SEDIMENT TRANSPORT

Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia

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Rivers originating in High Mountain Asia are crucial lifelines for one-third of the world's population. These fragile headwaters are now experiencing amplified climate change, glacier melt, and permafrost thaw. Observational data from 28 headwater basins demonstrate substantial increases in both annual runoff and annual sediment fluxes across the past six decades. The increases are accelerating from the mid-1990s in response to a warmer and wetter climate. The total sediment flux from High Mountain Asia is projected to more than double by 2050 under an extreme climate change scenario. These findings have far-reaching implications for the region's hydropower, food, and environmental security.

High Mountain Asia (HMA)—the Tibetan Plateau and the surrounding high Asian mountains—is Earth's third-largest ice reservoir and the origin of many of Asia's large rivers (*1*–*3*). Like the polar regions, HMA is experiencing amplified warming when compared with general global warming trends (*4*, *5*). The air temperature has warmed by ~2°C since the 1950s at a much faster rate than the global average (*4*). Precipitation across HMA has also increased over recent decades, although the increase is characterized by considerable spatial heterogeneity (*6*, *7*). Existing studies, based on large-scale cryospheric–hydrological models, have provided projections for future increases in the region's annual runoff due to climate change (*3*, *8*) and their potential impacts on agriculture, food, and ~2 billion people within HMA and downstream (*1*, *7*). One important potential consequence of these projected changes in runoff is the possibility of increased fluvial sediment fluxes across HMA, which would have important implications for hydropower generation and development, as well as water quality, and could affect the energy, food, and environmental security of the region (*2*, *9*, *10*). Here we investigate the impacts of the changing hydrology on fluvial sediment fluxes in this region.

We collate and analyze available flow and sediment load data for rivers in HMA, extending over the past six decades, to investigate changes in runoff and sediment flux in response to a warmer and wetter climate. To exclude the potential impact of human activities, we select 28 quasi-pristine headwater river basins with observations of both runoff and sediment flux (plus 14 basins that only have runoff observations) (table S1). The selection allows for the separation of climate change impacts on sediment flux from anthropogenic impacts (*2*, *11*, *12*). The dataset has not yet been included in current global discharge and sediment datasets (*2*, *9*, *10*, *13*). We examine the sensitivity of sediment flux to changing temperature and precipitation in HMA on the basis of observational data and a climate elasticity model (materials and methods). Projections for future sediment fluxes from HMA are offered with a qualitative assessment of downstream impacts.

Time series of observed runoff from the headwaters of HMA show substantial increases over the past six decades (5.06 ± 0.51%/10 years, mean ± SE) (Fig. 1 and table S2). The magnitude of these increases exhibits large spatial heterogeneities across the region, as well as between different stations within the same river basin. In the HMA-east basins (stations S1 to S11), the decadal trends of increasing runoff vary from 0.95 ± 1.19%/10 years at Shigu (Yangtze) to 12.08 ± 3.05%/10 years at Tuotuohe (Yangtze). In the HMA-west basins (stations S12 to S28), runoff exhibits significant decadal upward trends in most headwaters, with local rates of increase varying from 1.69 ± 1.39%/10 years at Yingxiongqiao (Tienshan North) to 8.94 ± 2.97%/10 years at Keerguti (Tarim).

The observed sediment fluxes from the headwaters of HMA exhibit larger rates of increase (12.99 ± 1.18%/10 years, mean ± SE) than runoff and again reveal distinct spatial heterogeneities (Fig. 1 and table S3). In the HMA-east basins, increases in sediment flux vary from 3.67 ± 5.71%/10 years at Jimai (Yellow) to 25.40 ± 4.92%/10 years at Daojiebe (Salween), whereas the equivalent rates of increase for runoff are only 2.56 ± 2.76%/10 years and 2.13 ± 1.30%/10 years, respectively. In the HMA-west basins, increases in sediment flux vary from 5.30 ± 2.04%/10 years at Shaliguilanke (Tarim) to 24.68 ± 8.57%/10 years at Yuzimenleke (Tarim), whereas the equivalent decadal rates of runoff increase are only 4.00 ± 1.52%/10 years and 9.07 ± 1.67%/10 years, respectively. The increase of water and sediment discharge accelerated after 1995 (Fig. 2, D and E, and fig. S7), which is consistent with the faster warming and wetting trend in HMA after the mid-1990s (Fig. 2, A and B).

