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

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Abstract

Global warming-induced melting and thawing of the cryosphere are severely altering the volume and timing of water supplied from High Mountain Asia (HMA), adversely affecting downstream food and energy systems relied upon 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 end 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 HMA, in large part based on improved monitoring and prediction of compound and cascading hazards.

1. Introduction

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/decade compared with the global average of 0.16°C/decade[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 snowpacks in the near future (e.g., slightly before or after 2050) coupled with population growth will likely 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 Table S1). 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 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 (e.g., 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; (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.

2. Melting and thawing of the cryosphere and slope instability

Global warming has caused the rapid melting or thawing of the cryosphere (e.g., 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].

2.1 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 (-21.1 ± 5.2 Gt/y) during 2000-2019, particularly in South-East HMA (Fig. 3a)[34–36]. Future projections indicate that HMA glaciers will shrink by ~40% under Representative Concentration Pathway (RCP) 2.6, ~50% under RCP4.5, and ~70% under RCP 8.5 by 2100 (Fig. 3b), with equilibrium line altitudes (ELA) rising up to 800 m[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%[41,42]. The snow water equivalent of mountain snowpacks has also declined in recent years and is projected to decline drastically in spring and early summer in the future[12].

2.2 Changing slope instability

Glacier retreat and permafrost thaw cause slope instabilities (e.g., glacier detachments, rock/ice avalanches, rockfalls, landslides, and debris flows)[43–46]. Climate change alters the thermal and basal properties of glaciers and can 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 (e.g., thaw slumps and active layer detachments, Fig. 3c and Fig. S1), 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 past 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] (Fig. S2). Modelling studies suggest that future landslides in the Himalaya (e.g., the border region between China and Nepal where considerable glacial lakes exsist) 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] (Fig. S1). 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 (e.g., the 2013 Kedarnath disaster)[30].

3. Extreme floods

Slope failures triggered by rapid climatic change and cryosphere degradation typically have significant local impacts (i.e., several kilometres downstream), but 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].

3.1 Landslide lake outburst floods (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] (Table S2). 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 (the 10,000-year return period discharge estimated for the site is 11,500 m^3/s[66]) that 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 (Fig. 4c). The debris flow originated from a very steep tributary valley characterized by an elevation drop of ~5000 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 (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] (Fig. S3).

3.2 Glacial lake outburst floods (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] (Fig. S1b). The 1985 Dig Tsho GLOF was triggered by an 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 (Table S1), 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, likely 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 mainly due 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 time 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].

3.3 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-year 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].

4. Erosion and sediment fluxes

As HMA has overall been getting warmer and wetter over the past decades[4,9], both runoff 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 runoff (~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 likely 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 occuring 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 non-linear 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 further downstream[49].

With glacier retreat, sediment transport will likely 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/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-y period[100]. The 2016 Gongbatongsha GLOF mobilized channel-defining boulders and produced a very 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].

5. 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/GLOFs are the most destructive hazards, since they have downstream impacts extending over tens to hundreds of kilometres and will continue to cause major social-economic losses involving roads, bridges, and HPPs[66,76] (Table S1). Rainstorm/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 (e.g., <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 (Fig.1a, Fig. 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 (Table S1). The Koshi (China/Nepal) and the upper Indus (China/India/Pakistan) have high specific suspended sediment yields (over 1800 $t/km^2/y$) 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 (e.g., 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 (Table S1), 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].

6. 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 (EWS) should be further developed and implemented. Strategically oriented monitoring networks that measure high-altitude climate (e.g., >4000 m a.s.l.), glacier and permafrost dynamics, glacial lakes, unstable slopes, and water and sediment fluxes should be expanded for high-risk areas. High-resolution optical and SAR satellite imagery and seismic data offer a means of continually monitoring and assessing slope evolution, glacial lakes, potential LLOF/GLOFs, and potential 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 (e.g., 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.

