Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The 2021 Melamchi Flood: A massive erosional cascade in the Himalayan Mountains of central Nepal

Chan-Mao Chen

chanmaoc@usc.edu

University of Southern California

James Hollingsworth

Université Grenoble-Alpes https://orcid.org/0000-0003-0122-296X

Marin Clark

University of Michigan

Dimitrios Zekkos

Department of Civil and Environmental Engineering, University of California at Berkeley

Deepak Chamlagain

Department of Geology, Tri-Chandra Multiple Campus

Sujata Bista

Department of Geology, Tri-Chandra Multiple Campus

Anuj Siwakoti

Department of Geology, Tri-Chandra Multiple Campus

A. Joshua West

University of Southern California https://orcid.org/0000-0001-6909-1471

Article

Keywords:

Posted Date: April 6th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2766739/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: There is **NO** Competing Interest.

Version of Record: A version of this preprint was published at Nature Geoscience on December 4th, 2024. See the published version at https://doi.org/10.1038/s41561-024-01596-x.

Abstract

Large, sediment-laden floods in mountainous terrain can have disastrous consequences and play important roles in landscape evolution. These events often unfold as a series of interconnected processes, but understanding of such “hazard cascades” has been hampered by lack of quantitative data on sediment movement. Here, we use a time series of high-resolution satellite imagery to quantify erosion and aggradation during the 2021 Melamchi Khola Floods in the Himalaya of central Nepal, providing a unique sediment budget for such an event. Our analysis reveals massive headwater erosion via remobilization of Gorkha landslides, gullying, debris-flows, and incision of glacial deposits. Unlike many other high mountain floods, the widely distributed erosion suggests this event was not primarily driven by a single source, e.g., glacial lake or landslide dam failure. High sediment supply caused aggradation in a high-elevation, low-relief glacial valley and triggered catastrophic incision into associated ancient fills. As this material was transported downstream, it caused further riverbed incision that in turn resulted in failures of surrounding hillslopes. Further downstream, as river steepness diminished, the main channel in the lower basin was widened by 3-5-fold and aggraded by ~ 5–20 m. However, deposition in the Melamchi Khola was not enough to accommodate the vast amount of flood material, and over 70% was delivered from the Melamchi Khola to the downstream Indrawati basin. Our sediment budget provides rare insight into the chain of events involved in a massive flood and helps shed light on how such floods can magnify hazard and reshape the fluvial landscape.

Main Text

The frequent occurrence of catastrophic flooding events along the Himalayan arc poses a threat to the rapidly growing populations in South Asia (Wasson et al., 2013; Dimri et al., 2016; Veh et al., 2020). These floods can form in various ways (Ruiz-Villanueva et al., 2017; Cook et al., 2018; Shugar et al., 2021), and understanding of their mechanisms and dynamics is critical for hazard management (Merz et al., 2021; Gautam et al., 2022; S. Sharma et al., 2022) as well as for understanding their role in landscape evolution (Cenderelli & Wohl, 2003; Larsen & Montgomery, 2012; Hu et al., 2021; Dahlquist & West, 2022). Several insights have been gained from observations and modeling of recent events (Sundriyal et al., 2015; Cook et al., 2018; Kumar et al., 2018; Turzewski et al., 2019) as well as paleo-floods (Montgomery et al., 2004; Srivastava et al., 2017; C. P. Sharma et al., 2022). A common theme in this past work is the importance of sediment in magnifying flooding hazards and determining their long-term landscape imprint. Yet quantitative information about sediment erosion and deposition along river courses during major floods is scarce (Anderson et al., 2015; Heckmann & Vericat, 2018; Calle et al., 2020). The 2021 Melamchi Flood in central Nepal provides a rare opportunity to quantify how a complex sediment-driven flood initiates and how sediment is transported during extreme events in steep landscapes.

The 2021 Melamchi Floods occurred in the Melamchi Khola Valley, where topography changes from more subdued in the south to high mountains in the north associated with a pronounced gradient in rock uplift and exhumation driven by Himalayan tectonics (Medwedeff et al., 2022). Approximately 6 years before the flood, the 2015 Mw7.8 Gorkha earthquake produced more than 1500 landslides in the

catchment (Roback et al., 2018). The Melamchi Flood occurred on June 15, 2021, during the monsoon season, when accumulated rainfall reached 800 mm following monsoon initiation on May 25 (Maharjan et al., 2021). Weather stations installed in high elevation areas suggest that pre-saturation of the watershed, snowmelt, and rain-on-snow may have played roles in generating the flood volume (Maharjan et al., 2021). Landslide or glacial damming and subsequent outburst flooding have also been proposed (Maharjan et al., 2021; Takamatsu et al., 2022; Talchabhadel et al., 2023). The flood was one of the most damaging geohazards in recent years in Nepal, killing 25 people, destroying hundreds of houses, and damaging critical infrastructure, including the headworks of the Melamchi Water Supply Project (MWSP) that was designed to supply 170 million liters of drinking water to Kathmandu Valley per day (Joshi et al., 2021; Pandey et al., 2021). Despite its severity, how this disaster unfolded remains unclear. Some sediment sources have been identified by previous reports (Maharjan et al., 2021; Takamatsu et al., 2022), but the erosion and deposition patterns have not yet been examined comprehensively.