Increasing sediment discharge appears to be related to the rapidly retreating glaciers, which can intensify glacial sediment production (*14*–*16*), although their spatial extent is relatively small (Figs. 2 and 3). Accelerating permafrost thaw appears to increase sediment flux (Fig. 2) as permafrost disturbance–related sediment sources [e.g., thaw slumps (fig. S1)] become active in a warming climate. The previously frozen landscapes then become prone to erosion and increased water and sediment fluxes (*17*). The large spatial heterogeneity associated with the magnitude of the increases in sediment flux can be attributed to variations in the magnitude of changes in runoff (Fig. 1C) and is also likely to reflect the varying storage capacity of the sediment transfer pathways. In the upper Brahmaputra River (above S11), ~40% of the upstream annual sediment supply has been deposited in the wide valleys (*18*). Similarly, substantial amounts of sediment are deposited in the Kosi River floodplain, a tributary of the upper Ganges (*19*). Our findings provide robust evidence of landscape change in a warming climate similar to those reported for other cold environments (e.g., polar regions) (*15*, *20*).

Increasing fluvial sediment fluxes in HMA are mainly the result of accelerated thermally driven glacier-permafrost melt and increased precipitation and associated erosion processes (Fig. 2 and figs. S1 to S3) (*20*, *21*). To estimate the geomorphic impacts of climate change on HMA, we analyze the sensitivity of sediment fluxes to increases in temperature and precipitation, using a climate elasticity model based on the past six-decadal observations of climate, runoff, and sediment flux and a conceptual framework of runoff-sediment generation in cold environments (materials and methods and fig. S3). On average, a 10% increase in precipitation results in a 24 ± 5% increase in sediment flux, and a 1°C increase in air temperature results in a 32 ± 10% increase in sediment flux (Fig. 3 and materials and methods). Our data also show that the sensitivity of sediment flux to increasing precipitation decreases with increased glacierization (percentage of glacier cover for a headwater basin). By contrast, the sensitivity of sediment flux to increasing temperature generally increases with increased glacierization. The four outliers from this trend are possibly biased by low sediment connectivity and low erodibility (fig. S11). The sensitivity results provided by the elasticity model are in agreement with historical observations

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(fig. S10) and evidence a greater susceptibility to change than, for example, pan-Arctic rivers (*20*). The greater sensitivity of sediment flux to climate change in HMA as compared with that in the Arctic environments reflects some basic geomorphic facts: HMA has a high gradient of much softer lithologies as compared with lower-gradient Arctic environments and their hard craton lithologies (fig. S6) (*20*).

We provide projections for the increase of sediment flux from HMA by the middle of the 21st century in response to climate change, on the basis of the results of the sensitivity analysis and different future scenarios of climate change (Fig. 4 and table S4). By using an area-weighted–average approach and specific sediment-yield observations from 122 stations (materials and methods and table S5), the present-day fluvial sediment flux from HMA is estimated to be 1.94 ± 0.80 metric gigatons (Gt) per year [the area-weighted mean specific sediment yield is 410 ± 170 metric tons per square kilometer per year, and the area of HMA is 4.72×10^6 km^2 (*22*)]. For an extreme climate change scenario [i.e., temperature increases by 3°C and precipitation increases by 30% by 2050, relative to the period 1995–2015 (*4*, *23*)], the total sediment flux from the entire HMA will increase from the present 1.94 ± 0.80 Gt/year to 5.18 ± 1.64 Gt/year (Fig. 4 and table S4). However, the predicted future fluvial sediment flux from HMA represents projections that reflect the impact of climate change on sediment export from basin outlets located both within and toward the margins of HMA. As such, they are therefore not directly indicative of the actual sediment output from HMA, because sediment storage in downstream river reaches, future dam construction, and land-use changes could also affect the future sediment fluxes (*2*, *24*, *25*).