7. Summary and perspectives

In HMA, atmospheric warming, cryosphere degradation, and mountain landscape instability will likely increase over the next few decades and even into the next century. The potential increase in multiple, cascading hazards add 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 significantly 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 need 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 (e.g., 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 above 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 inlelligence and process-based modeling[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.

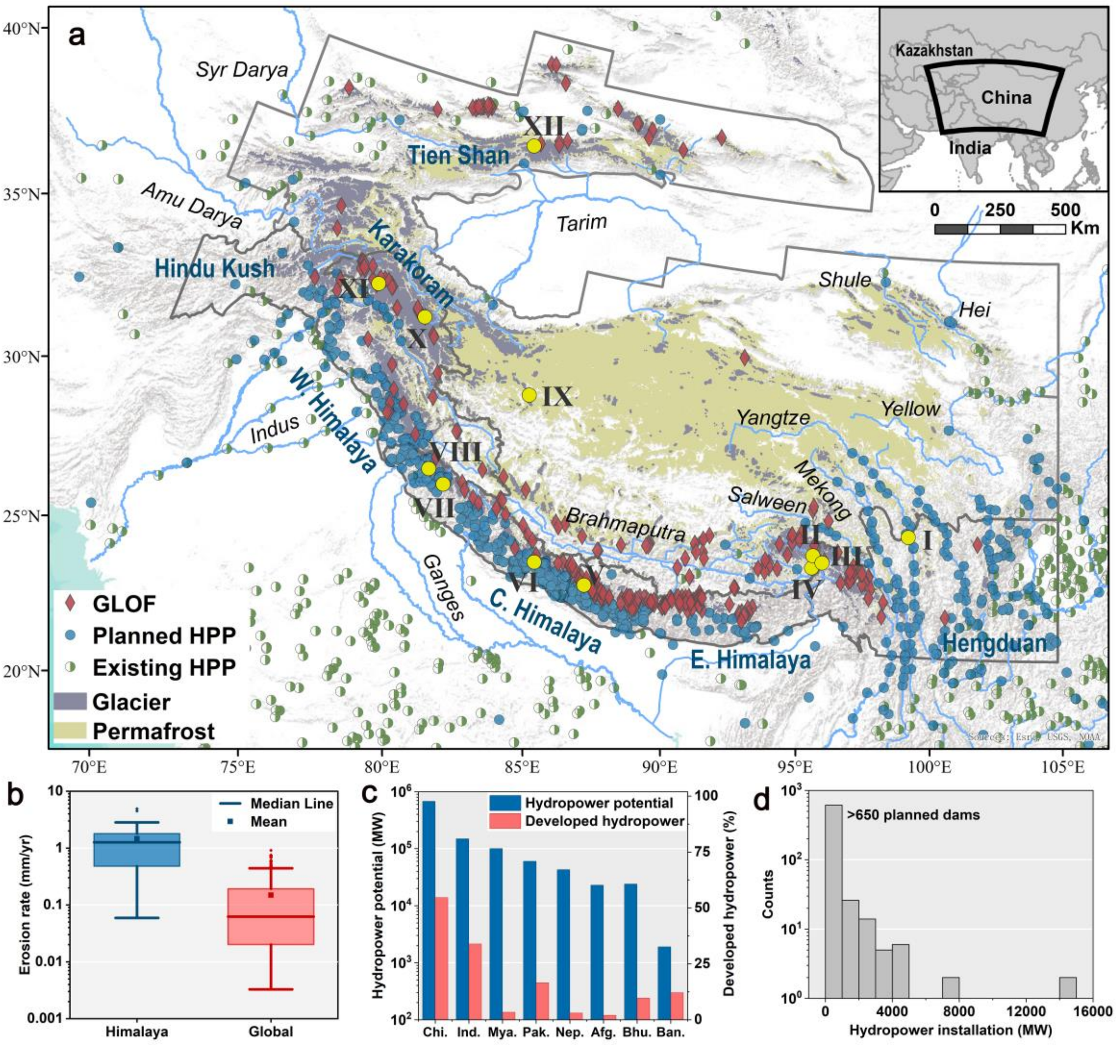


Fig. 1. Glacial lake outburst floods (GLOFs)[11,69–71], hydropower projects (HPPs), erosion rates, and hydropower potential in HMA. (a) Existing large HPPs and planned (or under construction) HPPs[20,21]. Yellow dots denote locations of key examples of cryospheric hazards, including, I, Baige LLOF (2018); 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). Boundaries of glaciers and permafrost are based on refs.[116,117]. Base map and the inset courtesy of ESRI, USGS, and NOAA. **(b)** A comparison of modern erosion rates (1950s-2000s) in the Himalaya vs global[29,118]. **(c)** Hydropower potential and developed hydropower as a percentage in eight major HMA countries

(updated from IHA and ref.[17]). **(d)** The statistics of the hydropower installation capacity of the planned HPPs in HMA.

