PERSPECTIVE
https://doi.org/10.1038/s41561-022-00953-y

nature geoscience

High Mountain Asia hydropower systems threatened by climate-driven landscape instability

Dongfeng Li[1]✉, Xixi Lu[1], Desmond E. Walling[2], Ting Zhang[1], Jakob F. Steiner[3], Robert J. Wasson[4,5], Stephan Harrison[6], Santosh Nepal[3,7], Yong Nie[8], Walter W. Immerzeel[9], Dan H. Shugar[10], Michèle Koppes[11], Stuart Lane[12], Zhenzhong Zeng[13], Xiaofei Sun[14,1], Alexandr Yegorov[15,16] and Tobias Bolch[17]

Global warming-induced melting and thawing of the cryosphere are severely altering the volume and timing of water supplied from High Mountain Asia, adversely affecting downstream food and energy systems that are relied on by billions of people. The construction of more reservoirs designed to regulate streamflow and produce hydropower is a critical part of strategies for adapting to these changes. However, these projects are vulnerable to a complex set of interacting processes that are destabilizing landscapes throughout the region. Ranging in severity and the pace of change, these processes include glacial retreat and detachments, permafrost thaw and associated landslides, rock–ice avalanches, debris flows and outburst floods from glacial lakes and landslide-dammed lakes. The result is large amounts of sediment being mobilized that can fill up reservoirs, cause dam failure and degrade power turbines. Here we recommend forward-looking design and maintenance measures and sustainable sediment management solutions that can help transition towards climate change-resilient dams and reservoirs in High Mountain Asia, in large part based on improved monitoring and prediction of compound and cascading hazards.

High Mountain Asia (HMA), the Earth's most important and vulnerable water tower[1,2], is warming at a rate that is double the global average (0.32 °C per decade compared with the global average of 0.16 °C per decade (refs. [3,4])) and is characterized by a rapidly changing cryosphere[5,6] and related changes in the hydrological and sedimentary regimes of mountain rivers[7–9]. The projected declining meltwater supply from HMA's glaciers and snow packs in the near future (for example, slightly before or after 2050) coupled with population growth will probably exacerbate water stress and social instability in the region[10–12]. Dam construction and the creation of reservoirs to temporarily store meltwater for subsequent release during the dry season for irrigation and consumptive use are key strategies for water resource management[1,13–15]. Dams also have the potential to mitigate climate change by producing clean hydropower and thus to support the achievement of carbon neutrality for HMA countries[16–19]. However, there are social and environmental concerns associated with the development of hydropower projects (HPPs, both run-of-river systems and dams with large reservoirs), including human losses to HPP-related hazards, ecological fragmentation and biodiversity loss[20–22]. The hydropower potential in HMA exceeds 500 GW, which could support over 350 million homes[17]; however, most is untapped (Fig. 1c). There are currently over 650 HPPs (~240 GW) under construction or planned in HMA, in addition to the nearly 100 existing large HPPs mainly in the upper Indus–Ganges–Yangtze river basins (with a median storage capacity of 0.25 km^3), according to the Global Dam Watch[20,21]. Importantly, the new HPPs are being planned in locations closer to glaciers and glacial lakes in higher-altitude areas, making them more hazard prone (Fig. 1a).

Dams and reservoirs are increasingly facing climate-related mountain landscape instabilities, including glacier collapses or detachments (and related hazard cascades)[23], rock–ice avalanches[24–26], permafrost thaw and related landslides[27], debris flows[28], extreme lake outburst floods[11], higher erosion rates[29] and elevated sediment loads[9] that impact the short-term safety and longer-term sustainability of dams and reservoirs (Fig. 2 and Supplementary Table 1). The rock–ice avalanche that triggered a flood in India's Chamoli district, Uttarakhand, in February 2021 destroyed two HPPs (including one still under construction) and resulted in 204 dead or missing persons (190 of them workers from the HPPs)[24,26]. The 2013 Kedarnath disaster, also in Uttarakhand, started with extreme rainfall and snowmelt and resulted in a hazard chain including landslides, the Chorabari Lake outburst, flash floods and debris flows, which killed more than 6,000 people and damaged at least ten HPPs[30,31]. Such catastrophic disasters, together with many other HPP failures and related loss of lives (Fig. 2), illustrate the

---

[1]Department of Geography, National University of Singapore, Kent Ridge, Singapore. [2]Department of Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, UK. [3]International Centre for Integrated Mountain Development, Kathmandu, Nepal. [4]College of Science and Engineering, James Cook University, Cairns, Queensland, Australia. [5]Fenner School of Environment and Society, Australian National University, Canberra, Australian Capital Territory, Australia. [6]College of Life and Environmental Sciences, University of Exeter, Penryn, UK. [7]International Water Management Institute (IWMI), Nepal Office, Kathmandu, Nepal. [8]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China. [9]Faculty of Geosciences, Department of Physical Geography, Utrecht University, Utrecht, The Netherlands. [10]Water, Sediment, Hazards, and Earth-surface Dynamics (waterSHED) Lab, Department of Geoscience, University of Calgary, Calgary, Alberta, Canada. [11]Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada. [12]Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland. [13]School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China. [14]Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu, China. [15]Institute of Geography and Water Security, Almaty, Kazakhstan. [16]Central Asian Regional Glaciological Center as a category II under the auspices of UNESCO, Almaty, Kazakhstan. [17]School of Geography and Sustainable Development, University of St Andrews, St Andrews, UK. ✉e-mail: dongfeng@u.nus.edu