The projected major increase in fluvial sediment flux within HMA has important implications for hydropower projects, water quality, and food and energy security in both HMA and its downstream river systems. A recent study reported that damming the deglacierizing basins of HMA could contribute to the region's energy production and help it adapt to climate change by temporarily storing the glacier meltwater and modifying the flow regime (*26*). Hydropower potential in Nepal and Bhutan exceeds their present electricity consumption (*26*). However, increasing

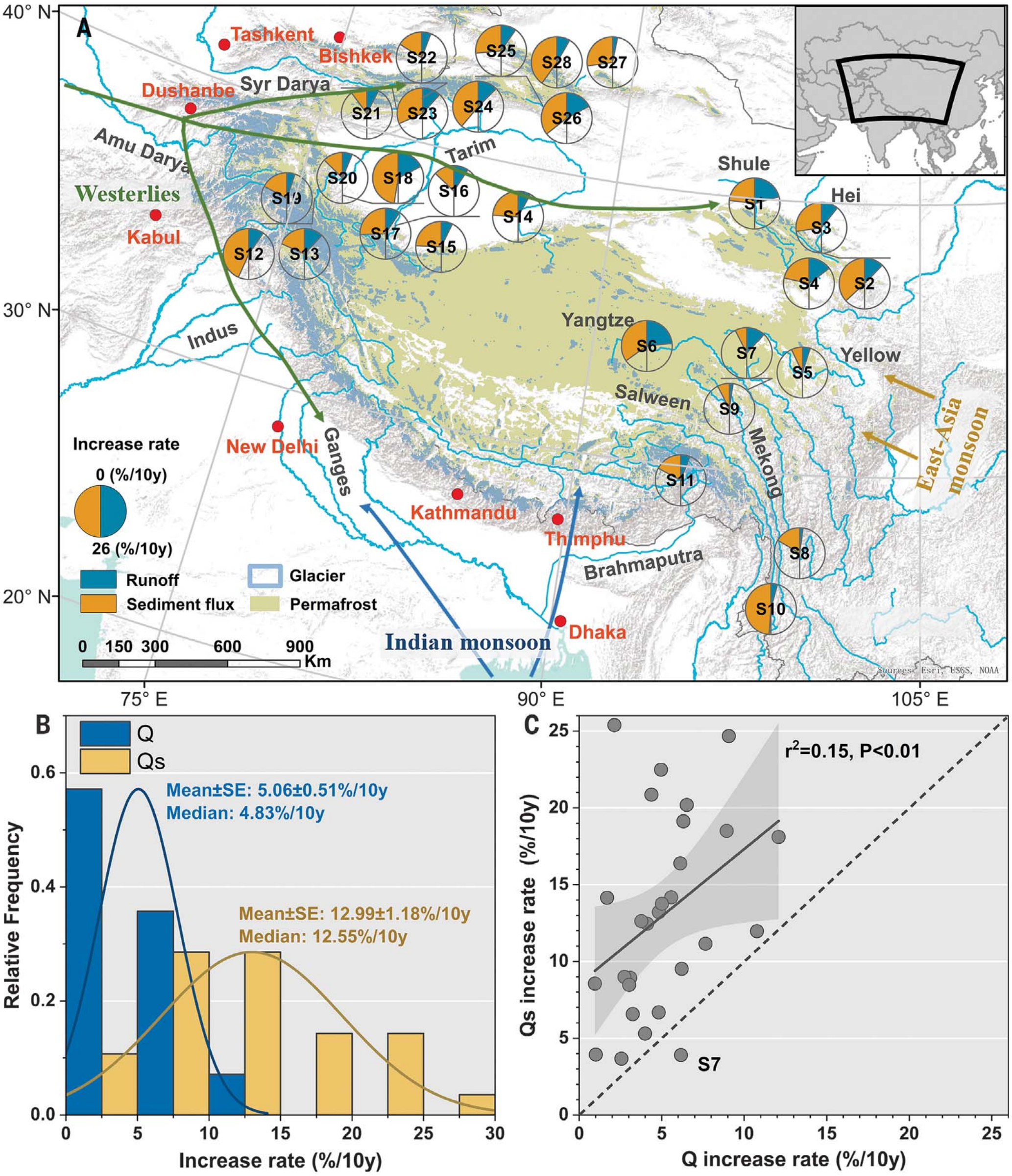

Fig. 1. Increasing annual runoff and fluvial sediment fluxes in a warming and wetting HMA. (**A**) Relative rates of increase of mean annual runoff and sediment flux over the past six decades. Stations S1 to S11 represent HMA-east basins (monsoon-dominated basins), and stations S12 to S28 represent HMA-west basins (westerly-dominated basins). S1 to S11 are also influenced by westerlies in some parts of their upstream basins (*33*, *34*). Details of the 28 headwater basins are in table S1. (**B**) Statistics on the rates of increase of annual runoff (Q) and sediment flux (Qs) (tables S2 and S3). (**C**) Relationship between the rate of increase of sediment flux and the rate of increase of runoff. Information on the distribution of glaciers and permafrost presented in (A) was sourced from (*34*, *35*). The dotted line represents the 1:1 line. The gray-shaded area denotes the 95% confidence interval of the best-fit line.

