REPORT

GEOMORPHOLOGY

Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya

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Himalayan rivers are frequently hit by catastrophic floods that are caused by the failure of glacial lake and landslide dams; however, the dynamics and long-term impacts of such floods remain poorly understood. We present a comprehensive set of observations that capture the July 2016 glacial lake outburst flood (GLOF) in the Bhotekoshi/Sunkoshi River of Nepal. Seismic records of the flood provide new insights into GLOF mechanics and their ability to mobilize large boulders that otherwise prevent channel erosion. Because of this boulder mobilization, GLOF impacts far exceed those of the annual summer monsoon, and GLOFs may dominate fluvial erosion and channel-hillslope coupling many tens of kilometers downstream of glaciated areas. Long-term valley evolution in these regions may therefore be driven by GLOF frequency and magnitude, rather than by precipitation.

Lake outburst floods (LOFs) have long been recognized as both a hazard and major agent of geomorphic change in the Himalaya (*1*–*5*). These floods originate from lakes that have formed behind a landslide dam or in association with a glacier, dammed by a frontal moraine or glacial ice. Such lakes can drain catastrophically for several reasons, including mass movements or avalanches into the lake, seismic activity, piping within the dam, overtopping of the dam, or degradation of blocking ice (*4*, *6*). The resulting floods can have short-lived discharges up to several orders of magnitude higher than background discharges in the receiving rivers (*7*). Because of their magnitude and unpredictability, LOFs can be highly destructive and compromise local infrastructure such as roads, buildings, and hydropower facilities (*3*, *8*–*10*).

Although large LOFs have been recognized as strongly affecting river morphology and dynamics (*4*, *11*–*13*), they are often treated as one-off events. The potential impact of repeated LOFs, particularly the less dramatic small-to-medium magnitude floods, on the longer-term behavior of the fluvial system has received little attention. The impact of individual LOF events must be considered along with LOF frequency and measured against the accumulated effect of annual monsoon floods of variable size. We evaluate the importance of glacial lake outburst floods (GLOFs) in driving fluvial erosion by examining the Bhotekoshi/Sunkoshi River, where we compare monsoon floods to a GLOF that occurred in July 2016. In addition to documenting relative impacts and discharges, we use seismic observations to gain insight into GLOF dynamics, and we explore the role of boulder-sized sediment in promoting GLOF-driven erosion.

On the night of 5 July 2016, Gongbatongshacuo Lake, a 1.7×10^4–m^2 moraine-dammed lake in the Tibet Autonomous Region, China, drained catastrophically, releasing approximately 1.1×10^5 m^3 of water (*14*). The cause of the breach is unknown, but fresh deposits above the lake suggest that it may have been associated with a debris flow event, possibly increasing the volume of the flood (Fig. 1B). The flood proceeded down the Zhangzangbo River into the Poiqu/Bhotekoshi/Sunkoshi River and caused severe damage in the Bhotekoshi valley, destroying the intake dam of a hydropower project, the Araniko highway, and numerous buildings in the towns of Kodari and Tatopani. The zone of damage sits within the area affected by strong ground motion and landsliding induced by the 2015 moment magnitude 7.8 Gorkha earthquake, which had an estimated return time of a few hundred years (*15*, *16*).

The 2016 GLOF passed through an array of six broadband seismometers installed in 2015 along the Bhotekoshi River valley, 28 to 35 km downstream of the Zhangzangbo confluence (Fig. 1). Because both turbulent flow (*17*) and bedload transport (*18*) in rivers can generate detectable seismic ground motion (*19*), the seismic record of the GLOF can be used to probe the flood and sediment dynamics at high temporal and spatial resolution. The seismic records for each near-river station contain two distinct pulses of high-amplitude noise (Fig. 1C). The first is the flood front, which propagates between stations at 8.7 m/s. The abrupt rise of seismic power at each station suggests that the maximum flow depth was reached within 2 min. At Chaku station, this corresponded to a calculated maximum discharge of 1500 to 2100 m^3/s (Fig. 2 and table S1). The second pulse is of higher magnitude but travels slower, at 5 m/s. The total duration of the flood, including both pulses, at each of the stations was less than an hour. We interpret the first pulse as a water wave and the second as a package of coarse sediment, on the basis of the following reasoning: If both pulses were associated with propagating water waves, then the more energetic second wave should have a greater flow depth and travel faster (*17*). The prediction from theory is that near-river stations should be especially sensitive to coarse sediment, whereas far-river stations should be predominantly sensitive to water flow (*17*, *18*) (fig. S1). The second wave was prominent at near-river stations but much weaker at farther seismic stations, consistent with the theory (fig. S2). Theory also predicts that coarse-sediment transport generates seismic noise at higher frequencies compared to turbulent flow (*17*, *18*) (fig. S1), and power spectra from the two pulses indicate an increase in power at higher frequencies during the second pulse (fig. S3).