This study takes advantage of a time series of high-resolution (< 1 m spatial resolution), optical satellite imagery to provide unique constraints on erosion and aggradation associated with this event. We analyzed satellite imagery of the Melamchi Valley collected at 4 times that span the time period of the 2015 Gorkha earthquake and the 2021 Melamchi Floods: imagery collected in 2014 (before the earthquake), in 2017 (after the earthquake), in 2020 (before the flood), and in October 2021 (shortly after the flood). We primarily used Astrium's Pléiades imagery, supplemented with DigitalGlobe Worldview-2 data and Google Earth imagery (Figure S1). We used visible spectral contrast to map landslides and changes in the river channel between image collection times. We also generated digital elevation models (DEMs) from the 2020 and 2021 Pléiades imagery via the NASA Ames Stereo Pipeline (ASP) (Broxton & Edwards, 2008; Moratto et al., 2010; Beyer et al., 2018). We compared the 2020 and 2021 DEMs to quantify erosion and deposition associated with the flood and calculate a sediment budget (Methods).

Complex And Widely Distributed Erosion In The Headwaters

Our mapping indicates that the flood caused 1529 mass movements, concentrated at the headwater areas (Figs. 1, 2, S2). One quarter of these were re-activations of pre-existing landslides associated with the Gorkha earthquake, representing 6.4% and 9.4% of the co-seismic and post-seismic landslides in the catchment, respectively. The other ~ 75% of the mass movements during the flood were from various processes, primarily (1) gullying on hillslopes, (2) debris flows in low-order channels, and (3) lateral erosion and incision of ancient glacial deposits and valley fills. In terms of fluvial connectivity (Li et al., 2016), over 90% of these three types of mass movements were linked to the rivers, whereas only a half of re-activated Gorkha landslides were connected. These processes were observed in all of the headwater tributaries of the Melamchi Khola, suggesting a widely distributed style of erosion rather than a single dominant source (Figure S4). Yet the degree of erosion varied in each tributary. The Pemdang Khola experienced the most intense erosion where local moraine deposits were incised by up to 40 m, and hillslopes developed tens of new gullies (Fig. 2d). According to our DEM differencing results, headwater erosion in the four major headwater tributary rivers supplied 10.1 $\pm$ 8.11 million m^3 of sediment

(reported uncertainties are upper bounds; see Methods). The Pemdang Khola accounted for three quarters this headwater sediment supply, likely facilitated by breaching of a small (1175 m^2) moraine-dam lake at 4725 m.

As the sediment was transported out from the low-order tributaries into the mainstem of the Melamchi Khola, 5.75 $\pm$ 3.04 Mm^3 of the material was deposited in the low-relief, braided glacial valley at Bremthang. The riverbed in this area aggraded by 5–10 m, forming a 500 x 1900 m floodplain at 3600 m (Fig. 2e). The aggradation created favorable conditions for backwater damming that could have been responsible for later phases of flooding, including on July 31. Before the Melamchi Flood, the valley at Bremthang already preserved a large volume of sediment (Cook et al., 2022), likely a combined product of fluvial, colluvial, and glacial processes. A prominent knickpoint had developed at the downstream end of the valley fills (Fig. 1d). During the flood, the river cut into the fill as it drained through the steepened reach, causing massive knickpoint retreat and a 2500-m-long stretch of erosion with tens of large riverbank landslides. Our DEM differencing reveals incision up to 133 m, and 50.27 $\pm$ 9.75 million m^3 of material released into the fluvial system, served as the largest sediment source of the flood. Outburst flooding may have occurred at Bremthang (Maharjan et al., 2021; Takamatsu et al., 2022; Talchabhadel et al., 2023), potentially contributing to incision at the knickpoint, but cannot have been the primary cause of the disaster as a whole since we observe widespread erosion in the tributaries upstream (Fig. 1, S4).

A Cascade Of Sediment Hazard: Undercutting And Slope Failure, Then Aggradation

Taking advantage of steep narrow channels and high flood discharge, almost all the sediment from the headwater areas was transported to the lower basin. This led to 10–30 m downcutting of the riverbed in the middle reach and several large failures on surrounding hillslopes and terraces that were undercut (Fig. 1d, e). The largest failure occurred on the flank of the terrace where the village of Melamchigaon is located. Some debris still remains on the slope, but 6.23 $\pm$ 1.02 million m^3 of material has been released into the river. A simple slope stability analysis shows that 10–20 m undercutting at the terrace foot, similar to the incision we observe during the flood, could have caused this failure (Figure S6). Previous studies suggested that the Melamchigaon landslide caused temporary damming of the Melamchi Khola and worsened the flood damage (Pandey et al., 2021; Takamatsu et al., 2022). We cannot rule out such damming from our analysis but note that this collapse and damming was neither the primary cause of the flood, which must have initiated further upstream, nor the dominant sediment source. However, our data suggest that it may have magnified the downstream effects by contributing additional sediment, emphasizing the role of multiple connected processes in this cascade.