fluvial sediment fluxes could severely threaten existing and planned reservoirs in HMA and its downstream margins (fig. S12) by decreasing their storage capacities faster than anticipated and abrading power turbines. Increasing sediment flux from the headwaters of the Yangtze River over recent decades is reported to be affecting the cascade of reservoirs in the upper Yangtze River, China's largest hydropower production region (*21*, *27*). Under the extreme climate change scenario, we predict that from 2020 to 2050, a total of ~2000 metric megatons (Mt) of sediment will likely be deposited in existing and planned reservoirs located on the upper Yangtze River, equivalent to a reduction of storage capacity by ~1.5×10^9 m^3 (approximately two times the designed storage capacity of the downstream Liyuan Reservoir) (fig. S13). For the upper Indus River, the water storage capacity of the Tarbela Reservoir, the largest hydropower and irrigation project in Pakistan, decreased by >3.5×10^9 m^3 (~30% loss of original storage capacity and therefore much faster than the original expectation) between 1974 and 2006 (*28*), which threatens the expected life span of the reservoir, water supply, irrigation capacity, hydropower generation, flood control, and thereby food, energy, and environment security. Furthermore, in many rivers of HMA, sediment mostly comprises hard minerals such as quartz and feldspar that are known for causing abrasion and damaging turbine components. In the Sutlej River of the upper Indus basin, the turbines of the Nathpa Jhakri hydropower project (1500 MW) were replaced after <1 year of operation because of the severe abrasion problem (*28*).

Increasing runoff and sediment flux from HMA and associated increases in nutrient, pollutant, and carbon fluxes will affect not only water availability and storage but also water quality and flooding in the densely populated downstream locations (fig. S3). Previous studies have reported increasing levels of mercury released from melting glaciers and thawing permafrost in recent years across the Tibetan Plateau (*4*). Additionally, fine suspended sediment is an important vector for the transport of phosphorus and most heavy metals (e.g., chromium, arsenic, and lead) because of its high specific surface area and associated reactivity (*2*, *10*). Thus, increasing fluvial sediment flux from HMA is likely to increase sediment-associated nutrient and contaminant fluxes, which can negatively affect water quality and aquatic ecosystems. Furthermore, suspended sediment is a key vector for organic carbon transport (*29*); and the precise role of erosion and sediment delivery in mobilizing organic carbon from melting permafrost landscapes and delivering it to the fluvial system remains uncertain and represents an important research need. Quantifying this process is important when assessing the positive feedback between climate warming, permafrost degradation, and carbon cycling (*30*). Assuming a sediment carbon content of 1 to 3% (*9*), the total carbon flux associated with the sediment output from HMA could reach 50 to 150 Mt/year by 2050 under the extreme climate change scenario. A substantial