The ratio of the pulse velocities is 0.6, matching bedload/water velocity ratios observed experimentally and in small-river settings (*20*). This velocity difference ensured that the flood front outpaced any entrained sediment and therefore remained depleted in bedload.

Field- and satellite-based observations show that the GLOF affected the river channel over a ~40-km stretch between the confluence with the Zhangzangbo River and Barabise town (Fig. 1). The flood impact extended into the adjacent hillslopes through undercutting and destabilization of the river banks, leading to bank collapses, slumps, and landslides. The extensive flood-induced damage to local infrastructure was almost exclusively the result of bank erosion and mass wasting, rather than inundation (fig. S4).

We quantified the magnitude of channel, bank, and hillslope change with repeat terrestrial lidar surveys from October 2015, March 2016, and November 2016 in nine locations that together covered 20% of the channel length between Khukundol and Barabise (Fig. 1 and table S2). Eight of the scanned reaches experienced downcutting varying from 1 to 10 m, whereas one had no bed-elevation change (Fig. 3).

We observed bank erosion in numerous sections of the channel, and all scanned reaches contained segments with at least 2 m of lateral erosion (Fig. 3 and fig. S5). Bank erosion included parallel retreat of steep banks and erosion and undercutting at the base of slopes. Analysis of 5-m-resolution RapidEye imagery (table S3) indicates that the 2016 GLOF caused the mean width of the active channel between the Zhangzangbo confluence and Barabise to increase from 29.5 ± 3 m

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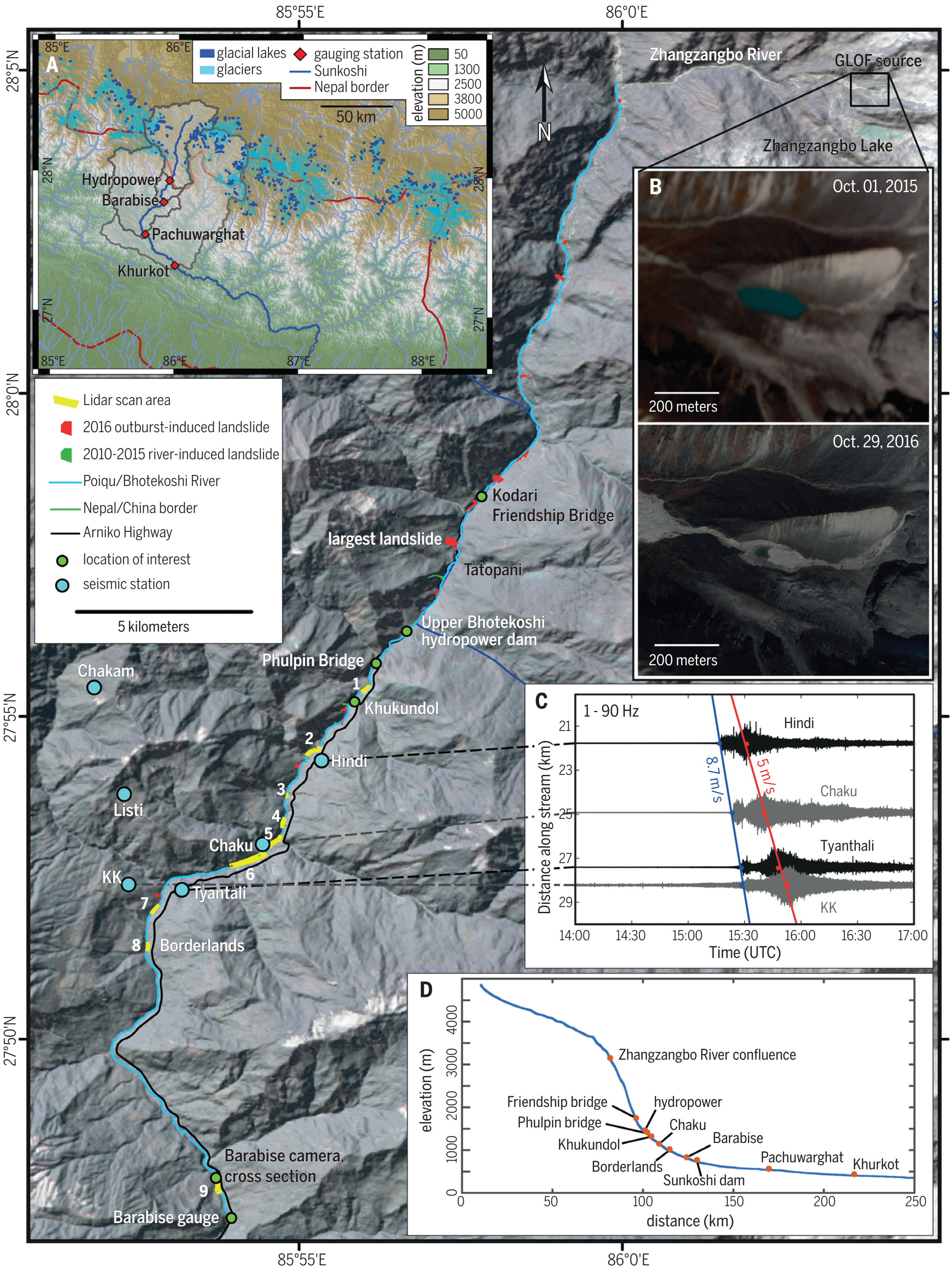