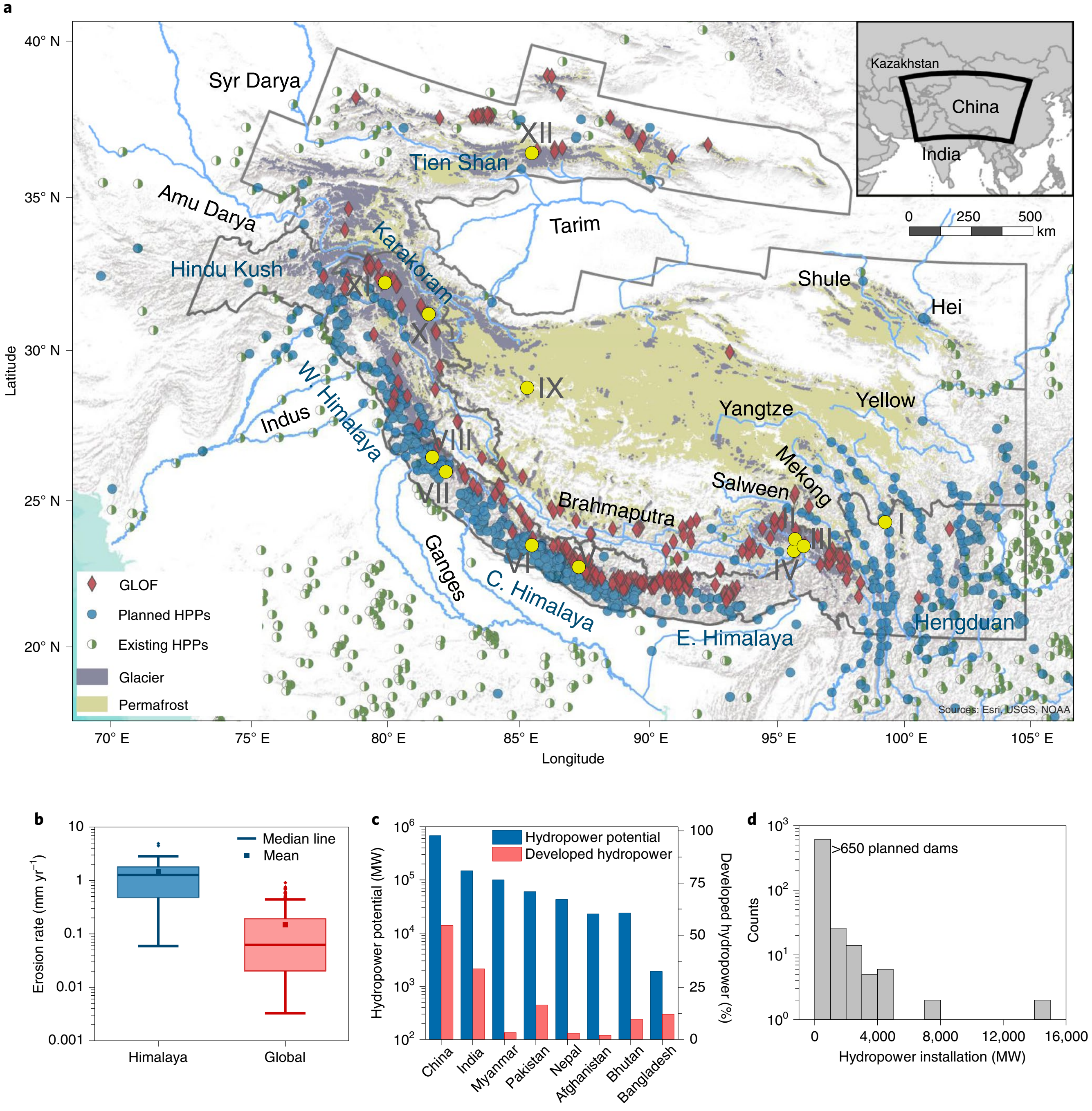


Fig. 1 | GLOFs, HPPs, and erosion rates in HMA. **a**, Existing large HPPs and planned (or under construction) HPPs[20,21]. Yellow dots denote locations of key examples of cryospheric hazards: I, Baige LLOF (2018); II, Yigong LLOF (2000); III, Tianmo periglacial debris flows (2007; 2010); IV, Gyalha glacier detachment–debris flow–LLOF (2018); V, Gongbatongsha Tsho GLOF (2016); VI, Seti rockfall–debris flow (2012); VII, Chamoli rock–ice avalanche–debris flow (2021); VIII, Kedarnath GLOF–landslide–debris flow (2013); IX, Aru glacier detachment (2016); X, Kyagar GLOF (frequently); XI, Attabad landslide and landslide-dammed lake (2010), XII, Merzbacher GLOF (frequently). GLOFs are from refs. [11, 69–71]. Boundaries of glaciers and permafrost are based on refs. [116,117]. Base map and inset courtesy of ESRI, USGS and NOAA. **b**, A comparison of modern erosion rates (1950s–2000s) in the Himalaya versus global[29,118]. The box ranges from the 25th percentile to the 75th percentile. The whiskers denote the 1.5 interquartile range (IQR). **c**, Hydropower potential and developed hydropower as a percentage in eight major HMA countries (updated from International Hydropower Association[121] and ref. [17]). **d**, The statistics of the hydropower installation capacity of the planned HPPs in HMA.

increasing risks to hydropower development and public safety in the steep mountain valleys of HMA[18,19].

In this Perspective, we present an overview of climate-related mountain landscape instabilities and their threats to hydropower dams and reservoirs in HMA. We characterize mountain landscape instabilities across three broad categories: (1) melting and thawing of the cryosphere and slope instability (for example, glacier detachments, rock–ice avalanches, rockfalls, landslides and debris flows); (2) glacial lake outburst floods (GLOFs) and landslide lake outburst floods (LLOFs) associated with cryospheric changes and slope instability;

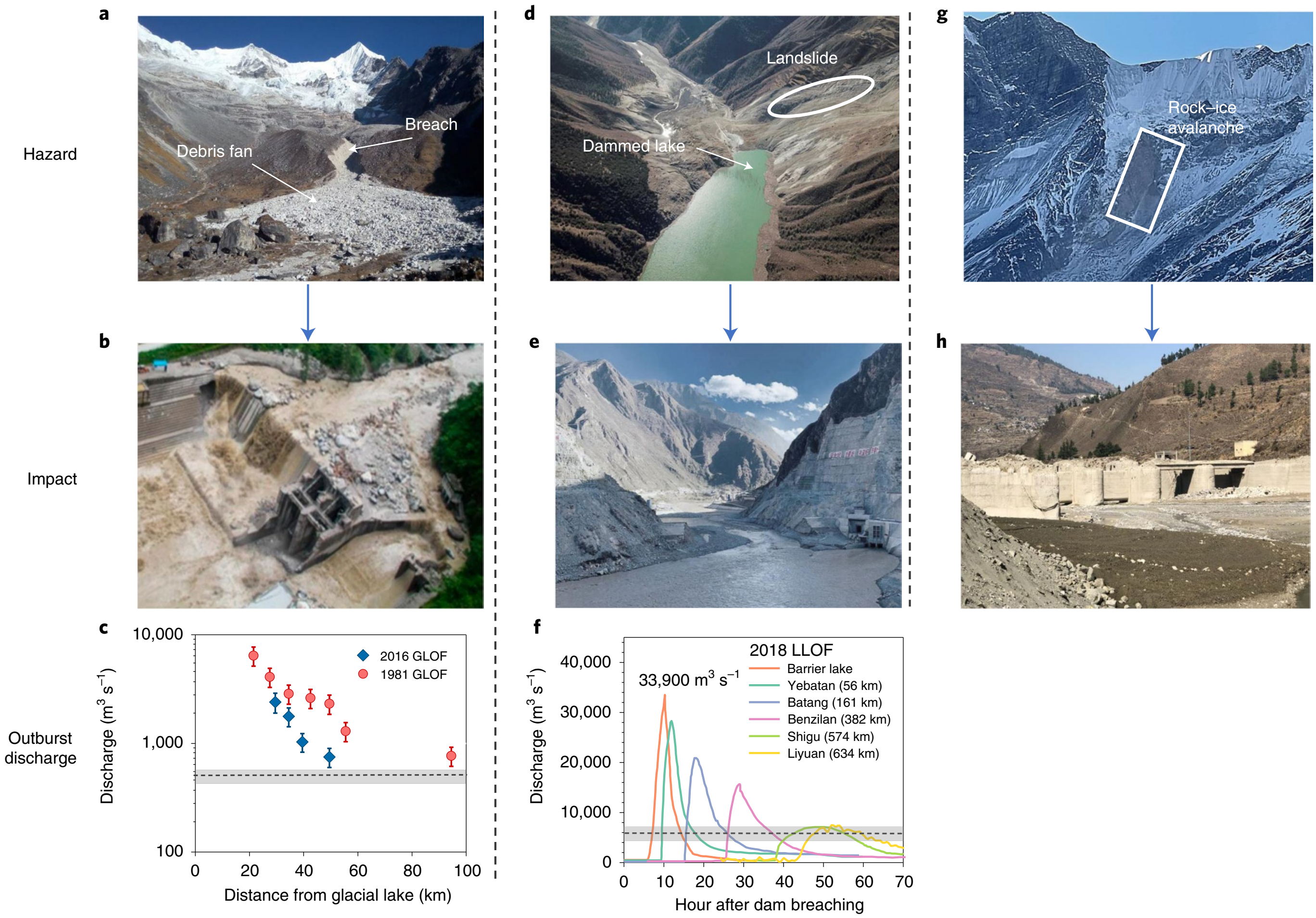


Fig. 2 | Field photos, outburst flood discharges and destruction of HPPs caused by three types of hazard chain. a–c, The destruction of the Upper Bhote Koshi HPP (Nepal) caused by the 2016 Gongbatongsha Tsho (Tibet, China) GLOF: glacial lake after breach (**a**); destroyed Bhote Koshi HPP (**b**); outburst peak discharges (**c**). In **c**, the peak discharges of outburst floods in 2016 (Gongbatongsha GLOF from Zhangzangbu Valley) and 1981 (Cirenmaco GLOF, a nearby GLOF from Zhangzangbu Valley) at different downstream sites were substantially higher than monsoon flood peak discharges (grey dotted line)[77]. Error bars indicate estimated uncertainty. **d–f**, The Baige landslide-dammed lake on the upper Yangtze River in November 2018 (**d**), the impacted Suwalong dam site after the Baige LLOF (**e**) and downstream hydrographs following dam breaching (**f**). In **f**, the dotted line denotes the monsoon flood peak discharge and the numbers in brackets indicate the distances downstream from the barrier lake[66]. **g**,**h**, The damaged Tapovan Vishnugad HPP (**h**) after the 2021 Chamoli rock–ice avalanche (**g**) in Uttarakhand, India. The dam and valley were fully covered by sediment and debris, including large boulders up to ~8 m in diameter. Credit: **a**,**c**, M. Liu; **d**,**e**, Y. J. Zhou for the Changjiang Water Resources Commission; **g**,**h**, M. F. Azam.

(3) erosion and sediment loads associated with changing slope processes and extreme floods. We detail each of these first, and then discuss their impacts on dams and reservoirs and provide recommendations for climate change-resilient hydropower development in the region. Finally, future research priorities, challenges and opportunities for a deeper understanding of mountain landscape instability and cryospheric hazards and their societal impacts are presented.

Melting and thawing of the cryosphere and slope instability

Global warming has caused the rapid melting or thawing of the cryosphere (for example, glaciers, snow and permafrost) in the world's high-mountain areas, with accelerating ice-mass losses in recent years[5,6]. The rapid decline in glaciers and permafrost thaw have altered the magnitude and frequency of related slope instabilities such as glacier detachments, rock–ice avalanches, rockfalls, landslides and debris flows[5,32,33].

Melting and thawing of the cryosphere. HMA is characterized by accelerating glacier retreat and permafrost thaw, shifting glacier equilibrium lines and permafrost boundaries to higher altitudes[5–7]. The glaciers experienced substantial mass loss of 21.1 ± 5.2 Gt yr^{-1} during 2000–2019, particularly in southeast HMA (Fig. 3a)[34–36]. Future projections indicate that HMA glaciers will shrink by ~40% under representative concentration pathway (RCP) 2.6, ~50% under RCP 4.5 and ~70% under RCP 8.5 by 2100 (Fig. 3b), with equilibrium line altitudes rising up to 800 m (refs. [5–7,37,38]). The permafrost ground temperatures are increasing, and the active layer is thickening[39,40]. Active layer thickness over the Tibetan Plateau is projected to increase from the present 2.3 ± 0.7 m to 3.1 ± 0.9 m (RCP 4.5) and 3.9 ± 1.0 m (RCP 8.5) by 2100 (Fig. 3c), with a reduction of the permafrost area up to 42% (refs. [41,42]). The snow-water equivalent of mountain snow packs has also declined in recent years and is projected to decline drastically in spring and early summer in the future[12].