The flood started to deposit sediment as it reached lower-slope channels in the lower basin. Before the flood, the mainstem of the Melamchi Khola was ~ 30–60 m wide. To accommodate vast flood materials (17.2 $\pm$ 6.23 million m^3), it widened to 100–300 m while aggrading by ~ 5–20 m (Fig. 1e, 3c). The river section 10–20 km upstream from the confluence experienced the most intense aggradation. Such

sediment aggradation and river widening also caused significant erosion (e.g., by removal of debris fans, terrace collapses and riverbank landslides; totaling 5.34 ± 2.35 million m^3) and destroyed local communities. Our mapping from satellite imagery revealed that more than 700 houses were lost or damaged, and about 3 km^2 of farmland disappeared (Figure S7).

Our sediment budget from DEM differencing indicates that the total erosion along the river was 83.24 million m^3, whereas deposition in the Melamchi Valley was only 23.24 million m^3 (Fig. 4). This implies that more than 70% of sediment has been transported into the Indrawati Khola, the river immediately downstream. Since most of the material was from the headwater areas, the sediment transport distance was over 30–40 km in this event. This information may help develop better flood hydraulic modeling of the Melamchi Floods (Takamatsu et al., 2022; Talchabhadel et al., 2023). In the field, we observed plentiful meter-scale boulders throughout the middle-lower reach, demonstrating the strong transport capacity of the flood (Figure S7). With the evidence of large boulder transport over km distances and significant bank erosion, the 2021 Melamchi flood can be described as a “debris flood”. Compared to debris flows, debris floods are larger scale mass movements in which the entire bed of the mainstem (including grains bigger than D_{84}) mobilizes for at least a few minutes (Church & Jakob, 2020). In our case, the flood duration was longer – tens of hours based on eye-witness reports (Pandey et al., 2021) – though the time length of boulder mobilization was likely shorter. In any case, the steep topography and high availability of mobilizable sediment make the Himalaya a perfect setting for such debris flooding (Bookhagen & Burbank, 2006).

Implications For Landscape Evolution And Fluvial Hazards In Steep Mountainous Landscapes

The 2021 Melamchi Flood was a cascading disaster that incorporated multiple erosion processes and sediment sources and linked to past seismicity and tectonic history. It started with small mass movements in the low-order headwaters that also saw intensive landsliding during the Gorkha earthquake and for several years after. However, the importance of earthquake-induced preconditioning for erosion during the flood remains enigmatic (Graf et al., 2023); most of the mass movements were new, though the earthquake legacy may have played a role by weakening the substrate (e.g., Parker et al., 2015; Jones et al., 2021). The mass movements in the low-order headwaters increased sediment supply, culminating in the massive incision of ancient glacial deposits and valley fills in the high-elevation main-stem valleys. Deposits preserved in Bremthang contributed 60% of the flood material, highlighting the importance of understanding sediment accumulation in high-elevation uplands and their distribution in other watersheds across the Himalaya. Future monitoring of the knickpoint migration in Bremthang specifically will be critical for hazard assessment in the Melamchi-Indrawati Basin, and for the future of the Melamchi Water Supply Project.

By documenting erosion and aggradation associated with a major flood in unprecedented detail, our study reveals several important features of the Melamchi Floods. First, although outburst events are

common causes of flood-related disasters in mountainous areas (Cenderelli & Wohl, 2003; Cook et al., 2018), our analysis shows that the Melamchi Floods initiated across widely distributed areas, illustrating how multiple flooding mechanisms can also produce devastating consequences. Second, this flood illustrates how complex interactions within a fluvial system can magnify the impacts, for example by undercutting of slopes in the mid-reaches of the Melamchi Valley that failed and contributed additional sediment to the river. At a larger scale, the deposits from the Melamchi Floods (Fig. 4) are located in similar areas to pre-existing fluvial terraces (Fig. 1). Floods similar to this event may have played a role in past basin-filling events in other catchments in the Himalaya, potentially complicating the interpretation of such deposits as definitively related to past earthquakes (Schwanghart et al., 2016). Finally, we note that erosion during the Melamchi flood redistributed a significant mass from the steep topography of the High Himalaya, and that most of this was exported to basins downstream. Such events may play important roles as efficient agents of erosion, and therefore in the coupling of uplift, climate, and erosion.

Declarations

Acknowledgement

This work was supported by the US NSF Frontier Research in Earth Sciences program awards 2021619 to AJW, 2020970 to MKC, and 2021299 to DZ. We thank Josh Roering, Kristen Cook, Jakob Steiner for helpful discussions, and Bhairab Sitaula for assistance with field logistics. Pléiades images (©CNES, 2023; distribution Airbus) and Worldview images (©Maxar, 2017) were obtained via the DINAMIS platform and the Polar Geospatial Center, respectively.