Fig. 1. Map of the Bhotekoshi study region. Scanned reaches, mapped landslides, seismic stations, and locations discussed in the text are shown. White numbers 1 to 9 indicate each scan location, with reference to table S1. (**A**) The inset provides the regional context, with glaciers and glacial lakes shown (*9*). The shading and black outlines indicate drainage basins upstream of Khurkot, Pachuwarghat, Barabise, and the Upper Bhotekoshi hydropower dam. (**B**) Google Earth and RapidEYE imagery showing a magnified view of the lake that was the source of the outburst flood, both before the bursting event in October 2015 (top) and after in October 2016 (bottom). (**C**) Seismic record of GLOF propagation. Normalized ground velocity time series from four stations at different distances downstream of the Zhangzangbo confluence. Dots indicate the manually picked pulse arrivals. Straight lines correspond to linear fits of distance versus time and yield the pulse velocities. UTC, universal time coordinated. (**D**) Longitudinal profile from the Advanced Land Observing Satellite 12.5-m digital elevation model of the Poiqu/Bhotekoshi/Sunkoshi River, with locations of interest marked.

in 2015 to 41.3 ± 3 m in 2016, with highly variable widening throughout the mapped area (Fig. 3). The lateral changes in 2016 contrast with the stability of the river between 2010 and 2015. During these six monsoon seasons, changes to the river channel were minimal and were associated with external influences such as anthropogenic modification, local landsliding, and tributary input. Despite the large amount of landslide debris produced during the 2015 Gorkha earthquake (*15*, *16*), the channel underwent minimal modification during the 2015 monsoon (Fig. 3 and fig. S6).

Lateral erosion of the channel by the GLOF led to the activation of landslides that propagated

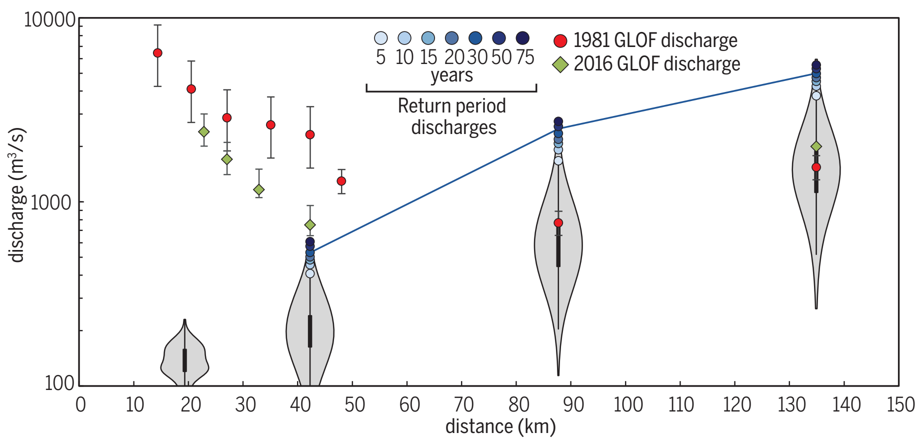

Fig. 2. Discharge with distance downstream of the Zhangzangbo confluence. Data from table S4. Estimated discharges for the 1981 (*11*) and 2016 GLOFs and the calculated discharges for floods of varying return periods (5 to 75 years). The blue line connects the 30-year-return discharges. The violin plots show the full distribution of monsoon discharges (July and August) for each hydrological station (hydropower dam, Barabise, Pachuwarghat, and Khurkot). Error bars indicate estimated uncertainty (for details, see materials and methods).

