up to Le Boréon, showing widespread sediment mobilization, valley widening and undermined glacial sediment on hillslopes. Source of (a, b, d): Google Earth, © 2025 CNES / Airbus; source of (c, e): M. Attal.

Another event further north exemplifies that extremely intense rainfall events are mobilizing sediment stores that had been stable historically. The hamlet of La Bérarde in the French Alps (location 44.93288961822468, 6.2914449436261535) was destroyed by a flash flood in June 2024. While the hamlet was clearly built on an alluvial fan, the fan had not been active in historical times, as demonstrated by the existence and destruction of historical buildings within the hamlet, including a church built in 1892.

Identification and mitigation of risks

Better prediction of extreme storms and associated river discharges is an essential step forward (Wang et al., 2023; Ma et al., 2024; Pons et al., 2024). The resolution and accuracy of rainfall predictions is increasing in both space and time, with Gourbesville (2025) highlighting for example that the authorities were better prepared for the Maritime Alps floods of 2020 described in the previous section compared to an event of similar magnitude that occurred in the Var catchment (which contains the Tinée, Vésubie and Roya) on the 5th November 1995.

Importantly, the capacity that floods have in terms of mobilizing vast amounts of sediment, not only from hillslopes but also sediment that had been stored historically in valley bottoms, needs to be considered when forecasting risk and considering engineering solutions (Wang et al., 2023). The identification of “sediment bombs” (Cook et al., 2022) such as the Bremathang and St-Martin-Vésubie valley fills is an important step that may have been overlooked. It is important to consider that the mobilization of some of these sediment stores resulted from a threshold being overcome at a given location, e.g., incision of the landslide dam at the Bremathang which led to the exposure and erosion of the fine-grained, poorly consolidated valley fill (Figure 1). Identification of such potential “points of failure” and potential engineering solutions may be worth considering, although access challenges and prohibitive costs for high mountain areas may preclude such solutions; in such instances, early warning systems may be implemented to safeguard lives.

Many engineering solutions still ignore or poorly consider the importance of sediment. Embankments that are still regularly used to contain flood waters and allow urban expansion on floodplains can sometimes exacerbate flood risk when sediment transport has been overlooked, as exemplified by the recent floods in Kathmandu, Nepal, in September 2024 (Thapa et al., 2023, 2024; Cook, 2024). Engineering solutions that may also be effective on the short-term may heighten risks on the longer term. Following the Wenchuan earthquake in 2008, many check dams were built in steep tributaries of major rivers such as the Min River to retain sediment generated by hillslope instabilities following the earthquake (He et al., 2022). However, many of these tributaries experienced “catastrophic” or “large” debris flows years to decade later, with the debris flows reaching the main river valleys where they caused serious damage to dwellings and infrastructure that should have been safe (He et al., 2022; Harvey et al., 2025). Recent work by Harvey et al. (2025) shows that the accumulation of sediment within channels following the Wenchuan earthquake has contributed to the devastating nature of the subsequent debris flows. They showed that while the degree of bed saturation is an important driver of large debris flows, the amount of sediment stored on the channel bed is the primary factor controlling the likelihood of large, highly mobile debris flows occurring. The entrainment of sediment available on the valley floor can lead to the bulking of the debris flows and extend their reach, with runouts potentially exceeding tens of km and total volumes of entrained sediment far exceeding the initial volume mobilized on the hillslopes (Harvey et al., 2025). Sediment stored in the check dams may “fuel” large debris flows, thereby increasing risk for the population and infrastructure that they should have protected.

While there may be no engineering solution capable of completely negating the risks associated with extreme storm events due to their sheer magnitude (Gourbesville, 2025), better identification of potential sediment sources, including those that have been historically stable, can help better quantify the risks associated with sediment-related hazards (see also Yanites et

al., 2025), develop more effective engineering solutions and warning systems, better prepare communities and local authorities, and therefore reduce the risks and the costs, both economic and human, associated with such events.

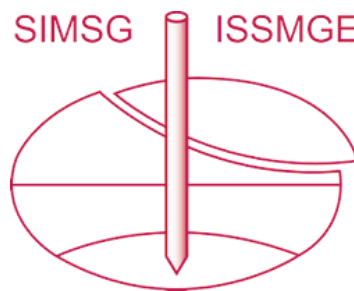
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