Changing slope instability. Glacier retreat and permafrost thaw cause slope instabilities (for example, glacier detachments, rock–ice avalanches, rockfalls, landslides and debris flows)[43–46]. Climate change alters the thermal and basal properties of glaciers and can

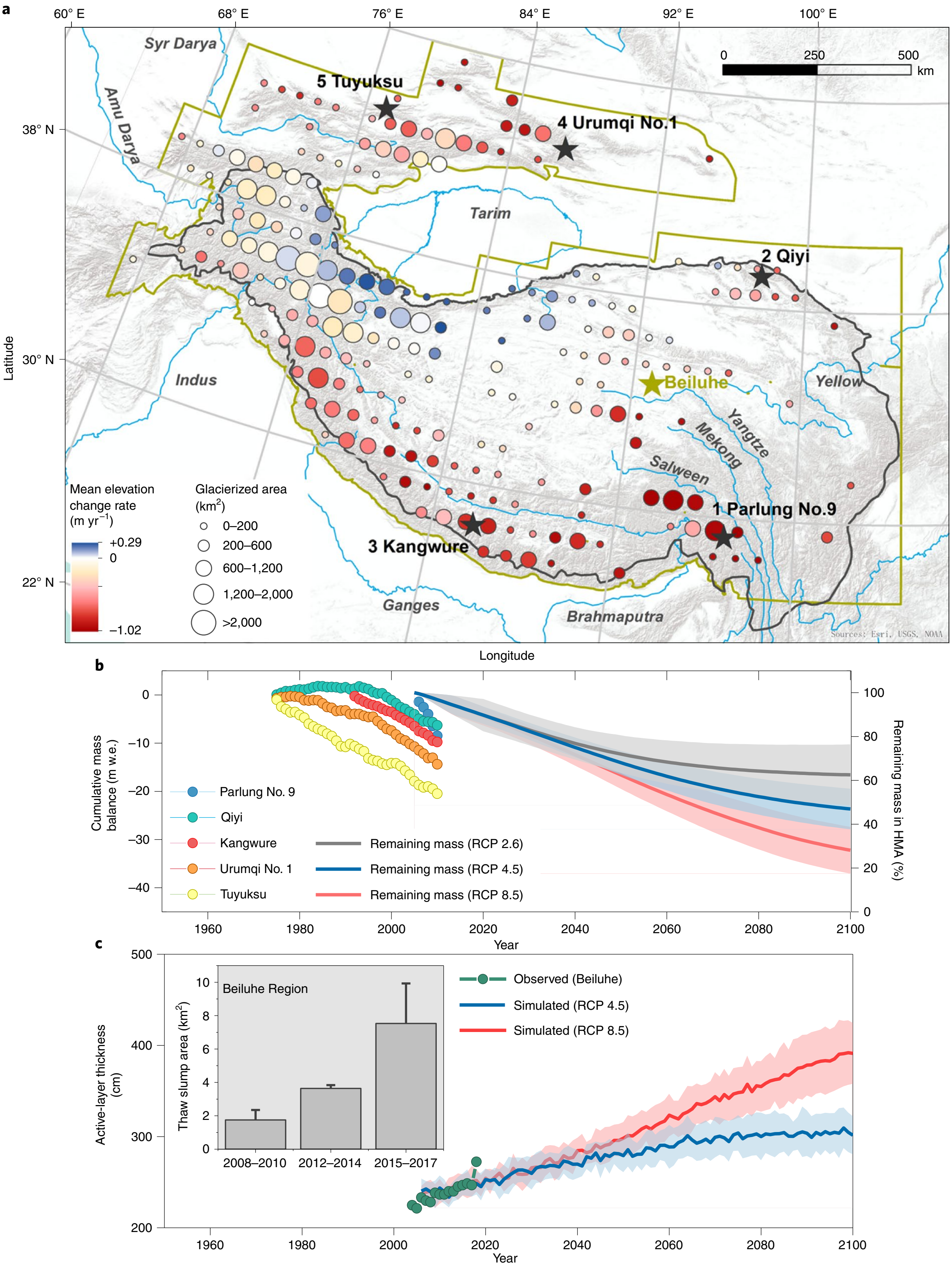


Fig. 3 | Melting of glaciers and thawing of permafrost in a warming HMA. **a**, Changes in glacier mean elevation in HMA[34]. The dark-grey boundary marks the Tibetan Plateau. Base map courtesy of Esri, USGS and NOAA. **b**, Observed past and projected future glacier mass loss. The five glaciers (black stars in **a**) shown reflect different climate zones: Parlung No. 9 (monsoon-dominated zone), Qiyi and Kangwure (transitional zone), Urumqi No.1 and Tuyuksu (westerly dominated zone)[6,119,120]. The projected glacier mass loss denotes the total glacier mass of HMA[38]. **c**, Increasing permafrost active layer thickness on the Tibetan Plateau[40,41] and expanding areas in thaw slumps[53]. The shading associated with the two projections denotes standard errors. w.e., water equivalent.

cause large-scale detachments of low-angle valley glaciers such as the collapses of the Aru twin glaciers in 2016 (this event caused the deaths of nine herders)[23,47]. Valley slopes newly exposed after glacier retreat are unstable paraglacial landscapes due to the debuttressing effect[48–52]. Degradation of bedrock permafrost and increased water availability during the thaw season also destabilize slopes[45,46]. Permafrost degradation also intensifies thermokarst development (for example, thaw slumps and active layer detachments; Fig. 3c and Supplementary Fig. 1), particularly in ice-rich environments[53].

The magnitude and frequency of slope instabilities have increased in high-mountain areas such as the European Alps and New Zealand in recent decades[43–45] and are projected to increase further in the near future, causing increasing risks to expanding population and infrastructure[5]. However, robust trend statistics for slope instability over the recent decades are currently lacking across HMA[5]. Recent examples of slope instabilities include the 2021 Chamoli disaster, which was triggered by a rock–ice avalanche that impacted older mass wasting deposits in previously glaciated terrain in the valley bottom and resulted in a disastrous debris flow[24–26]; the 2012 Seti disaster, caused by a rockfall onto a glacier that generated debris flows in the Seti valley, central Himalaya, and caused 72 deaths[54]; and the 2010 Attabad landslide in the Hunza Valley, Karakoram, and the resulting landslide-dammed lake that occurred in a periglacial environment, damaging over 200 houses and causing 20 deaths[55] (Supplementary Fig. 2). Modelling studies suggest that future landslides in the Himalaya (for example, the border region between China and Nepal where considerable glacial lakes exist) will increase in response to more-frequent rainstorm events[56].

Loose sediment exposed by glacial retreat or deposited by landslides can be remobilized during heavy rainfall or by further slope failures and evolve into debris flows[57–59] (Supplementary Fig. 1). The 2010 debris flows in Tianmo Valley, Tibet, were attributed to heavy rainfall and meltwater in a periglacial environment where frequent landslides increased sediment availability[57,60]. Precipitation is projected to increase in HMA associated with more rainstorms that may exacerbate slope instability[5]. Increased rainfall and its occurrence earlier in the year, coinciding with snowmelt, can increase the incidence of debris flows in valleys filled with glacial deposits (for example, the 2013 Kedarnath disaster)[30].

Extreme floods

Slope failures triggered by rapid climatic change and cryosphere degradation typically have notable local impacts (that is, several kilometres downstream), but they can also trigger a cascade of other hazards such as lake outburst floods that can extend hundreds of kilometres downstream and have important implications for the safety of mountain communities and infrastructure[5,55,61–63].

LLOFs. Large-scale mass movements often occur on the slopes of deeply incised valleys and can block rivers, temporarily impounding lakes and potentially triggering LLOFs[63–65] (Supplementary Table 2). These temporary natural dams can either be rapidly overtopped or continue to impound water for several days or months[63]. When such dams fail, large volumes of water can be suddenly released, causing floods with peak discharges up to several orders of magnitude greater than monsoon flood discharges[65]. In 2018, the Baige landslide blocked the Upper Yangtze River (an environment transitioning from permafrost to seasonally frozen ground; Fig. 1a) and created a landslide-dammed lake, which suddenly drained after ten days. This resulted in a peak discharge of 33,900 m^3 s^{-1} (the 10,000 yr return period discharge estimated for the site is 11,500 m^3 s^{-1} (ref. [66])), which was 10 times higher than the normal flood discharge and had a runout distance exceeding 500 km (Fig. 2f).