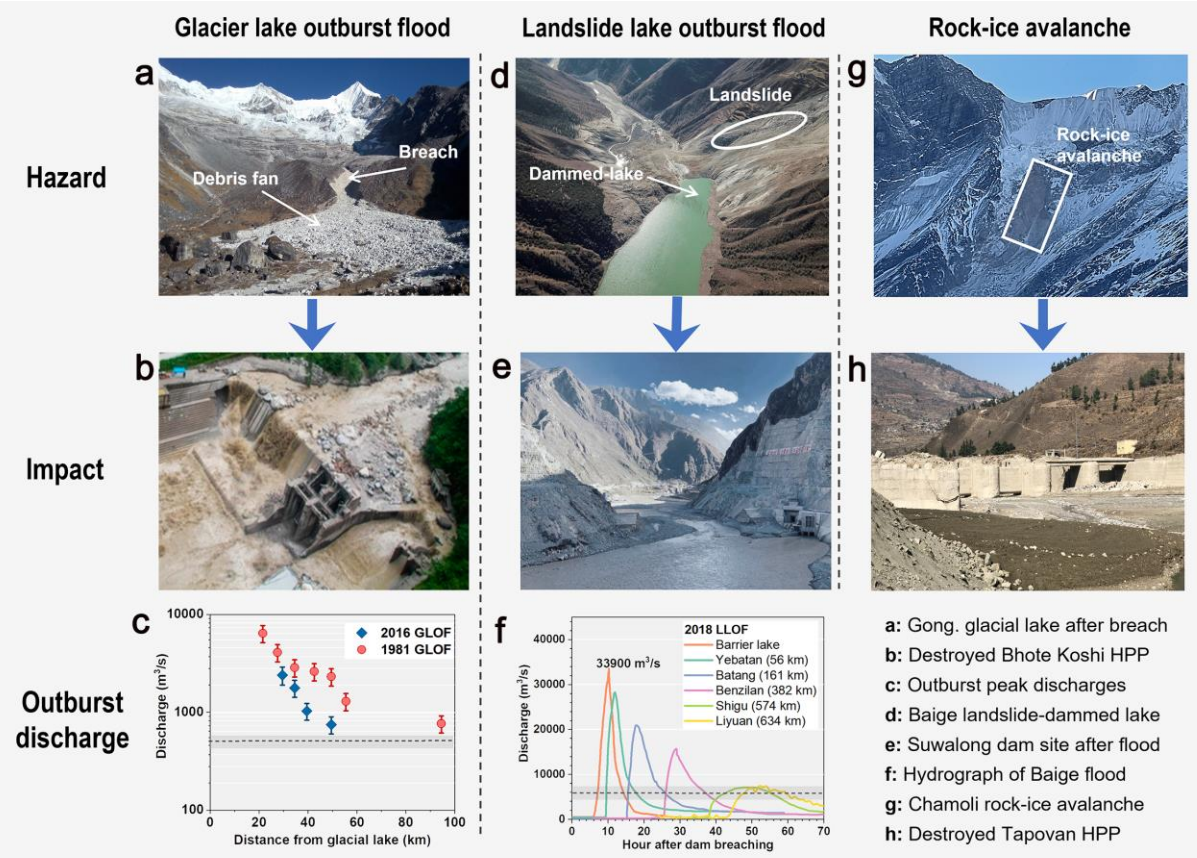


Fig. 2. Field photos, outburst flood discharges, and destruction of HPPs caused by three types of hazard chain. (a-c) The destruction of the Upper BhoteKoshi HPP (Nepal) caused by the 2016 Gongbatongsha Tsho (Tibet, China) GLOF (Photos courtesy of Bhote Koshi hydroelectric project and M. Liu)**.** The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