References

1. Cenderelli, D. A., & Wohl, E. E. (2003). Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, *28*(4), 385–407.
2. Montgomery, D. R., Hallet, B., Yuping, L., Finnegan, N., Anders, A., Gillespie, A., & Greenberg, H. M. (2004). Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. Quaternary Research, *62*(2), 201–207.
3. Bookhagen, B., & Burbank, D. W. (2006). Topography, relief, and TRMM-derived rainfall variations along the Himalaya. Geophysical Research Letters, *33*(8).
4. Broxton, M. J., & Edwards, L. J. (2008). The Ames Stereo Pipeline: Automated 3D surface reconstruction from orbital imagery. 39th Annual Lunar and Planetary Science Conference,
5. Moratto, Z. M., Broxton, M. J., Beyer, R. A., Lundy, M., & Husmann, K. (2010). Ames Stereo Pipeline, NASA's open source automated stereogrammetry software. Lunar and Planetary Science Conference,

6. Larsen, I. J., & Montgomery, D. R. (2012). Landslide erosion coupled to tectonics and river incision. Nature Geoscience, *5*(7), 468–473.
7. Wasson, R. J., Sundriyal, Y., Chaudhary, S., Jaiswal, M. K., Morthekai, P., Sati, S., & Juyal, N. (2013). A 1000-year history of large floods in the Upper Ganga catchment, central Himalaya, India. Quaternary Science Reviews, *77*, 156–166.
8. Anderson, S. W., Anderson, S. P., & Anderson, R. S. (2015). Exhumation by debris flows in the 2013 Colorado Front Range storm. Geology, *43*(5), 391–394.
9. Parker, R., Hancox, G., Petley, D., Massey, C., Densmore, A., & Rosser, N. (2015). Spatial distributions of earthquake-induced landslides and hillslope preconditioning in the northwest<? xmltex\newline?> South Island, New Zealand. Earth Surface Dynamics, *3*(4), 501–525.
10. Sundriyal, Y., Shukla, A. D., Rana, N., Jayangondaperumal, R., Srivastava, P., Chamyal, L., Sati, S., & Juyal, N. (2015). Terrain response to the extreme rainfall event of June 2013: Evidence from the Alaknanda and Mandakini River Valleys, Garhwal Himalaya, India. Episodes Journal of International Geoscience, *38*(3), 179–188.
11. Dimri, A., Thayyen, R., Kibler, K., Stanton, A., Jain, S., Tullos, D., & Singh, V. (2016). A review of atmospheric and land surface processes with emphasis on flood generation in the Southern Himalayan rivers. Science of the Total Environment, *556*, 98–115.
12. Li, G., West, A. J., Densmore, A. L., Hammond, D. E., Jin, Z., Zhang, F., Wang, J., & Hilton, R. G. (2016). Connectivity of earthquake-triggered landslides with the fluvial network: Implications for landslide sediment transport after the 2008 Wenchuan earthquake. Journal of Geophysical Research: Earth Surface, *121*(4), 703–724.
13. Schwanghart, W., Bernhardt, A., Stolle, A., Hoelzmann, P., Adhikari, B. R., Andermann, C., Tofelde, S., Merchel, S., Rugel, G., & Fort, M. (2016). Repeated catastrophic valley infill following medieval earthquakes in the Nepal Himalaya. Science, *351*(6269), 147–150.
14. Ruiz-Villanueva, V., Allen, S., Arora, M., Goel, N. K., & Stoffel, M. (2017). Recent catastrophic landslide lake outburst floods in the Himalayan mountain range. Progress in Physical Geography, *41*(1), 3–28.
15. Srivastava, P., Kumar, A., Chaudhary, S., Meena, N., Sundriyal, Y., Rawat, S., Rana, N., Perumal, R., Bisht, P., & Sharma, D. (2017). Paleofloods records in Himalaya. Geomorphology, *284*, 17–30.
16. Beyer, R. A., Alexandrov, O., & McMichael, S. (2018). The Ames Stereo Pipeline: NASA's open source software for deriving and processing terrain data. Earth and Space Science, *5*(9), 537–548.
17. Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R., & Hovius, N. (2018). Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. Science, *362*(6410), 53–57.
18. Heckmann, T., & Vericat, D. (2018). Computing spatially distributed sediment delivery ratios: Inferring functional sediment connectivity from repeat high-resolution digital elevation models. Earth Surface Processes and Landforms, *43*(7), 1547–1554.
19. Kumar, A., Gupta, A. K., Bhambri, R., Verma, A., Tiwari, S. K., & Asthana, A. (2018). Assessment and review of hydrometeorological aspects for cloudburst and flash flood events in the third pole region (Indian Himalaya). Polar Science, *18*, 5–20.