LLOFs in paraglacial environments have been frequently recorded in HMA. In October 2018, a glacier detachment-triggered debris flow blocked the Yarlung Tsangpo River Gorge[23,67]. The resulting lake reached a volume of 550 million m^3 before overtopping and draining, generating a peak discharge of 32,000 m^3 s^{-1} (Fig. 4c). The debris flow originated from a very steep tributary valley characterized by an elevation drop of ~5,000 m within 10 km (Fig. 4b). Similar large-scale LLOFs include the Yigong, Tianmo and Guxiang LLOFs[57,60,64]. In 2000, a large landslide-dammed lake on the Yigong River breached after 62 days, resulting in an unprecedented peak discharge of ~120,000 m^3 s^{-1} (Fig. 4c) impacting as far downstream as India and Bangladesh[68]. Such slope failures and associated LLOFs in paraglacial environments are likely to increase in a rapidly warming atmosphere[33] (Supplementary Fig. 3).

GLOFs. GLOFs, another type of lake outburst flood, have caused devastating human and infrastructure losses in HMA[69–75]. Glacial lakes, impounded behind a moraine or ice dam, have the potential for sudden outburst, triggered by heavy rainfall, glacier avalanches or surges, increased hydrostatic pressure and rapid ice melt[62,75]. Many moraine-dammed GLOFs are caused by ice avalanches or landslides into the lakes that generate displacement waves and result in dam failure through overtopping and erosion of the moraines[62,70] (Supplementary Fig. 1b). The 1985 Dig Tsho GLOF was triggered by a rock–ice avalanche and destroyed the Namche HPP, causing five deaths and over US$3 million damage[61,76]. Heavy rainfall-related GLOFs that destroyed downstream HPPs have also been reported in recent years (Supplementary Table 1), including the 2013 Chorabari GLOF[30] and 2016 Gongbatongsha GLOF[77,78]. Schwanghart et al.[18] estimated that two-thirds of the existing and planned HPPs in the Himalaya are located in potential GLOF pathways, and up to one-third of the HPPs could face GLOF discharges exceeding the local design flood.

Globally, rapid glacier retreat has expanded the number and size of glacial lakes, probably increasing the magnitude and frequency of GLOFs[74,77,79–81]. An updated inventory for the Himalayas suggests that the frequency of GLOFs increased after ~1950 (Fig. 4e)[11]. In the Karakoram, 179 GLOFs have been recorded from 1533 to 2020 (mostly associated with ice-dammed lakes), with an increasing trend in recent decades[69]. From 1810 to 2018 in Kyagar, 34 GLOFs were recorded, due mainly to glacier surges; 26 of those GLOFs occurred since 1960, indicating a marked increase in occurrence frequency[82]. In the central Tien Shan, GLOFs from the ice-dammed Merzbacher Lake have also increased in recent decades, with 65 being recorded during 1932–2011 and half of them occurring after 1990[83]. In the northern Tien Shan, the occurrence of GLOFs and related debris flows has increased since the 1950s, but their frequency reduced after 2000[84]. The attribution of GLOFs to anthropogenic global warming has strengthened[85] but remains uncertain, in part because of the relatively short period since the advent of the satellite era[62,72] and biases in GLOF reporting[73] but also due to the competing topographic and seismic factors[19]. However, it is clear that the risks of GLOFs in HMA will increase in the next few decades[70], associated with glacial lake expansion[80], more-frequent precipitation extremes[5] and avalanches[86], possibly shortened glacier surge cycles[87] and growing population and infrastructure exposure[18].

Heavy rainfall and snowmelt floods. In addition to LLOFs/GLOFs, the incidence of floods triggered by heavy rainfall, snowmelt and rain-on-snow events is also changing in HMA[5]. Climate change is likely to affect future rainfall patterns, and more extreme rainfall events are projected[4,88]. These changes in the rainfall regime also translate into changes in river discharge. Wijngaard et al.[88] projected a substantial increase in the 50 yr return period discharge in the upstream Indus, Ganges and Brahmaputra. A shift from snowfall to rainfall and rain-on-snow events in a warming atmosphere are also likely to trigger more flash floods in HMA[5].

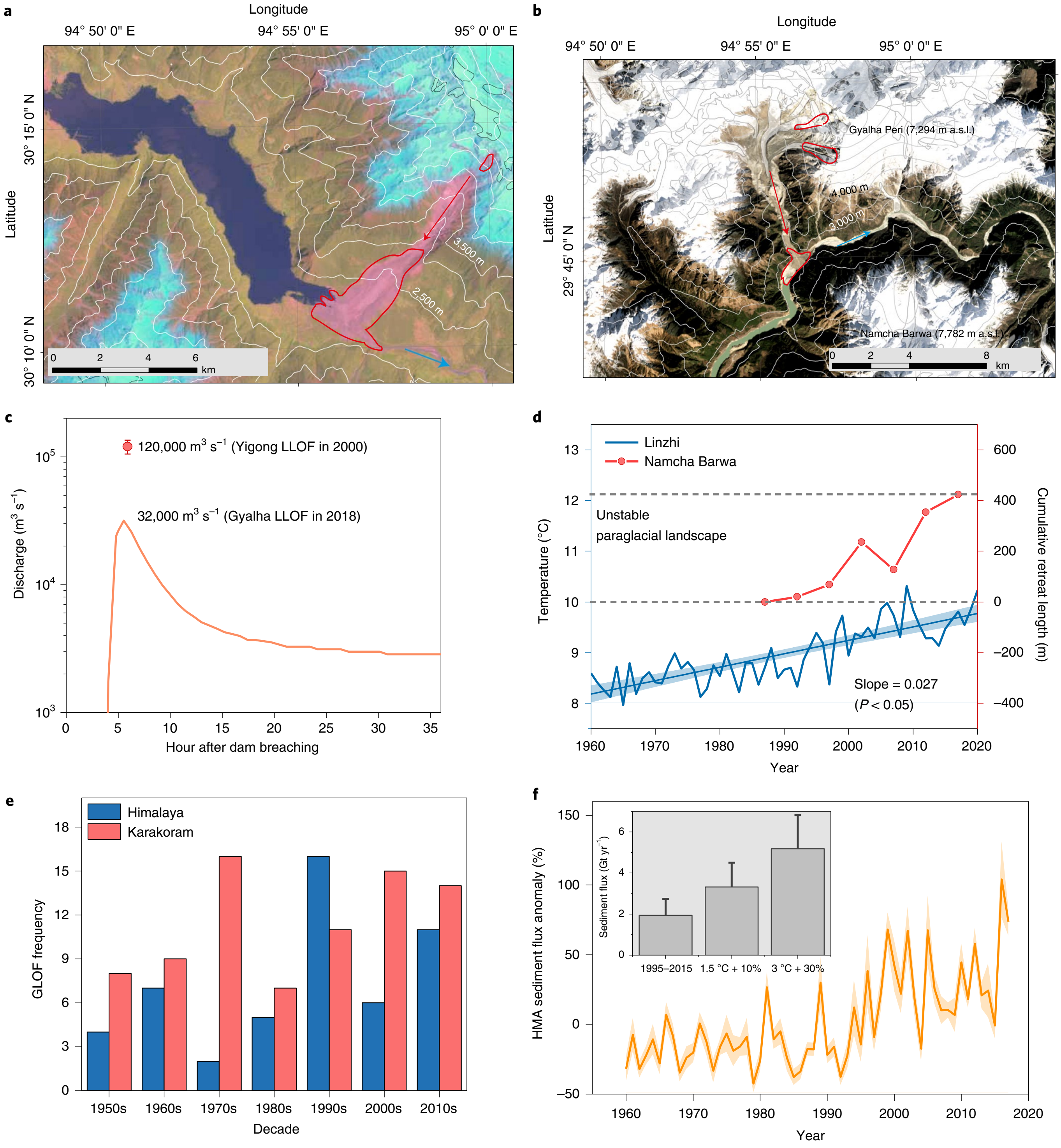


Fig. 4 | LLOFs, GLOFs and changing sediment fluxes in a rapidly warming HMA associated with glacier retreat. a–c, The Yigong landslide-dammed lake (May 2000; Landsat 5) (**a**), the Gyalha (Sedongpu Valley) debris flow-dammed lake (October 2018; Sentinel-2A) (**b**) and their outburst floods[67,68] (**c**). **d**, Glacier retreat at nearby Namcha Barwa due to atmospheric warming (data processed from Landsat 5–8 images). **e**, Increasing GLOF frequency in the Himalaya and Karakoram[11,69]. **f**, Increasing fluvial sediment fluxes from 28 quasi-pristine headwaters in HMA[9]. The inset shows the comparison between the present-day sediment flux and the projected sediment flux under a conservative (extreme) climate change scenario of an increase in temperature by 1.5 °C (3 °C) and an increase in precipitation by 10% (30%) from 1995–2015 to the middle of the twenty-first century. Error bars indicate estimated standard errors. a.s.l., above sea level.