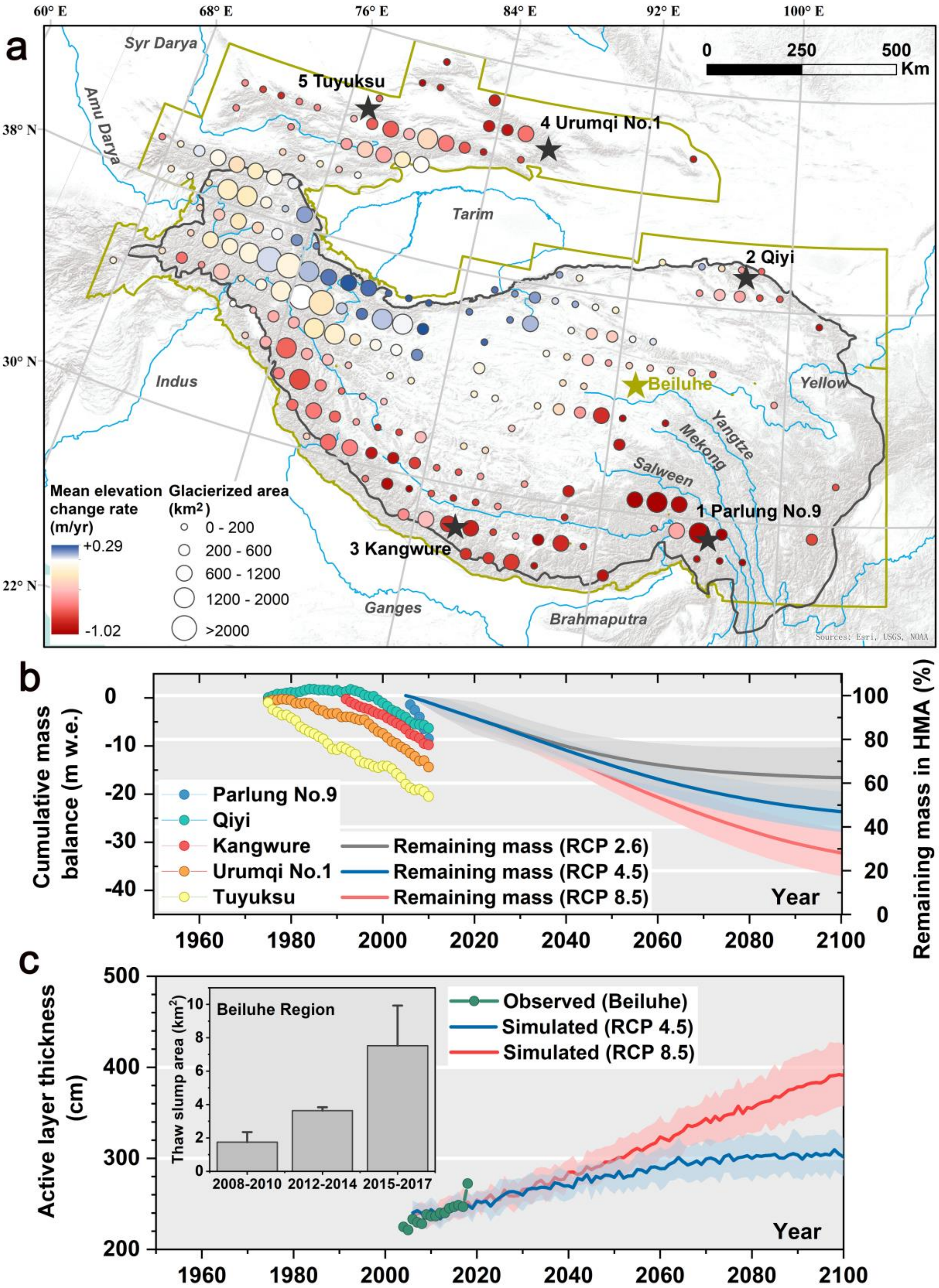


Fig. 3. Melting of glaciers and thawing of permafrost in a warming HMA. (a) Changes in glacier mean elevation in HMA[34]. The dark-gray boundary marks the Tibetan Plateau. Base map courtesy of Esri, USGS, and NOAA. **(b)** Observed past and projected future glacier mass loss. The five glaciers (black 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[41] and expanding areas in thaw slumps[53]. The shading associated with the two projections denotes standard errors.