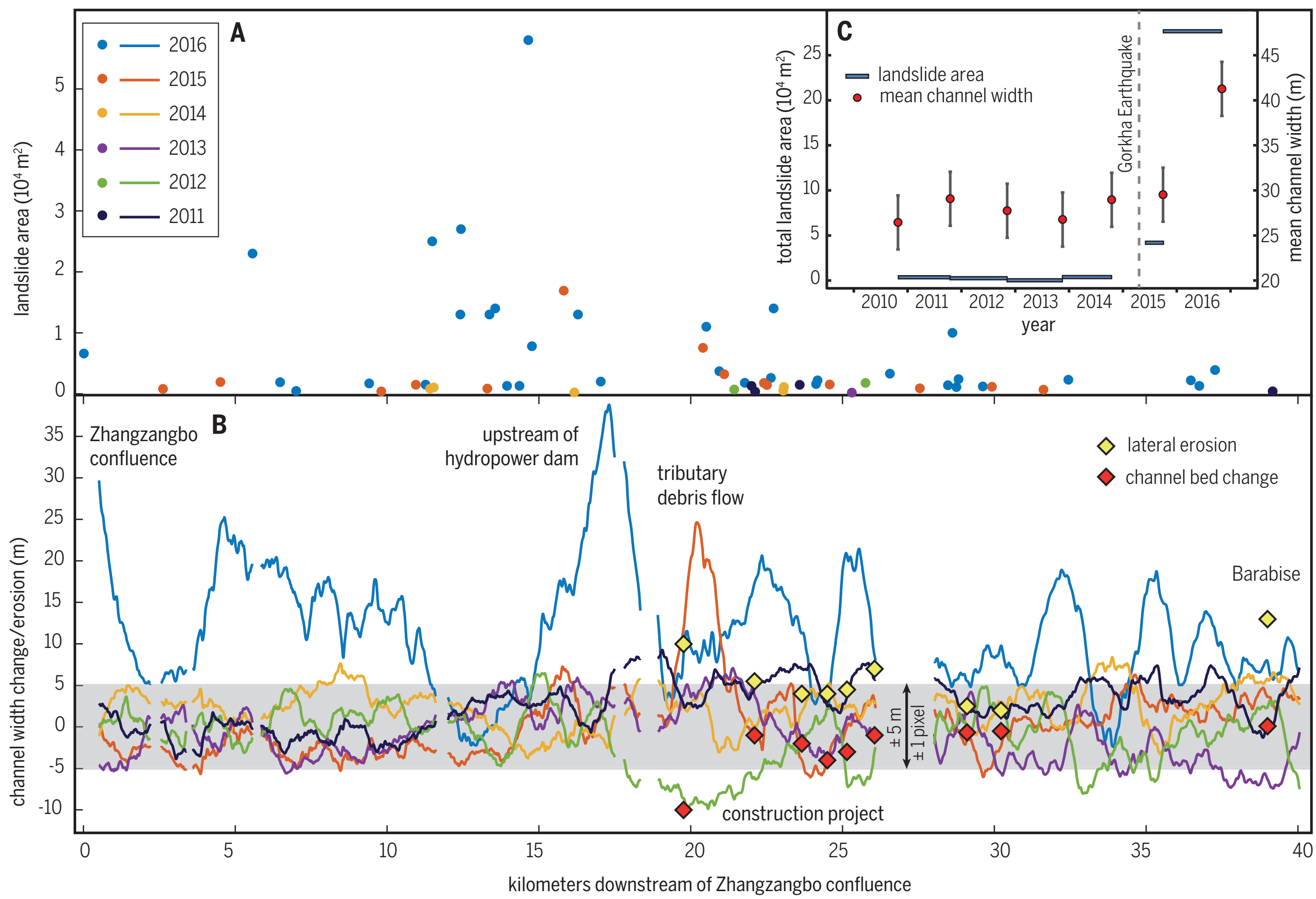

Fig. 3. Summary of monsoon- and GLOF-driven changes in the Poiqu/Bhotekoshi channel. (**A**) Landslide areas with distance downstream of the Zhangzangbo confluence from 2010 to 2016; each point represents one landslide. (**B**) Width changes from 2010 to 2016 and lidar-derived GLOF changes. The gray bar indicates an uncertainty of ±5 m, equivalent to ±1 pixel in the satellite imagery. Data have been smoothed by applying a running average over a 1-km window. Diamonds show the maximum values of lateral erosion and channel-bed elevation change from each of the lidar-scanned reaches. The lidar-derived lateral erosion values are not expected to match the satellite-derived width changes because the satellite-derived data have been smoothed. (**C**) Time series summary of data from (A) and (B). The mean channel widths through time and areas of river-related landslides that occurred during each monsoon season are shown.