Erosion and sediment fluxes

As HMA has overall been getting warmer and wetter over the recent decades[4,9], both run-off and fluvial sediment yields have been increasing, the latter in response to expanding erodible landscapes, increasing thermally and pluvially driven sediment sources and increasing rainfall erosivity and sediment transport capacity[9,89–92]. Observations from 28 quasi-pristine headwater catchments in HMA indicate that their annual fluvial sediment yields have increased at an average rate of ~13% per decade (notwithstanding substantial sediment storage along river pathways[93]) (Fig. 4f), much faster than the increase in annual run-off (~5% per decade)[9]. Approximately 40% of HMA is underlain by permafrost[4,9], and the increasing permafrost disturbances[28,53], especially channel-connected thaw slumps[89], in a warming climate will increase sediment sources from slopes to river systems.

With glacier mass loss, glacial erosion will change due to the reduced glacier velocity[94] on average, eventually reducing sediment supply. However, the basal sliding velocity of cold and polythermal glaciers, which are particularly common on the northern-central Tibetan Plateau[6], may initially increase (and hence also the erosion), driven by an increase in lubricating subglacial meltwater before the peak water discharge[95,96]. Moreover, sediment yields from glacierized basins will probably initially increase and continue to remain high, even after peak water discharge, as increased meltwater in previously hydrologically less-active subglacial zones at higher altitudes begins to export accumulated sediment[97], followed by an eventual decline[95]. Similarly, as glaciers shrink, sediment yields from newly exposed proglacial landscapes will also exhibit a similar trend, with an initial increase in sediment yield due to the increased availability of unconsolidated sediment on oversteepened slopes, followed by a decline when paraglacial landscapes progressively stabilize via negative feedbacks[48–52]. How long the increase in sediment yield lasts is likely to be scale dependent, with a rapid decline occurring close to the source region but the increase potentially lasting decades to centuries (and even a millennium) at more distal locations[49,50]. Further, initial increases in supply will be modified by changing transport capacity[90]. Glacier retreat initially increases sediment transport capacity as a result of the increased meltwater but also because the intensity of discharge variation increases[98]. Higher daily peak flows can substantially increase sediment transport capacity since the latter is commonly a nonlinear function of discharge excess over the critical value required for sediment transport. As peak water discharge passes, meltwater and the intensity of discharge variation will fall, and so will sediment transport capacity. Thus, peak sediment yield may occur close to, or just after, the peak water discharge (~2050 on average under RCP 4.5 in HMA[8]) close to the source region but much later farther downstream[49].

With glacier retreat, sediment transport will probably become more dependent on extreme flood events[51,99]. Extreme floods can further increase fluvial sediment yields by exceeding topographic and erosional thresholds and flushing previously stored sediment. LLOFs and GLOFs scour riverbanks, undercut hillslopes and even cause secondary landslides and thus transport substantial amounts of sediment downstream[77,100]. The 2000 Yigong LLOF triggered translational landslides and resulted in substantial hillslope erosion, which accounted for ~70% of the total landslide-induced erosion occurring over a 33 yr period[100]. The 2016 Gongbatongsha GLOF mobilized channel-defining boulders and produced a peak of sediment flux in a Himalaya river[77]. Extreme rainfall events can also abruptly increase sediment loads, as shown in the headwaters of the Yangtze[89] and Brahmaputra[92].

Impacts of mountain landscape instability on dams and reservoirs

Current infrastructure in HMA may face more damage in the future due to the increasing magnitude and frequency of multiple hazards. LLOFs and GLOFs are the most destructive hazards since they have downstream impacts extending over tens to hundreds of kilometres and will continue to cause major socioeconomic losses involving roads, bridges and HPPs[66,76] (Supplementary Table 1). Rainstorm- and snowmelt-induced flash floods can also threaten HPP safety by exceeding normal reservoir storage capacity and spillway design thresholds. Thus, existing HPPs that were designed using short-term historical gauge records, or climate-driven models where there are no records, may be exposed to higher-magnitude damage (Box 1). For planned HPPs at higher altitudes that are close to glaciers and glacial lakes (for example, <90 km in the Himalaya; Fig. 1a), the likelihood of HPP failures due to extreme floods will probably increase[11,18].

The high erosion rates and the increase in fluvial sediment flux in a changing climate can threaten the sustainability of both reservoirs and run-of-river systems (Figs. 1a and 4f and Box 1). Higher sediment loads increase sedimentation in reservoirs and reduce their storage capacity, jeopardizing their role in water supply, irrigation, flood control and hydropower generation[22,101]. The design of many existing reservoirs in HMA underestimates the potential for increasing sediment inflow (Supplementary Table 1). The Koshi (China/Nepal) and the upper Indus (China/India/Pakistan) have high specific suspended sediment yields (over 1,800 $\mathrm{t\,km^{-2}\,yr^{-1}}$) and high reservoir sedimentation rates[93,102]. Compared with suspended sediment, bedload (commonly over 10% and up to 50% of the total load in mountain rivers and proglacial rivers, respectively[103]) is more destructive to dams and reservoirs since this coarse sediment (for example, gravels and boulders) is readily deposited and cannot be readily flushed through a dam, even with a sediment-sluicing strategy[22].

In addition, the deposition of coarser sediment behind a dam may block bottom outlets, and the finer fractions enter water intakes, causing severe abrasion of turbine blades and damage to hydraulic structures[102]. Many examples of turbine abrasion and subsequent reduction of power generation efficiency have been reported in the Himalaya and Tien Shan (Supplementary Table 1), where the sediment contains high proportions of harder minerals. The turbines of the Nathpa Jhakri HPP (1,500 MW, the largest HPP on the Sutlej River) had to be replaced shortly after commencing operation due to abrasion[102].

Towards climate change-resilient hydropower systems

To minimize the adverse impacts of climate-driven mountain landscape instability on dams and reservoirs, we identify the following future actions (Box 1). First, maps of the distribution of paraglacial zones, sediment yield and hazard susceptibility that better delineate current and future unstable landscapes and erosion-prone regions should be produced, particularly for the HPP hotspots. Policy development regarding maintaining existing HPPs and planning of new HPPs should be guided by such hazard and risk maps.

Second, sediment issues must be viewed as a fundamental consideration for hydropower development. Sustainable sediment management strategies should be developed before reservoir construction. When planning future reservoirs, storage capacity design should consider potential storage losses associated with increasing sediment loads due to climate change[9] and provide additional storage to cope with climate-related hazards[66]. Sediment bypassing, sluicing, dredging and drawdown flushing need to be considered as possible means of minimizing reservoir sedimentation and increasing reservoir lifespans[22]. Catchment management plans targeted at reducing slope instability and erosion rates, and involving measures such as reforestation and check dams, should be developed and implemented to reduce sediment discharge into new reservoirs[104,105]. For existing reservoirs, a reassessment of sediment management solutions aimed at enhancing sustainable sediment management is recommended.

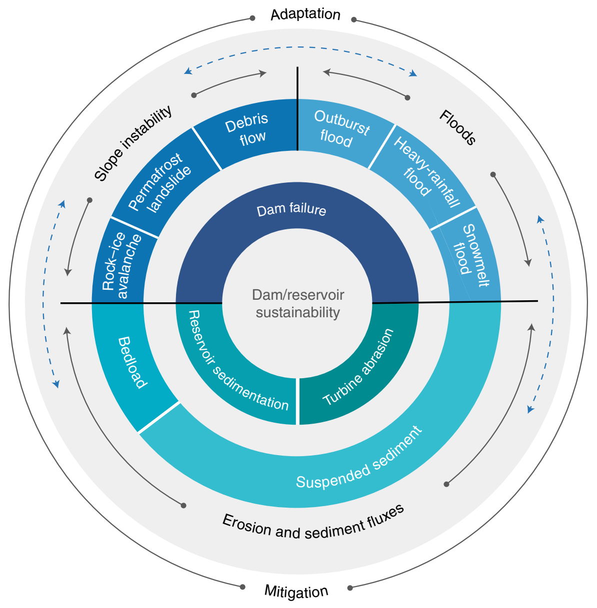
Third, monitoring, forecasting and early-warning systems (EWSs) should be further developed and implemented. Strategically oriented monitoring networks that measure high-altitude climate (for example, >4,000 m above sea level), glacier and permafrost dynamics, glacial lakes, unstable slopes and water and sediment fluxes should be expanded for high-risk areas. High-resolution optical and synthetic-aperture radar satellite imagery and seismic data offer a means of continually monitoring and assessing slope

Box 1 | Conceptualizing the increasing threats to dam and reservoir sustainability due to climate change with recommended solutions

The outer light-grey ring denotes broad types of mountain landscape instabilities (slope instability, floods, and erosion and sediment fluxes) associated with a changing climate. The dashed lines highlight interactions between different components of mountain landscape instability. The inner ring highlights specific threats to dams and reservoirs from different components of mountain landscape instabilities. Consideration of these interactions in a changing climate must be seen as a fundamental requirement when planning adaptation and mitigation strategies.