20. Roback, K., Clark, M. K., West, A. J., Zekkos, D., Li, G., Gallen, S. F., Chamlagain, D., & Godt, J. W. (2018). The size, distribution, and mobility of landslides caused by the 2015 Mw7. 8 Gorkha earthquake, Nepal. Geomorphology, *301*, 121–138.
21. Turzewski, M. D., Huntington, K. W., & LeVeque, R. J. (2019). The geomorphic impact of outburst floods: Integrating observations and numerical simulations of the 2000 Yigong flood, eastern Himalaya. Journal of Geophysical Research: Earth Surface, *124*(5), 1056–1079.
22. Calle, M., Calle, J., Alho, P., & Benito, G. (2020). Inferring sediment transfers and functional connectivity of rivers from repeat topographic surveys. Earth Surface Processes and Landforms, *45*(3), 681–693.
23. Church, M., & Jakob, M. (2020). What is a debris flood? Water Resources Research, *56*(8), e2020WR027144.
24. Veh, G., Korup, O., & Walz, A. (2020). Hazard from Himalayan glacier lake outburst floods. *Proceedings of the National Academy of Sciences*, *117*(2), 907–912.
25. Hu, K., Wu, C., Wei, L., Zhang, X., Zhang, Q., Liu, W., & Yanites, B. J. (2021). Geomorphic effects of recurrent outburst superfloods in the Yigong River on the southeastern margin of Tibet. Scientific Reports, *11*(1), 1–11.
26. Jones, J. N., Boulton, S. J., Stokes, M., Bennett, G. L., & Whitworth, M. R. (2021). 30-year record of Himalaya mass-wasting reveals landscape perturbations by extreme events. Nature communications, *12*(1), 6701.
27. Joshi, I., Chaudhary, R. K., & Diwakar, K. (2021). Engineering Perspective of Melamchi Disaster and Mitigation Methods. *Zenodo*, 1–4.
28. Maharjan, S. B., Steiner, J. F., Shrestha, A., Maharjan, A., Nepal, S., Shrestha, M. S., Bajracharya, B., Rasul, G., Shrestha, M., & Jackson, M. (2021). The Melamchi flood disaster: Cascading hazard and the need for multihazard risk management. *International Centre for Integrated Mountain Development (ICIMOD), Kathmandu*, *10*.
29. Merz, B., Blöschl, G., Vorogushyn, S., Dottori, F., Aerts, J. C., Bates, P., Bertola, M., Kemter, M., Kreibich, H., & Lall, U. (2021). Causes, impacts and patterns of disastrous river floods. Nature Reviews Earth & Environment, *2*(9), 592–609.
30. Pandey, V., Gautam, D., Gautam, S., Adhikari, R., Lamsal, P., Talchabhadel, R., & Bijaya, P. (2021). Multiperspective field reconnaissance after the melamchi debris flow of June 15, 2021 in central Nepal. *Nepal Engineers' Association (NEA), Lalitpur, Nepal*.
31. Shugar, D., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., De Vries, M. V. W., & Mergili, M. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science, *373*(6552), 300–306.
32. Cook, K., Schwanghart, W., Puri, B., Andermann, C., & Adhikari, B. R. (2022). *Himalayan sediment bombs–generalizing from the 2021 Melamchi Khola disaster*.
33. Dahlquist, M. P., & West, A. J. (2022). The imprint of erosion by glacial lake outburst floods in the topography of central Himalayan rivers. Earth Surface Dynamics, *10*(4), 705–722.

34. Gautam, D., Adhikari, R., Gautam, S., Pandey, V. P., Thapa, B. R., Lamichhane, S., Talchabhadel, R., Thapa, S., Niraula, S., & Aryal, K. R. (2022). Unzipping flood vulnerability and functionality loss: tale of struggle for existence of riparian buildings. Natural Hazards, 1–21.
35. Medwedeff, W. G., Clark, M. K., Zekkos, D., West, A. J., & Chamlagain, D. (2022). Near-surface geomechanical properties and weathering characteristics across a tectonic and climatic gradient in the Central Nepal Himalaya. Journal of Geophysical Research: Earth Surface, *127*(2), e2021JF006240.
36. Sharma, C. P., Chahal, P., Kumar, A., Singhal, S., Sundriyal, Y., Ziegler, A. D., Agnihotri, R., Wasson, R. J., Shukla, U. K., & Srivastava, P. (2022). Late Pleistocene–Holocene flood history, flood-sediment provenance and human imprints from the upper Indus River catchment, Ladakh Himalaya. GSA Bulletin, *134*(1–2), 275–292.
37. Sharma, S., Talchabhadel, R., Nepal, S., Ghimire, G. R., Rakhal, B., Panthi, J., Adhikari, B. R., Pradhanang, S. M., Maskey, S., & Kumar, S. (2022). Increasing risk of cascading hazards in the central Himalayas. Natural Hazards, 1–10.
38. Takamatsu, M., Karelia, H. D., Lnu, T. O., & Dahal, R. K. (2022). Melamchi Flood Disaster in Nepal: Damage and Risk Quantification with Drone Survey, Satellite-Based Land Displacement Analysis, and 2D Flood Modeling.
39. Graf, E. L., Sinclair, H. D., Attal, M., Gailleton, B., Adhikari, B. R., & Baral, B. R. (2023). Geomorphological and hydrological controls on sediment export in earthquake-affected catchments in the Nepal Himalaya. *EGUsphere*, 1–41.
40. Talchabhadel, R., Maskey, S., Gouli, M. R., Dahal, K., Thapa, A., Sharma, S., Dixit, A. M., & Kumar, S. (2023). Multimodal multiscale characterization of cascading hazard on mountain terrain. Geomatics, Natural Hazards and Risk, *14*(1), 2162443.