up the hillslopes (Fig. 1). Mapping from RapidEye imagery shows that 26 landslides in which the zone of failure is connected to the channel formed during the 2016 monsoon. The cumulative area of these landslides was ~100 times larger than the landslide area during a typical year (2009 to 2014) and five times larger than that during the 2015 monsoon, which solicited an unusually high rate of landsliding after the Gorkha earthquake (Figs. 1 and 3).

The 2016 GLOF had an impact on the river and adjacent hillslopes that far outstripped that of the monsoon floods of 2009 to 2016. The effects of the 2016 GLOF are similar to the documented effects of a previous GLOF on the Poiqu/Bhotekoshi/Sunkoshi River on 11 July 1981. This flood contained an estimated 1.9×10^7 m^3 of water released from the Zhangzangbo Lake, near the source of the 2016 flood (*11*) (Fig. 1). The damage from the 1981 flood mirrors that from the 2016 flood and included the destruction of a hydropower dam, sections of the Araniko highway, and several bridges. Numerous landslides related to this outburst flood occurred along the Bhotekoshi River (*11*).

We attribute the large discrepancy between the impacts of the GLOFs and the monsoon floods to the ubiquity of extremely coarse landslide-derived boulders (>1 m in diameter) in the bed and banks of the Bhotekoshi River (fig. S7). River-channel stability during floods is related to the stability of boulder-sized clasts that define the channel geometry (*21*, *22*). Although the threshold discharge for mobilizing these boulders varies with clast location and size, the threshold generally does not appear to be exceeded during the monsoon. On the basis of field observations and Google Earth imagery, movement of large boulders has not taken place during monsoon floods since at least 2004 (fig. S8). The smallest boulders we can reliably identify as stable in Google Earth imagery are about 2 to 3 m in diameter, smaller than boulders that moved in these reaches during the 2016 and 1981 GLOFs [up to 5.7 m (fig. S5) and 13.4 m in diameter, respectively (*11*)].

GLOFs can mobilize boulders, owing to their high discharge and other characteristics that enhance sediment entrainment. Outburst floods, in which a water bore propagates downstream, have a higher capacity to mobilize sediment than a monsoon flood of similar magnitude. This is due to the velocity difference between water flow and entrained bedload, which ensures that the leading edge of the flood will remain relatively bedload free and under transport capacity. This is fundamentally different from run-off–driven floods, which have more smoothly varying hydrographs and sediment loads delivered from outside the channel.

The ability to mobilize the channel-defining coarse sediment determines the degrees to which a flood can incise bedrock and erode the channel banks. The bedrock bed of the observed section of the Bhotekoshi River is covered by a sediment layer of unknown thickness. A flood that does not move the large boulders armoring this sediment mantle therefore cannot cause bedrock incision.