Recommendations and future needs to create climate change-resilient hydropower systems

- Expand satellite- and ground-based mapping and monitoring networks for the climate, glaciers and permafrost, glacial lakes, paraglacial landscapes, unstable slopes, erosion rates and sediment yields
- Understand the cascading links between climate change, glacier retreat and permafrost thaw, slope instability, evolution of glacial lakes and landslide-dammed lakes, lake outburst floods and downstream impacts
- Predict future fluvial sediment loads and reservoir sedimentation in response to a changing climate and the associated evolving glacial, paraglacial and fluvial processes
- Develop forward-looking and sustainable sediment management solutions to minimize reservoir sedimentation and turbine abrasion
- Establish real-time early-warning systems using seismic signals[25] and enhance social awareness and drills and response strategies, especially for HPPs under construction, to minimize human and infrastructure losses
- Further enhance transboundary cooperation by establishing data-sharing schemes and adopting joint-operation strategies to better cope with hazards and optimize sediment flushing
- Assess the long-term trade-offs of using hydropower as an adaptation solution for climate change, including the economic effects on hydropower generation of changing run-off, sediment load and hazard, the environmental effects on ecosystem fragmentation and biodiversity, societal effects on population migration and the reduction in greenhouse gas emissions contributed by hydropower
- Promote the inclusion of indigenous and local knowledge in policy, governance and management and secure local gains from dam and reservoir construction



evolution, glacial lakes, potential LLOF/GLOFs and hazard cascades[24,25,106]. Importantly, open data-driven dialogues among HMA countries must be enhanced to support both scientific research and risk reduction.

EWSs are in general lacking although several GLOF EWSs (for example, the Kyagar GLOF EWS[82]) have been recently established. New EWSs should be forward-looking[70] and coupled with effective land-use zoning, community participation, social awareness and emergency response strategies and drills[24,107]. When potential hazard conditions are forecast, response mechanisms should be in place to permit reservoir regulation, such as drawing down the reservoir to limit the impacts of incoming floods. Where cascade reservoirs, particularly in a transboundary setting, exist or are planned, there is a need to establish coordination and data-sharing schemes and to adopt joint-operation strategies to better cope with hazards and to flush sediment through the cascade.

Summary and perspectives

In HMA, atmospheric warming, cryosphere degradation and mountain landscape instability will probably increase over the next few decades and even into the next century. The potential increase in multiple cascading hazards adds more uncertainty to the sustainability and resilience of the fragile HMA, with major implications for the safety of humans and infrastructure.

Future research in the region must target less-studied landscape responses to climate change[91], including paraglacial adjustments, slope instability, hazard cascades and glacial/permafrost erosion and related sediment yields rather than focusing solely on cryosphere reduction and changes to freshwater supply[1,2,7,8,10–12,15]. Recently, glacier status and glacial lakes in HMA have been mapped[34–36,79–81,108–110], and knowledge regarding glacial lake evolution in relation to glacier changes has improved[79,111]. Predictions of future glacial lake development and GLOF risks are also being produced[70,86,112]. However, well-validated, high-resolution, regional-scale maps of mountain permafrost, slope instability, evolving paraglacial landscapes and sediment yields across HMA do not exist, and their absence needs urgent attention.

The challenges are to better understand the climatic, topographic, tectonic and cryospheric drivers and potential increases of the compound and cascading hazards associated with climate change (for example, uncertainties remain as to whether climate change and permafrost thaw played a role in triggering the 2021 Chamoli disaster[24]). Many of the disasters cited in the preceding occurred in steep paraglacial terrain and are characterized by hazard-cascading processes[24–26,67,68,77,113]. Slope instabilities and megafloods produce high sediment loads that have important geomorphological, ecological and societal implications.

Opportunities are emerging. Real-time monitoring networks that integrate data from remote-sensing images, seismic signals, hydro-meteorological stations, community observations and social media are being developed[24,25,114] and need rapid expansion into higher altitudes at finer resolution and larger scales. The real-time monitoring networks need to be integrated with improved artificial intelligence and process-based modelling[56,115] and forward-looking

EWSs[70] to benefit reductions of both the short- and long-term risks facing both humans and infrastructure systems. The engineers, practitioners, policymakers and stakeholders responsible for planning, designing, constructing and managing infrastructure (in particular, dams and reservoirs) in the region are urged to take account of these emerging processes, develop proactive adaptation measures and adopt sustainable solutions to minimize the negative impacts of climate change on these systems.

Data availability

The data shown in the figures are available in the publications cited and at https://github.com/geolidf/HMA-hydropower. Air-temperature data are sourced from the China Meteorological Administration. Satellite images are available from the ESA/EC Copernicus Sentinels Scientific Data Hub (Sentinel-2 data) and the United States Geological Survey (Landsat data). Glacier boundary is available at the Randolph Glacier Inventory (RGI 6.0; https://www.glims.org/RGI/rgi60_dl.html). Data on existing and planned HPPs are available at the Global Dam Watch (http://globaldamwatch.org/fhred/; http://globaldamwatch.org/grand/). Data on hydropower potential and developed hydropower are available from the International Hydropower Association (IHA; https://www.hydropower.org/status-report).

Code availability

The code used to produce Figs. 3 and 4 is available from the corresponding author on request.

Received: 11 June 2021; Accepted: 25 April 2022;

References

1. Immerzeel, W. W. et al. Importance and vulnerability of the world's water towers. *Nature* **577**, 364–369 (2020).
2. Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. & Wada, Y. Increasing dependence of lowland populations on mountain water resources. *Nat. Sustain.* **3**, 917–928 (2020).
3. Pepin, N. et al. Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Change* **5**, 424–430 (2015).
4. Yao, T. et al. Recent third pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: multidisciplinary approach with observations, modeling, and analysis. *Bull. Am. Meteorol. Soc.* **100**, 423–444 (2019).
5. Hock, R. et al. in *Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner, H. O. et al.) Ch. 2 (IPCC, 2019).
6. Bolch, T. et al. in *The Hindu Kush Himalaya Assessment* (eds Wester, P. et al.) 209–255 (Springer, 2019); https://doi.org/10.1007/978-3-319-92288-1_7
7. Rounce, D. R., Hock, R. & Shean, D. E. Glacier mass change in High Mountain Asia through 2100 using the open-source Python Glacier Evolution Model (PyGEM). *Front. Earth Sci.* **7**, 331 (2020).
8. Huss, M. & Hock, R. Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Change* **8**, 135–140 (2018).
9. Li, D. et al. Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science* **374**, 599–603 (2021).
10. Pritchard, H. D. Asia's shrinking glaciers protect large populations from drought stress. *Nature* **569**, 649–654 (2019).
11. Nie, Y. et al. Glacial change and hydrological implications in the Himalaya and Karakoram. *Nat. Rev. Earth Environ.* **2**, 91–106 (2021).
12. Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T. & Immerzeel, W. W. Climate change decisive for Asia's snow meltwater supply. *Nat. Clim. Change* **11**, 591–597 (2021).
13. Farinotti, D., Round, V., Huss, M., Compagno, L. & Zekollari, H. Large hydropower and water-storage potential in future glacier-free basins. *Nature* **575**, 341–344 (2019).
14. Dhaubanjar, S. et al. A systematic framework for the assessment of sustainable hydropower potential in a river basin—the case of the upper Indus. *Sci. Total Environ.* **786**, 147142 (2021).
15. Sorg, A., Bolch, T., Stoffel, M., Solomina, O. & Beniston, M. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nat. Clim. Change* **2**, 725–731 (2012).
16. Hussain, A. et al. Hydropower development in the Hindu Kush Himalayan region: issues, policies and opportunities. *Renew. Sustain. Energy Rev.* **107**, 446–461 (2019).
17. Vaidya, R. A., Molden, D. J., Shrestha, A. B., Wagle, N. & Tortajada, C. The role of hydropower in South Asia's energy future. *Int. J. Water Resour. Dev.* **37**, 367–391 (2021).
18. Schwanghart, W., Worni, R., Huggel, C., Stoffel, M. & Korup, O. Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods. *Environ. Res. Lett.* **11**, 074005 (2016).
19. Schwanghart, W., Ryan, M. & Korup, O. Topographic and seismic constraints on the vulnerability of Himalayan hydropower. *Geophys. Res. Lett.* **45**, 8985–8992 (2018).
20. Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L. & Tockner, K. A global boom in hydropower dam construction. *Aquat. Sci.* **77**, 161–170 (2015).
21. Lehner, B. et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ.* **9**, 494–502 (2011).
22. Kondolf, G. M. et al. Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents. *Earths Future* **2**, 256–280 (2014).
23. Kääb, A. et al. Sudden large-volume detachments of low-angle mountain glaciers—more frequent than thought? *Cryosphere* **15**, 1751–1785 (2021).
24. Shugar, D. H. et al. A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science* **373**, 300–306 (2021).
25. Cook, K. L. et al. Detection and potential early warning of catastrophic flow events with regional seismic networks. *Science* **374**, 87–92 (2021).
26. Sain, K. et al. A perspective on Rishiganga-Dhauliganga flash flood in the Nanda Devi Biosphere Reserve, Garhwal Himalaya, India. *J. Geol. Soc. India* **97**, 335–338 (2021).
27. Gruber, S. et al. Review article: inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. *Cryosphere* **11**, 81–99 (2017).
28. Ding, Y. et al. Increasing cryospheric hazards in a warming climate. *Earth Sci. Rev.* **213**, 103500 (2021).
29. Koppes, M. N. & Montgomery, D. R. The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales. *Nat. Geosci.* **2**, 644–647 (2009).
30. Allen, S. K., Rastner, P., Arora, M., Huggel, C. & Stoffel, M. Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. *Landslides* **13**, 1479–1491 (2016).
31. Bhambri, R. et al. Devastation in the Kedarnath (Mandakini) Valley, Garhwal Himalaya, during 16–17 June 2013: a remote sensing and ground-based assessment. *Nat. Hazards* **80**, 1801–1822 (2016).
32. Huss, M. et al. Toward mountains without permanent snow and ice. *Earths Future* **5**, 418–435 (2017).
33. Evans, S. G., Delaney, K. B. & Rana, N. M. in *Snow and Ice-Related Hazards, Risks, and Disasters* 2nd edn (eds Haeberli, W. & Whiteman, C.) 541–596 (Elsevier, 2021); https://doi.org/10.1016/B978-0-12-817129-5.00004-4
34. Hugonnet, R. et al. Accelerated global glacier mass loss in the early twenty-first century. *Nature* **592**, 726–731 (2021).
35. Shean, D. E. et al. A systematic, regional assessment of High Mountain Asia glacier mass balance. *Front. Earth Sci.* **7**, 363 (2020).
36. Brun, F., Berthier, E., Wagnon, P., Kääb, A. & Treichler, D. A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nat. Geosci.* **10**, 668–673 (2017).
37. Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. & Immerzeel, W. W. Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature* **549**, 257–260 (2017).
38. Marzeion, B. et al. Partitioning the uncertainty of ensemble projections of global glacier mass change. *Earths Future* **8**, e2019EF001470 (2020).
39. Biskaborn, B. K. et al. Permafrost is warming at a global scale. *Nat. Commun.* **10**, 264 (2019).
40. Zhao, L. et al. A synthesis dataset of permafrost thermal state for the Qinghai–Tibet (Xizang) Plateau, China. *Earth Syst. Sci. Data* **13**, 4207–4218 (2021).
41. Wang, T. et al. Permafrost thawing puts the frozen carbon at risk over the Tibetan Plateau. *Sci. Adv.* **6**, eaaz3513 (2020).
42. Ni, J. et al. Simulation of the present and future projection of permafrost on the Qinghai–Tibet Plateau with statistical and machine learning models. *J. Geophys. Res. Atmos.* **126**, e2020JD033402 (2021).
43. Allen, S. K., Cox, S. C. & Owens, I. F. Rock avalanches and other landslides in the central Southern Alps of New Zealand: a regional study considering possible climate change impacts. *Landslides* **8**, 33–48 (2011).
44. Fischer, L., Purves, R. S., Huggel, C., Noetzli, J. & Haeberli, W. On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas. *Nat. Hazards Earth Syst. Sci.* **12**, 241–254 (2012).