Figures

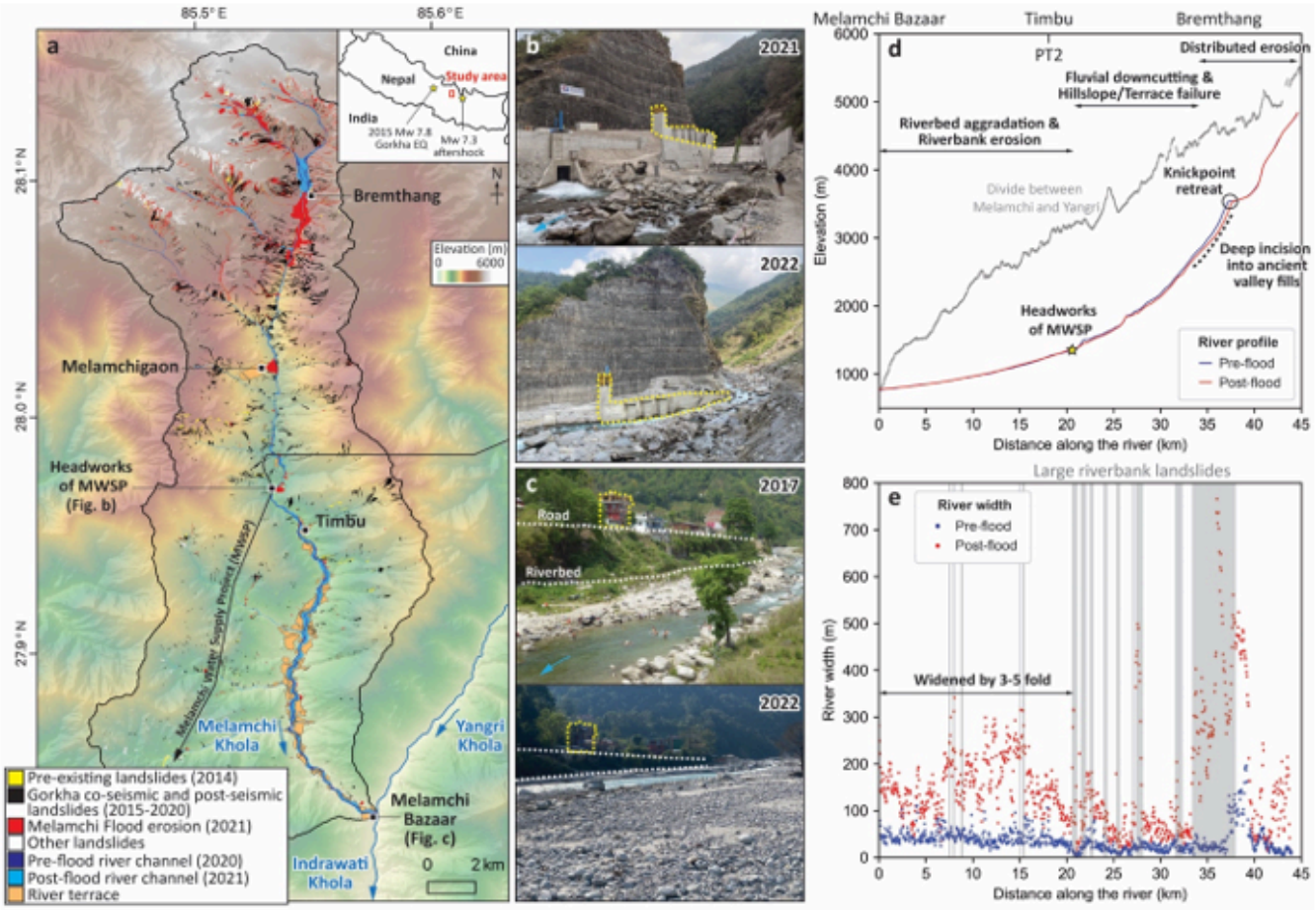


Figure 1

(a) Map of the Melamchi Valley with major geomorphic features including landslides, active river channels, and fluvial terraces. Erosion associated with the 2021 Melamchi Floods was mostly in headwater areas and was widely distributed. (b) The floods severely damaged the headworks of the Melamchi Water Supply Project. The pre-flood photo is from social media (https://www.spotlightnepal.com/2021/07/07/melamchi-drinking-water-project-miraculous-survival/). (c) The floods resulted in devastating aggradation of 5-20 m in the populated areas downstream. (d) River profiles before and after the flood show the patterns of erosion and aggradation. The switch from erosion to deposition coincides with the Himalayan physiographic transition (PT2; Wobus et al., 2005) inferred from steepness index, valley confinement, and terrace distribution. (e) Flood-induced change in river width.