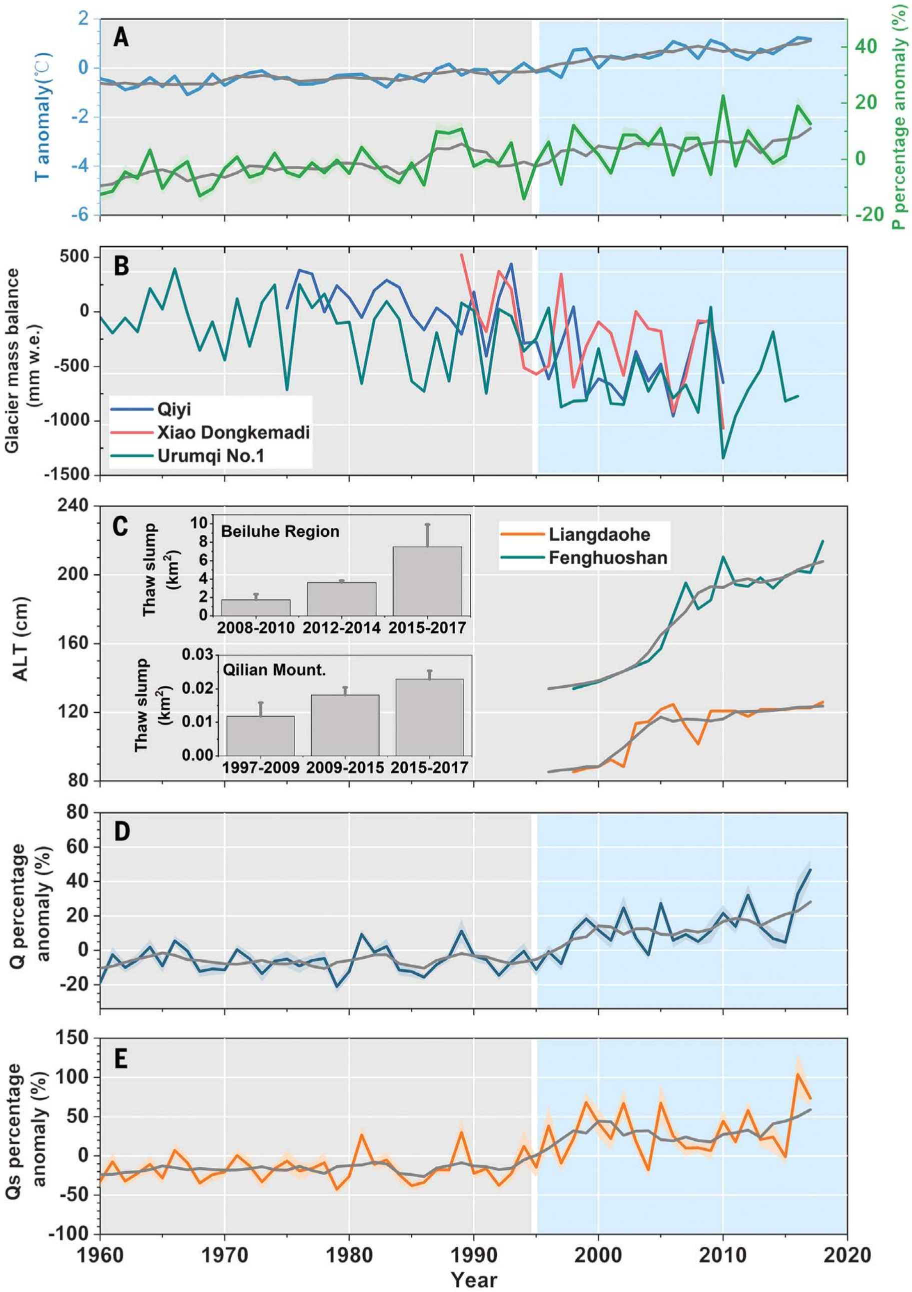

Fig. 2. Observed increases in the annual runoff and sediment flux in response to changes in air temperature, precipitation, glacier melt, and permafrost thaw. Gray lines denote the 5-year moving average for the data. (**A**) Increase in the annual mean air temperature (T) (0.32° ± 0.03°C/10 years, $P < 0.01$) and precipitation (P) (2.09 ± 0.53%/10 years, $P < 0.01$) anomalies over HMA based on 108 climate stations (materials and methods and fig. S12). (**B**) Increase in the glacier mass melt rates from Qiyi Glacier (near S3), Xiaodongkemadi Glacier (near S6), and Urumqi No. 1 Glacier (near S27), which represent three of the longest observed time series of glacier mass balance in HMA (*34*). w.e., water equivalent. (**C**) Increasing active-layer thickness (ALT) at Liangdaohe (near S6) and Fenghuoshan (near S6) (*35*) and the associated increase in thaw slumps (important sediment sources for permafrost environments) in the Beiluhe region and the Qilian Mountain (near S3 to S7) (*36*, *37*). (**D**) Increasing annual runoff (Q) anomaly (in percentage) for the entire HMA (mean ± SE of the 28 stations). (**E**) Increasing annual sediment flux (Qs) anomaly (in percentage) for the entire HMA (mean ± SE for the 28 stations). The light blue– and orange-shaded areas denote SEs.