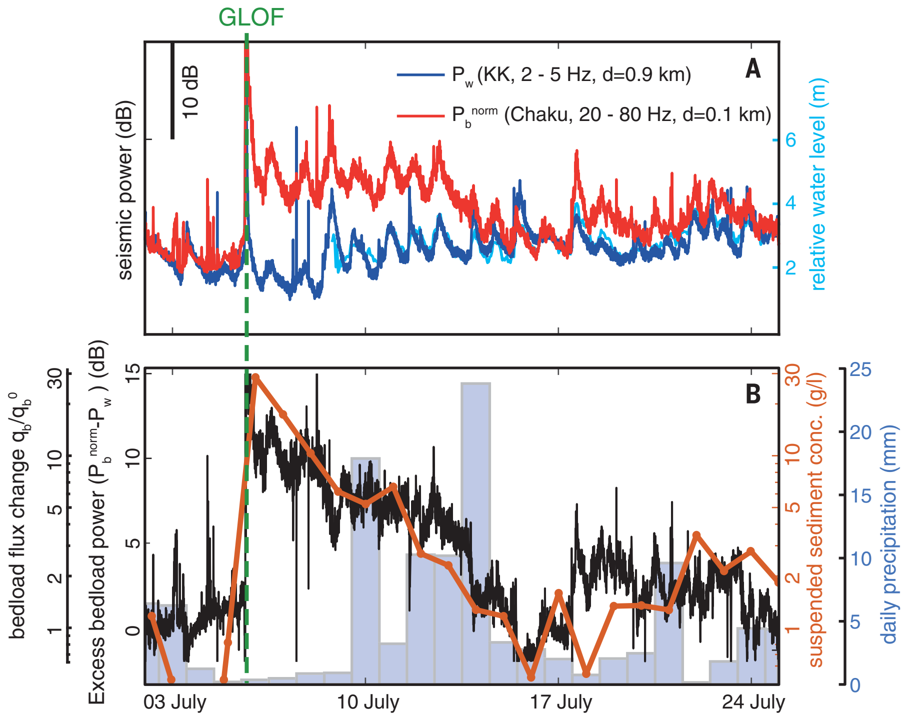

Fig. 4. Sediment dynamics after the GLOF. (**A**) Constraints on bedload transport. The dark blue line shows the seismic power in the 2- to 5-Hz frequency range (P_w) at station KK, a distance (d) of 0.9 km from the river, as a proxy for turbulent flow. The red line shows the seismic power in the 20- to 80-Hz frequency range (P_b^{norm}) at station Chaku, 0.1 km from the river, as a proxy for bedload flux. The light blue line shows the water level relative to the Nepal Department of Hydrology and Meteorology gauge at Barabise. Bedload power has been normalized to the turbulent flow power by using the period before the GLOF. Note that seismic power during the GLOF event itself is off the scale of this plot. (**B**) Excess sediment transport. The black line shows the excess bedload power, obtained by differencing the blue and red series in (A). The GLOF event is off the scale of this plot and is not considered in this analysis. The orange line shows the suspended-sediment concentration from daily samples. The bars show Global Precipitation Monitoring–derived catchment-wide daily precipitation. q_b, bedload flux; q_b^O, background bedload flux.

The impact of the 2016 and 1981 GLOFs on the bedrock below the sediment layer cannot be constrained; however, we can conclude that these GLOFs may have incised bedrock, whereas the monsoon floods since at least 2004 definitely did not.

GLOF-induced disruption of the boulder armor is reflected in increased rates of sediment transport during the 10 days after the 2016 GLOF. We used seismic signals in different frequency ranges from a far-river station and a near-river station to obtain proxies for water flow depth and bedload flux (*17*, *18*) (Fig. 4A and fig. S1). Before the GLOF, the bedload flux and water depth proxies are closely linked. After the GLOF, however, the two proxies show different trends. Whereas the flow depth proxy returns to preflood levels within hours, the bedload transport proxy is increased after the flood and gradually returns to preflood levels over 10 days (Fig. 4B). Daily suspended-sediment concentrations from Barabise show a very similar perturbation, with changes of the same magnitude and time evolution as the estimated excess bedload transport (Fig. 4B), suggesting that both fluxes are controlled by sediment availability from the same source. We interpret this as a signal of ongoing reorganization of the channel bed; the return to background levels of sediment transport occurs as easily transportable sediment is removed from the channel and the boulder armor reestablishes. Furthermore, the increase in bedload transport after the GLOF suggests that at most other times the river is under capacity and that bedload transport during the monsoon is typically limited by the delivery of sediment into the channel.

Because of the high discharge threshold for mobilizing the channel-defining boulders, monsoon floods primarily transfer sediment delivered from tributaries and hillslopes without major lateral or vertical erosion in the main channel, and only very large floods cross the threshold for boulder mobilization, perturb the river, and drive erosion. This allows individual floods, including GLOFs and landslide dam outbursts, to have a disproportionate impact on the river channel. The role of GLOFs in driving long-term erosion and hillslope-channel coupling therefore depends on their frequency and magnitude relative to that of extreme monsoon-driven floods.

The frequency of GLOFs in the central Himalaya is difficult to establish, because records are incomplete and recorded floods may not be correctly identified as GLOFs (*3*, *23*). Nevertheless, GLOFs are relatively common in the Himalaya, with a major flood occurring at least once every 2 years on average (*4*, *24*–*26*). The Bhotekoshi River has experienced GLOFs in 1935, 1964, 1981, and 2016, suggesting a return period of about 30 years (*2*). The Bhotekoshi/Sunkoshi catchment has 57 glacial lakes mapped upstream of Barabise (*10*). These lakes vary widely in size, but the median lake area of 32,600 m^2 is almost twice that of the lake that caused the 2016 flood. Yearly maximum monsoon discharge from a 42-year discharge record at Barabise is typically between 200 and 400 m^3/s, with flood peaks rarely exceeding 500 m^3/s (fig. S9). The estimated GLOF peak discharges at Barabise [700 to 900 m^3/s in 2016 and 2300 m^3/s in 1981 (*11*)] are larger than the expected 30-year flood discharge of 490 to 560 m^3/s (Fig. 2, fig. S11, and table S4). The impact of individual GLOFs on the Bhotekoshi River dwarfs that of monsoon discharges, and GLOFs occur with sufficient frequency to dominate geomorphic change in the valley.