45. Savi, S., Comiti, F. & Strecker, M. R. Pronounced increase in slope instability linked to global warming: a case study from the eastern European Alps. *Earth Surf. Process. Landf.* https://doi.org/10.1002/esp.5100 (2021).
46. Gruber, S. & Haeberli, W. Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *J. Geophys. Res. Earth Surf.* **112**, F02S18 (2007).
47. Kääb, A. et al. Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nat. Geosci.* **11**, 114–120 (2018).
48. Church, M. & Ryder, J. M. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Geol. Soc. Am. Bull.* **83**, 3059–3072 (1972).
49. Church, M. & Slaymaker, O. Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature* **337**, 452 (1989).
50. Ballantyne, C. K. Paraglacial geomorphology. *Quat. Sci. Rev.* **21**, 1935–2017 (2002).
51. Knight, J. & Harrison, S. Mountain glacial and paraglacial environments under global climate change: lessons from the past, future directions and policy implications. *Geogr. Ann. Ser. A* **96**, 245–264 (2014).
52. Antoniazza, G. & Lane, S. N. Sediment yield over glacial cycles: a conceptual model. *Prog. Phys. Geogr. Earth Environ.* https://doi.org/10.1177/0309133321997292 (2021).
53. Luo, J., Niu, F., Lin, Z., Liu, M. & Yin, G. Recent acceleration of thaw slumping in permafrost terrain of Qinghai–Tibet Plateau: an example from the Beiluhe Region. *Geomorphology* **341**, 79–85 (2019).
54. Hanisch, J., Koirala, A. & Bhandary, N. P. The Pokhara May 5th flood disaster: a last warning sign sent by nature? *J. Nepal Geol. Soc.* **46**, 1–10 (2013).
55. Fan, X. et al. The formation and impact of landslide dams—state of the art. *Earth Sci. Rev.* **203**, 103116 (2020).
56. Kirschbaum, D., Kapnick, S. B., Stanley, T. & Pascale, S. Changes in extreme precipitation and landslides over High Mountain Asia. *Geophys. Res. Lett.* **47**, e2019GL085347 (2020).
57. Yu, G. A., Yao, W., Huang, H. Q. & Liu, Z. Debris flows originating in the mountain cryosphere under a changing climate: a review. *Prog. Phys. Geogr.* **45**, 339–374 (2020).
58. Walter, F. et al. Direct observations of a three million cubic meter rock-slope collapse with almost immediate initiation of ensuing debris flows. *Geomorphology* **351**, 106933 (2020).
59. Church, M. & Jakob, M. What is a debris flood? *Water Resour. Res.* **56**, e2020WR027144 (2020).
60. Deng, M., Chen, N. & Liu, M. Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo Valley, south-eastern Tibetan Plateau. *Nat. Hazards Earth Syst. Sci.* **17**, 345–356 (2017).
61. Carrivick, J. L. & Tweed, F. S. A global assessment of the societal impacts of glacier outburst floods. *Glob. Planet. Change* **144**, 1–16 (2016).
62. Harrison, S. et al. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *Cryosphere* **12**, 1195–1209 (2018).
63. Liu, W. et al. Outburst floods in China: a review. *Earth Sci. Rev.* **197**, 102895 (2019).
64. Delaney, K. B. & Evans, S. G. The 2000 Yigong landslide (Tibetan Plateau), rockslide-dammed lake and outburst flood: review, remote sensing analysis, and process modelling. *Geomorphology* **246**, 377–393 (2015).
65. Wasson, R. J. et al. A 1000-year history of large floods in the Upper Ganga catchment, central Himalaya, India. *Quat. Sci. Rev.* **77**, 156–166 (2013).
66. Zhang, L., Xiao, T., He, J. & Chen, C. Erosion-based analysis of breaching of Baige landslide dams on the Jinsha River, China, in 2018. *Landslides* **16**, 1965–1979 (2019).
67. Chen, C., Zhang, L., Xiao, T. & He, J. Barrier lake bursting and flood routing in the Yarlung Tsangpo Grand Canyon in October 2018. *J. Hydrol.* **583**, 124603 (2020).
68. Shang, Y. et al. A super-large landslide in Tibet in 2000: background, occurrence, disaster, and origin. *Geomorphology* **54**, 225–243 (2003).
69. Bazai, N. A. et al. Increasing glacial lake outburst flood hazard in response to surge glaciers in the Karakoram. *Earth Sci. Rev.* **212**, 103432 (2021).
70. Zheng, G. et al. Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nat. Clim. Change* **11**, 411–417 (2021).
71. Zheng, G. et al. Numerous unreported glacial lake outburst floods in the Third Pole revealed by high-resolution satellite data and geomorphological evidence. *Sci. Bull.* **66**, 1270–1273 (2021).
72. Veh, G., Korup, O., von Specht, S., Roessner, S. & Walz, A. Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nat. Clim. Change* **9**, 379–383 (2019).
73. Veh, G. et al. Trends, breaks, and biases in the frequency of reported glacier lake outburst floods. *Earths Future* **10**, e2021EF002426 (2022).
74. Shugar, D. H. et al. Rapid worldwide growth of glacial lakes since 1990. *Nat. Clim. Change* **10**, 939–945 (2020).
75. Nie, Y. et al. An inventory of historical glacial lake outburst floods in the Himalayas based on remote sensing observations and geomorphological analysis. *Geomorphology* **308**, 91–106 (2018).
76. Richardson, S. D. & Reynolds, J. M. An overview of glacial hazards in the Himalayas. *Quat. Int.* **65**, 31–47 (2000).
77. Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R. & Hovius, N. Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science* **362**, 53–57 (2018).
78. Liu, M., Chen, N., Zhang, Y. & Deng, M. Glacial lake inventory and lake outburst flood/debris flow hazard assessment after the Gorkha earthquake in the Bhote Koshi Basin. *Water* **12**, 464 (2020).
79. King, O., Bhattacharya, A., Bhambri, R. & Bolch, T. Glacial lakes exacerbate Himalayan glacier mass loss. *Sci. Rep.* **9**, 18145 (2019).
80. Chen, F. et al. Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017. *Earth Syst. Sci. Data* **13**, 741–766 (2021).
81. Nie, Y. et al. A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sens. Environ.* **189**, 1–13 (2017).
82. Yin, B., Zeng, J., Zhang, Y., Huai, B. & Wang, Y. Recent Kyagar glacier lake outburst flood frequency in Chinese Karakoram unprecedented over the last two centuries. *Nat. Hazards* **95**, 877–881 (2019).
83. Shangguan, D. et al. Quick release of internal water storage in a glacier leads to underestimation of the hazard potential of glacial lake outburst floods from Lake Merzbacher in central Tian Shan Mountains. *Geophys. Res. Lett.* **44**, 9786–9795 (2017).
84. Medeu, A. R. et al. Moraine-dammed glacial lakes and threat of glacial debris flows in South-East Kazakhstan. *Earth Sci. Rev*. https://doi.org/10.1016/j.earscirev.2022.103999 (2022).
85. Stuart-Smith, R. F., Roe, G. H., Li, S. & Allen, M. R. Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat. *Nat. Geosci.* **14**, 85–90 (2021).
86. Sattar, A. et al. Future glacial lake outburst flood (GLOF) hazard of the South Lhonak Lake, Sikkim Himalaya. *Geomorphology* **388**, 107783 (2021).
87. Gao, Y. et al. Glacier-related hazards along the International Karakoram Highway: status and future perspectives. *Front. Earth Sci.* **9**, 611501 (2021).
88. Wijngaard, R. R. et al. Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra river basins. *PLoS ONE* **12**, e0190224 (2017).
89. Li, D., Overeem, I., Kettner, A. J., Zhou, Y. & Lu, X. Air temperature regulates erodible landscape, water, and sediment fluxes in the permafrost-dominated catchment on the Tibetan Plateau. *Water Resour. Res.* **57**, e2020WR028193 (2021).
90. Zhang, T., Li, D., Kettner, A. J., Zhou, Y. & Lu, X. Constraining dynamic sediment–discharge relationships in cold environments: the Sediment-Availability-Transport (SAT) Model. *Water Resour. Res.* **57**, e2021WR030690 (2021).
91. East, A. E. & Sankey, J. B. Geomorphic and sedimentary effects of modern climate change: current and anticipated future conditions in the western United States. *Rev. Geophys.* **58**, e2019RG000692 (2020).
92. Shi, X. et al. The response of the suspended sediment load of the headwaters of the Brahmaputra River to climate change: quantitative attribution to the effects of hydrological, cryospheric and vegetation controls. *Glob. Planet. Change* **210**, 103753 (2022).
93. Sinha, R. et al. Basin-scale hydrology and sediment dynamics of the Kosi River in the Himalayan foreland. *J. Hydrol.* **570**, 156–166 (2019).
94. Dehecq, A. et al. Twenty-first century glacier slowdown driven by mass loss in High Mountain Asia. *Nat. Geosci.* **12**, 22–27 (2019).
95. Herman, F., De Doncker, F., Delaney, I., Prasicek, G. & Koppes, M. The impact of glaciers on mountain erosion. *Nat. Rev. Earth Environ.* **2**, 422–435 (2021).
96. Koppes, M. et al. Observed latitudinal variations in erosion as a function of glacier dynamics. *Nature* **526**, 100–103 (2015).
97. Delaney, I. & Adhikari, S. Increased subglacial sediment discharge in a warming climate: consideration of ice dynamics, glacial erosion, and fluvial sediment transport. *Geophys. Res. Lett.* **47**, e2019GL085672 (2020).
98. Lane, S. N. & Nienow, P. W. Decadal-scale climate forcing of Alpine glacial hydrological systems. *Water Resour. Res.* **55**, 2478–2492 (2019).
99. Carrivick, J. L. & Tweed, F. S. Deglaciation controls on sediment yield: towards capturing spatio-temporal variability. *Earth Sci. Rev.* **221**, 103809 (2021).
100. Larsen, I. J. & Montgomery, D. R. Landslide erosion coupled to tectonics and river incision. *Nat. Geosci.* **5**, 468–473 (2012).
101. Li, D., Lu, X. X., Yang, X., Chen, L. & Lin, L. Sediment load responses to climate variation and cascade reservoirs in the Yangtze River: a case study of the Jinsha River. *Geomorphology* **322**, 41–52 (2018).
102. Annandale, G. W., Morris, G. L. & Karki, P. *Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower* (World Bank, 2016).