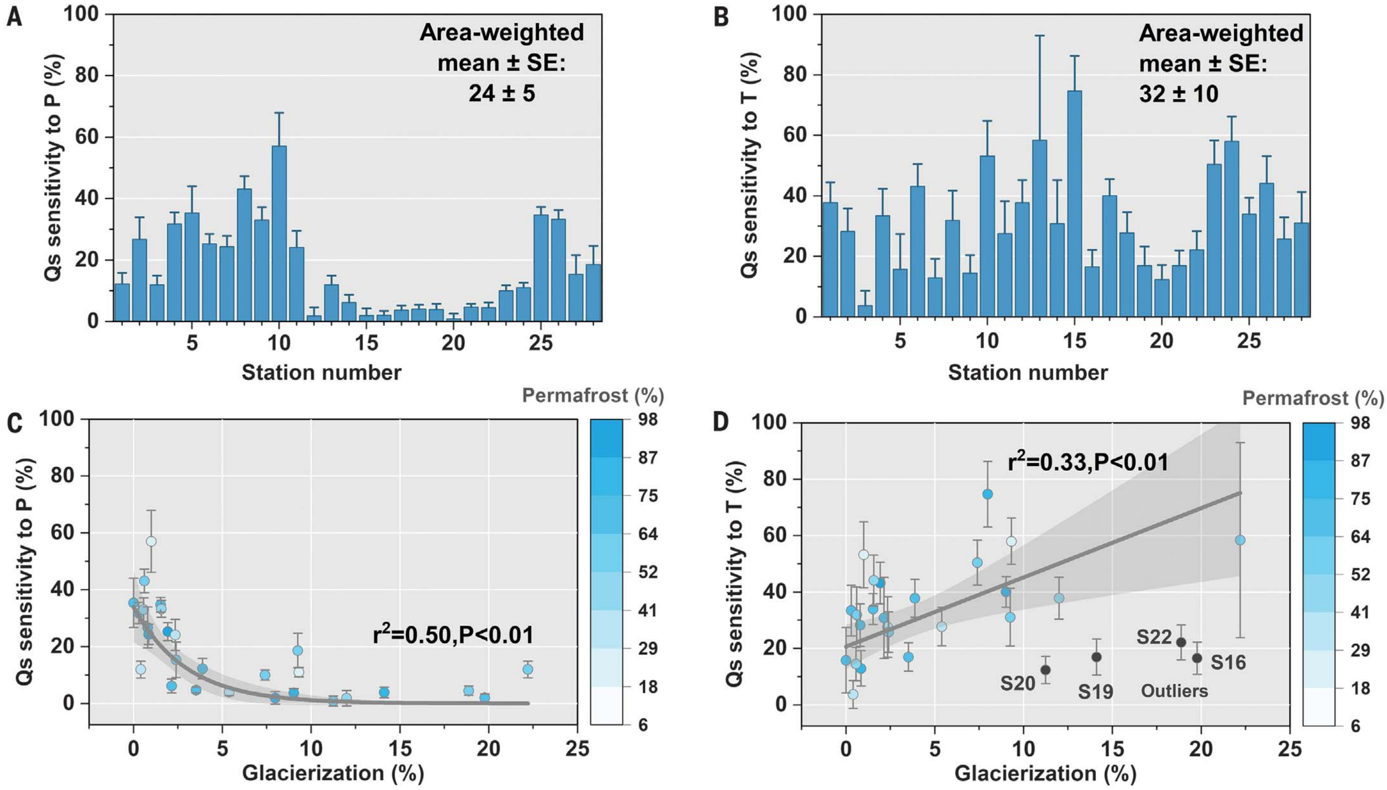

Fig. 3. Sensitivity of sediment flux to increased precipitation and temperature. (**A**) Sensitivity of sediment flux to precipitation (percentage change in sediment flux for every 10% increase in precipitation). (**B**) Sensitivity of sediment flux to air temperature (percentage change in sediment flux for every 1°C increase in air temperature). Each bar denotes one headwater basin ranked (from left to right) by the station number as shown in Fig. 1. (**C**) Sensitivity of sediment flux to precipitation significantly decreases with glacierization (percentage of glacier cover for a headwater basin). (**D**) Sensitivity of sediment flux to temperature shows a positive relationship with glacierization. The four outliers possibly reflect low sediment connectivity and low erodibility of their basins (fig. S11). The colored key represents the permafrost cover fraction for a basin. The permafrost cover fraction shows no significant correlations (r^2) with precipitation sensitivity (r^2 < 0.1, P > 0.5) or temperature sensitivity (r^2 < 0.1, P > 0.5), possibly because of the more important influence of the largely unknown permafrost ground ice conditions.