As a GLOF travels downstream, the flood peak attenuates and the peak discharge decreases, whereas the drainage area and background discharge increase, giving rise to a crossover point where GLOF discharges are no longer anomalous (*7*, *10*) (Fig. 2). Hence, the discrepancy between GLOF discharge and monsoon floods will be particularly dramatic in the high Himalayan headwaters, where the drainage areas are small and GLOFs will have experienced little attenuation (Fig. 2). For the 2016 and 1981 GLOFs, the crossover point with the 30-year monsoon flood was located about 45 and 55 km downstream of the Zhangzangbo confluence, respectively (Fig. 1). If GLOFs are less frequent, then their impact must be measured against larger monsoon floods with a longer return time, moving the crossover point upstream. Conversely, larger GLOFs have a crossover point farther downstream. Probabilistic modeling of glacial lake outbursts throughout the Himalaya suggests that more than 40% of 2359 mapped proglacial lakes could produce GLOFs that match the 100-year discharge about 20 km downstream, whereas large GLOFs may reach as far as 85 km downstream (*10*). Our observations suggest that, because of their distinct sediment dynamics, GLOFs of such magnitudes will have a disproportionate effect on fluvial erosion in these reaches.

Owing to their magnitude and enhanced ability to mobilize coarse sediment, we propose that LOFs are a fundamental part of the fluvial system and a primary control on fluvial erosion and channel-hillslope coupling, especially in catchments where very coarse sediment creates high thresholds for sediment mobilization, with GLOFs particularly effective in the upper portions of glaciated catchments. Landslide LOFs likely have a similar impact on channel dynamics and channel-hillslope coupling in landslide-prone regions with steep narrow valleys and abundant coarse sediment, conditions that are common in numerous mountain ranges throughout the world (*4*, *5*).

LOFs directly impact only the channel and adjacent hillslopes, but over the long term, fluvial incision sets the base level for the entire landscape and is ultimately the driver of hillslope erosion; thus, in LOF-prone regions, LOF magnitudes and recurrence intervals may control landscape evolution. As a result, monsoon strength or measures of precipitation may be poor predictors of landscape response in LOF-susceptible regions. Instead, erosion rates may be strongly influenced by nonclimatological LOF drivers such as earthquakes (*5*, *27*, *28*) and the climatic factors that affect the size and distribution of glacial lakes, for example, air temperature, variability of the equilibrium line altitude, and, to a degree, the glacial recharge (*29*, *30*). Even where LOF frequency can be linked to precipitation (that is, for landslide lake outbursts), the relationship between fluvial erosion and precipitation will become complicated and nonlinear.

A warming climate is thought to promote glacial lake formation in some areas as retreating glaciers create space for lakes behind abandoned end moraines and increased melting rates supply more water to potential lakes. This, in turn, may increase GLOF frequency and/or magnitude (*25*, *31*–*33*). The potential for increased GLOF activity in response to climate change therefore not only represents increased risk to communities in these regions but may also strongly affect the pace of landscape change in a way that is not reflected in precipitation-dependent erosion models.