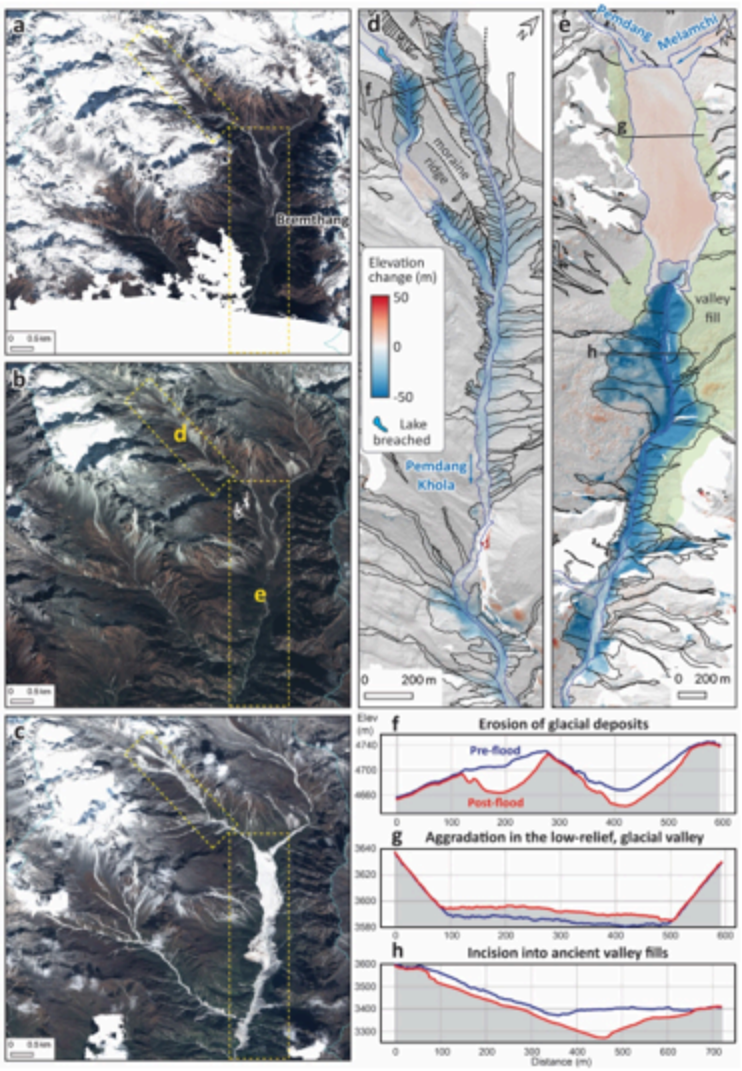


Figure 2

Pléiades imagery from (a) December 2014, (b) November 2020, and (c) October 2021 shows the change in the Melamchi Khola headwaters after the 2015 Gorkha earthquake and 2021 Melamchi Floods. The flood caused intense erosion in headwater tributaries, exemplified with the Pemdang Khola (d). Such widespread erosion further led to aggradation in the high-elevation valley of Bremthang (e), where ancient valley fill destabilized during the floods and released > 50.24 million m^3 of material, the largest sediment source in the event.