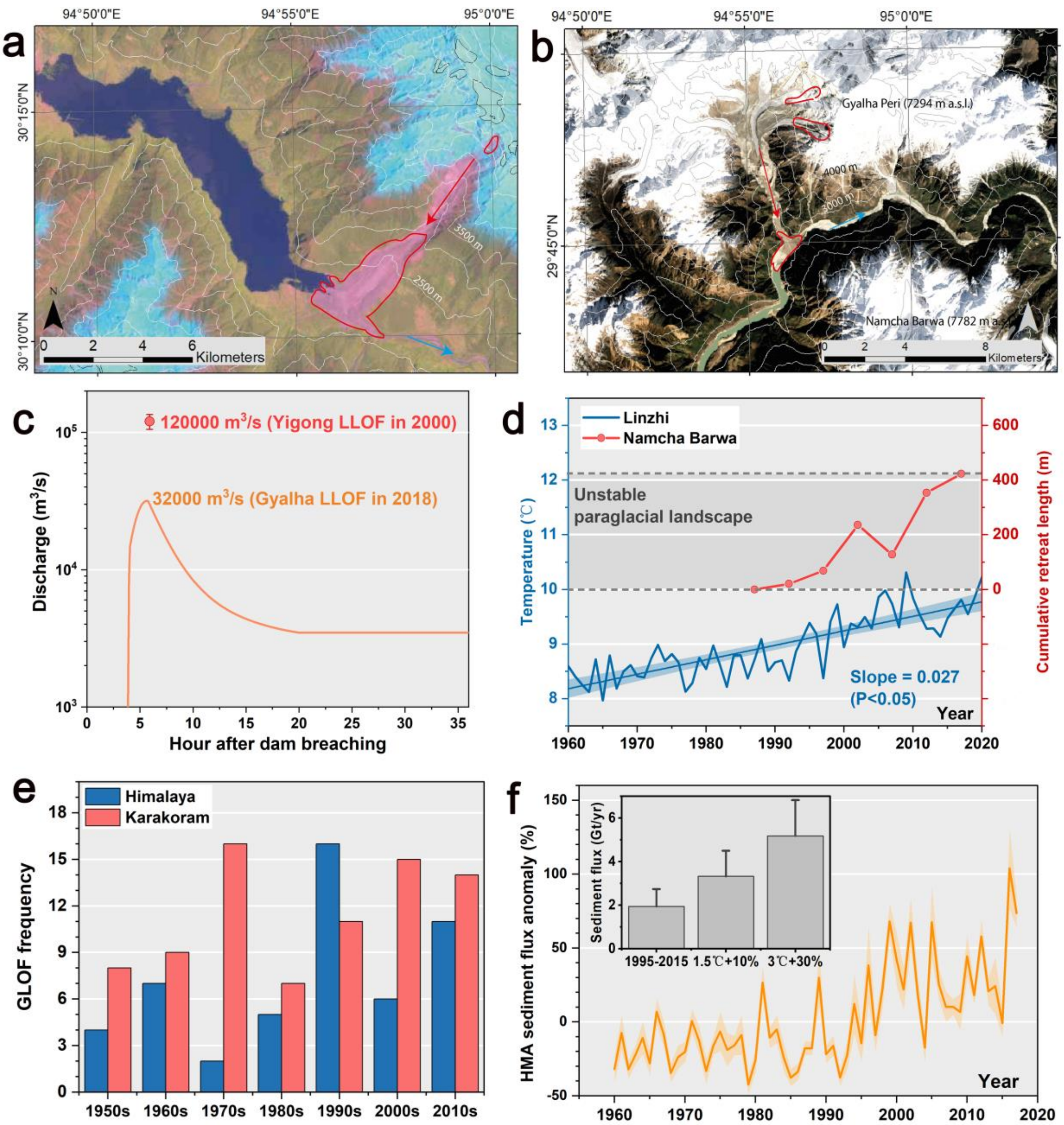
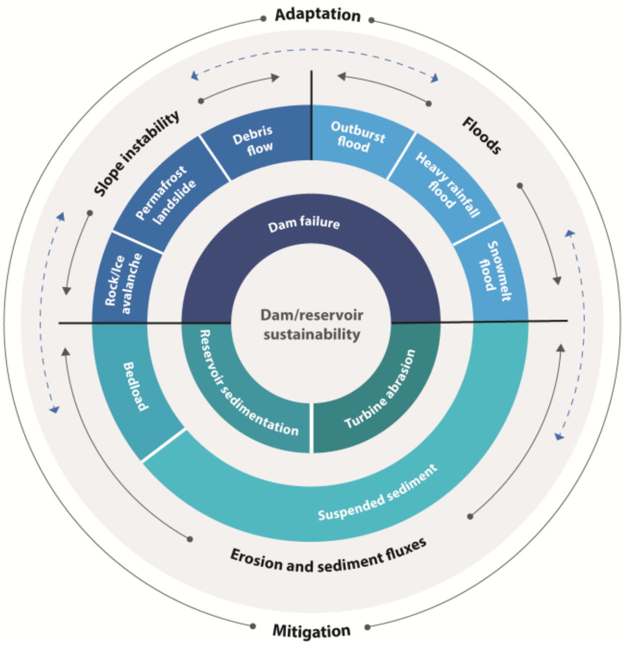


Fig. 4. LLOFs, GLOFs, and changing sediment fluxes in a rapidly warming HMA associated with glacier retreat. (a-c) the Yigong landslide-dammed lake (May 2000; Landsat-5), the Gyalha (Sedongpu Valley) debris flow-dammed lake (October 2018; Sentinel-2A), and their outburst floods[67,68]. **(d)** Glacier 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 21st century. Error bars indicate estimated standard errors.

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: towards 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 optimise 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 runoff, 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

Data availability

The data shown in the figures are available in the publications cited and also available 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 avaible at the Global Dam Watch (http://globaldamwatch.org/fhred/; http://globaldamwatch.org/grand/). Data on hydropower potential and developed hydropower are available at 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.

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Author contributions

DL and XL conceived the study. DL wrote the original draft. XL, DEW, TB, TZ, RJW, and SH edited the initial version and contributed ideas. DL and TZ designed the figures and the Box. JSF contributed to Fig. 4a-b. SN contributed to the Box. YN and AY contributed data on GLOFs. XS contributed to Supplementary Figs. 1-3. All authors contributed to ideas and edits of subsequent revisions.

Competing interests

The authors declare no competing interests.

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