REFERENCES AND NOTES

1. K. Hewitt, "Natural dams and outburst floods of the Karakoram Himalaya," in *Hydrological Aspects of Alpine and High-Mountain Areas*, J. W. Glen, Ed. (IAHS Publication No. 138, International Association of Hydrological Sciences, 1982), pp. 259–269.
2. P. K. Mool, *J. Nepal Geol. Soc.* **11**, 273–280 (1995).
3. International Centre for Integrated Mountain Development (ICIMOD), "Glacial lakes and glacial lake outburst floods in Nepal" (ICIMOD, Kathmandu, 2011).
4. O. Korup, F. Tweed, *Quat. Sci. Rev.* **26**, 3406–3422 (2007).
5. J. E. Costa, R. L. Schuster, *Geol. Soc. Am. Bull.* **100**, 1054–1068 (1988).
6. M. J. Westoby *et al.*, *Earth Sci. Rev.* **134**, 137–159 (2014).
7. D. A. Cenderelli, E. E. Wohl, *Geomorphology* **40**, 57–90 (2001).
8. A. B. Shrestha *et al.*, *Geomatics Nat. Hazards Risk* **1**, 157–169 (2010).
9. N. R. Khanal, J. M. Hu, P. Mool, *Mt. Res. Dev.* **35**, 351–364 (2015).
10. W. Schwanghart, R. Worni, C. Huggel, M. Stoffel, O. Korup, *Environ. Res. Lett.* **11**, 074005 (2016).
11. D. Xu, *GeoJournal* **17**, 569–580 (1988).
12. D. A. Cenderelli, E. E. Wohl, *Earth Surf. Process. Landf.* **28**, 385–407 (2003).
13. D. Higaki, G. Sato, *Glob. Environ. Res.* **16**, 71–76 (2012).
14. C. Huggel, A. Kääb, W. Haeberli, P. Teysseire, F. Paul, *Can. Geotech. J.* **39**, 316–330 (2002).
15. J. S. Kargel *et al.*, *Science* **351**, aac8353 (2016).
16. K. Roback *et al.*, *Geomorphology* **301**, 121–138 (2017).
17. F. Gimbert, V. C. Tsai, M. P. Lamb, *J. Geophys. Res. Earth Surf.* **119**, 2209–2238 (2014).
18. V. C. Tsai, B. Minchew, M. P. Lamb, J. P. Ampuero, *Geophys. Res. Lett.* **39**, L02404 (2012).
19. A. Burtin, L. Bollinger, J. Vergne, R. Cattin, J. L. Nábělek, *J. Geophys. Res. Solid Earth* **113**, B05301 (2008).
20. P. Chatanantavet, K. X. Whipple, M. A. Adams, M. P. Lamb, *J. Geophys. Res. Earth Surf.* **118**, 1161–1176 (2013).
21. D. A. Cenderelli, B. L. Cluer, "Depositional processes and sediment supply in resistant-boundary channels: Examples from two case studies," in *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, K. J. Tinkler, E. E. Wohl, Eds. (Geophysical Monograph Series, vol. 107, American Geophysical Union, Washington, DC, 1998), pp. 105–131.
22. A. C. Brayshaw, *Geol. Soc. Am. Bull.* **96**, 218–223 (1985).
23. Rastriya Samachar Samiti, "Heavy rain brings massive flood to Bhotekoshi River," *Himalyan Times*, 6 July 2016; https://thehimalayantimes.com/nepal/heavy-rain-brings-massive-flood-bhotekoshi-river.
24. J. D. Ives, R. B. Shrestha, P. K. Mool, "Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment" (ICIMOD, Kathmandu, 2010).
25. A. Lutz, W. W. Immerzeel, S. R. Bajracharya, M. Litt, A. Shrestha, "Impact of climate change on the cryosphere, hydrological regimes and glacial lakes of the Hindu Kush Himalayas: A review of current knowledge" (ICIMOD Research Report 2016/3, ICIMOD, Kathmandu, 2016).
26. D. R. Rounce, A. C. Byers, E. A. Byers, D. C. McKinney, *Cryosphere* **11**, 443–449 (2017).
27. W. Schwanghart *et al.*, *Science* **351**, 147–150 (2016).
28. J. D. Bricker *et al.*, *Mt. Res. Dev.* **37**, 5–15 (2017).
29. S. G. Evans, J. J. Clague, *Geomorphology* **10**, 107–128 (1994).
30. K. Hewitt, J. Liu, *Phys. Geogr.* **31**, 528–551 (2013).
31. S. R. Bajracharya, P. Mool, *Ann. Glaciol.* **50**, 81–86 (2009).
32. T. Bolch *et al.*, *Science* **336**, 310–314 (2012).
33. Y. Chen, C. Xu, Y. Chen, W. Li, J. Liu, *Quat. Int.* **226**, 75–81 (2010).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/362/6410/53/suppl/DC1
Materials and Methods
Figs. S1 to S12
Tables S1 to S6
References (*34*–*38*)

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A sudden outburst of erosion

Glacial lake outburst floods (GLOFs) are exactly what they sound like. The sudden emptying of a glacial lake in high-topography regions like the Himalaya can quickly destroy everything in its path. Cook *et al.* intercepted a GLOF in the Bhotekoshi and Sunkoshi river valleys in central Nepal as they were monitoring the region in the aftermath of the 2015 Gorkha earthquake. They found that a massive amount of erosion occurred during the outburst flood, which suggests that GLOFs may be the primary factor in landscape evolution for these regions.

Science, this issue p. 53

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