103. Turowski, J. M., Rickenmann, D. & Dadson, S. J. The partitioning of the total sediment load of a river into suspended load and bedload: a review of empirical data. *Sedimentology* **57**, 1126–1146 (2010).
104. Best, J. Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* **12**, 7–21 (2019).
105. Walling, D. E. Human impact on land–ocean sediment transfer by the world's rivers. *Geomorphology* **79**, 192–216 (2006).
106. Kirschbaum, D. et al. The state of remote sensing capabilities of cascading hazards over High Mountain Asia. *Front. Earth Sci.* **7**, 197 (2019).
107. Huggel, C. et al. Glacier Lake 513, Peru: lessons for early warning service development. *WMO Bull.* **69**, 45–52 (2020).
108. Farinotti, D. et al. A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nat. Geosci.* **12**, 168–173 (2019).
109. Miles, E. et al. Health and sustainability of glaciers in High Mountain Asia. *Nat. Commun.* **12**, 2868 (2021).
110. Bhattacharya, A. et al. High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. *Nat. Commun.* **12**, 4133 (2021).
111. Benn, D. I. et al. Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth Sci. Rev.* **114**, 156–174 (2012).
112. Furian, W., Maussion, F. & Schneider, C. Projected 21st-century glacial lake evolution in High Mountain Asia. *Front. Earth Sci.* **10**, 821798 (2022).
113. Hu, K. et al. Landslides and dammed lakes triggered by the 2017 M_s6.9 Milin earthquake in the Tsangpo gorge. *Landslides* **16**, 993–1001 (2019).
114. Kargel, J. S. et al. Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science* **351**, aac8353 (2016).
115. Mergili, M., Fischer, J.-T., Krenn, J. & Pudasaini, S. P. r.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows. *Geosci. Model Dev.* **10**, 553–569 (2017).
116. Pfeffer, W. T. et al. The Randolph Glacier Inventory: a globally complete inventory of glaciers. *J. Glaciol.* **60**, 537–552 (2014).
117. Ran, Y. et al. New high-resolution estimates of the permafrost thermal state and hydrothermal conditions over the Northern Hemisphere. *Earth Syst. Sci. Data* **14**, 865–884 (2022).
118. Syvitski, J. et al. Earth's sediment cycle during the Anthropocene. *Nat. Rev. Earth Environ.* **3**, 179–196 (2022).
119. Yao, T. et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Change* **2**, 663–667 (2012).
120. Severskiy, I. et al. Changes in glaciation of the Balkhash–Alakol basin, central Asia, over recent decades. *Ann. Glaciol.* **57**, 382–394 (2016).
121. *Hydropower Status Report 2021* (IHA, 2021); https://www.hydropower.org/publications/2021-hydropower-status-report

Acknowledgements

This work was supported by Singapore MOE (R-109-000-273-112 and R-109-000-227-115; X.L., D.L.), Cuomo Foundation and IPCC Scholarship Award (D.L.), Swiss National Science Foundation (IZLCZ2_169979/1; T.B.), European Research Council under the European Union's Horizon 2020 programme (676819; W.W.I., J.F.S.), Netherlands Organisation for Scientific Research (NWO) under the research programme VIDI (016.161.308; W.W.I., J.F.S.), NSFC (42171086; Y.N.), Natural Sciences and Engineering Research Council (NSERC) of Canada (04207-2020; D.H.S.) and Water and Air theme of ICIMOD (S.N., J.F.S.). We thank I. Overeem, A. Kettner, J. Syvitski and IAG DENUCHANGE working group for discussions on erosion and sediment fluxes. The views and interpretations in this publication are those of the authors and are not necessarily attributable to their organizations.

Author contributions

D.L. and X.L. conceived the study. D.L. wrote the original draft. X.L., D.E.W., T.B., T.Z., R.J.W. and S.H. edited the initial version and contributed ideas. D.L. and T.Z. designed the figures and the Box. J.F.S. contributed to Fig. 4a,b. S.N. contributed to the Box. Y.N. and A.Y. contributed data on GLOFs. X.S. contributed to Supplementary Figs. 1–3. All authors contributed to ideas and edits of subsequent revisions.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41561-022-00953-y.

Correspondence should be addressed to Dongfeng Li.

Peer review information *Nature Geoscience* thanks Mette Bendixen, Yongkang Xue and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editor: James Super, in collaboration with the *Nature Geoscience* team.