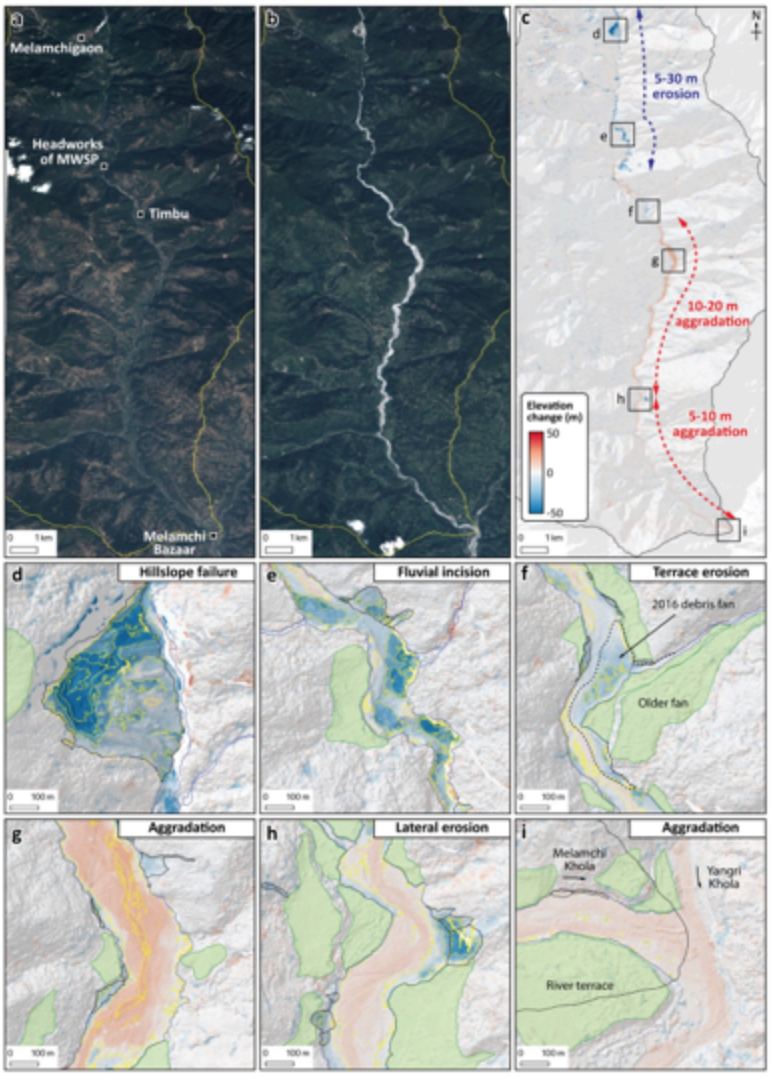


Figure 3

Comparison of Pléiades imagery between (a) November 2020 and (b) October 2021 shows the flood impact on the middle reach and lower basin of the Melamchi Khola. (c) DEM differencing results suggest that the middle reach experienced intense downcutting and hillslope/terrace failures (d-f), whereas the lower basin was dominated by sediment aggradation and channel widening (g-i). Yellow lines are 20-m-interval contours.

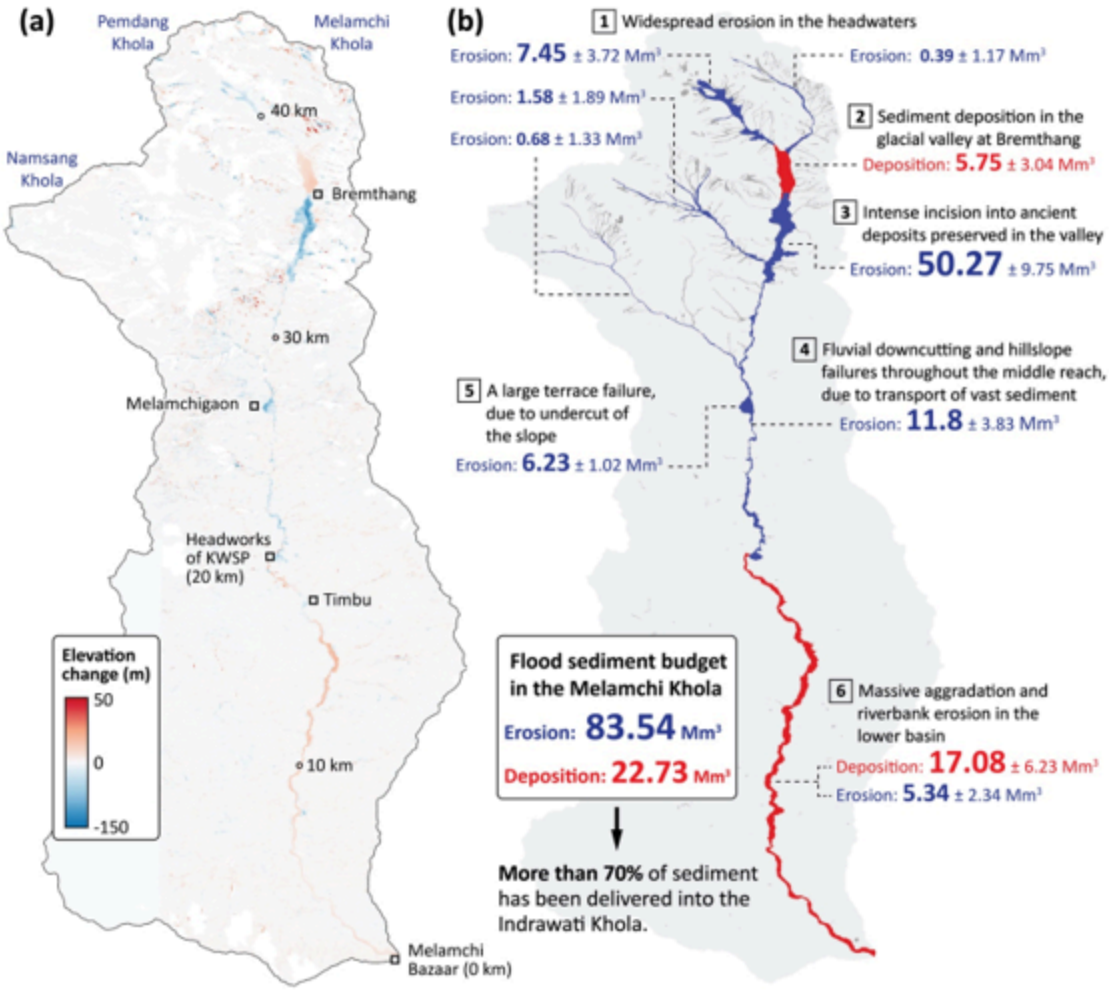


Figure 4

(a) DEM differencing results reveal the catchment-scale erosion (in blue) and aggradation (in red) patterns of the 2021 Melamchi Floods. Areas associated with large shallow and cloud covers are masked in white. Distance along the main river course is marked. (b) Summary of the hazard cascade and sediment budget of the 2021 Melamchi Floods. Sediment transport during this event, including for large boulders (>10m diameter; Figure S7), was estimated to extend over 30 km. Grey polygons are mass movements associated with the floods but not included in the sediment budget analysis.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- MelamchiFloodmethodsandsupplementarymaterials0402.docx