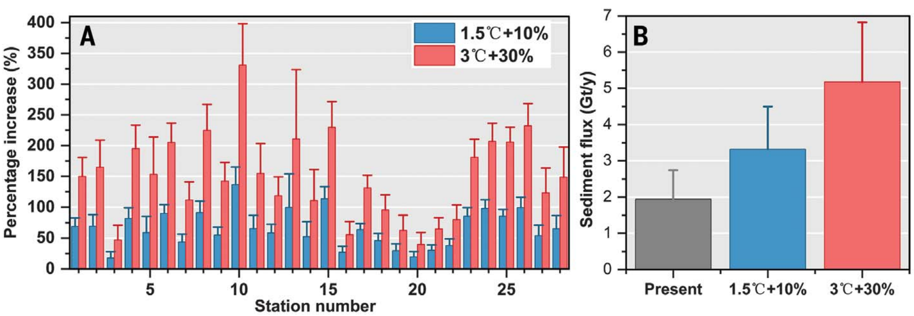

Fig. 4. Projection of future sediment fluxes in HMA. (**A**) Percentage increases in the sediment flux at each station under the conservative scenario (1.5°C + 10%; temperature increases by 1.5°C and precipitation increases by 10% by the middle of the 21st century relative to the period of 1995–2015) and the extreme scenario (3°C + 30%; temperature increases by 3°C and precipitation increases by 30% by the middle of the 21st century relative to the period 1995–2015). Each bar denotes one headwater basin ranked (from left to right) by the station number as shown in Fig. 1. (**B**) Projected increases in the sediment flux from the entire HMA from the present 1.94 ± 0.80 Gt/year to 3.32 ± 1.18 Gt/year (conservative scenario) and to 5.18 ± 1.64 Gt/year (extreme scenario) by the middle of the 21st century. Projections of other climate change scenarios are in table S4.

proportion of the increased sediment flux could be temporarily deposited in the river system (e.g., wide alluvial valleys and river floodplains) (*18*) and aggrade riverbeds (*19*), potentially triggering river avulsions (*31*) and increasing the risks of flooding, particularly during the summer melt season. Nevertheless, the increasing fluvial sediment flux can also provide more aggregates for construction, electronic materials, and other related services (*32*).

This study provides observational evidence of increasing water and sediment fluxes in the headwaters of HMA and the associated spatial variation of the rates of increase between individual basins and between tributaries within basins. Increasing sediment fluxes will negatively affect existing and planned hydropower projects, influence irrigation capacity, and therefore threaten the region's food and energy security. The increasing fluvial sediment flux and its associated nutrients, pollutants, and organic carbon also have implications for water quality and flooding, potentially affecting millions of people in HMA and downstream regions. This study sheds light on the importance and potential implications of the marked increases in recent and future sediment fluxes that have not been fully recognized by scientific communities, such as the Intergovernmental Panel on Climate Change (IPCC), and the region's policy-makers, nor have they been fully taken into account in the assessment of potential changes in the global carbon cycle.

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ACKNOWLEDGMENTS

We thank J. Best and Z. Li for earlier comments and field assistance, respectively. **Funding:** This study was supported by the MOE (grants R-109-000-273-112 and R-109-000-227-115). D.L. acknowledges IPCC Scholarship Award (jointly founded by the IPCC and Cuomo Foundation) and President's Graduate Fellowship. I.O. acknowledges NSF OPP awards (2001225 and 1553172). **Author contributions:** D.L. and X.L. designed the study; D.L. performed all analyses with assistance from T.Z.; D.L. prepared the draft. All authors contributed to the manuscript and figures. **Competing interests:** The authors have no competing financial conflicts of interest with this study. **Data and materials availability:** The data reported in the paper are available at https://github.com/geolidf/HMA-catchments. Other data are presented in the supplementary materials. Annual runoff and sediment data are sourced from the hydrological data yearbooks published by the Ministry of Water Resources, China (http://www.mwr.gov.cn/english/), and the Water and Power Development Authority, Pakistan (http://www.wapda.gov.pk/). Climate data are sourced from China Meteorological Administration (http://data.cma.cn/en) and ERA-5 reanalysis product (https://cds.climate.copernicus.eu/). Data on glacier and permafrost are available at the Randolph Glacier Inventory (RGI 6.0; https://www.glims.org/RGI/) and the National Tibetan Plateau Data Center (http://www.tpdc.ac.cn/en/).

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abi9649
Materials and Methods
Figs. S1 to S13
Tables S1 to S5
Google Earth kmz file of catchment properties
References (*38–71*)

12 April 2021; accepted 16 September 2021
10.1126/science.abi9649

Science

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Science, 374 (6567), • DOI: 10.1126/science.abi9649

Muddied waters
The climate of High Mountain Asia is becoming warmer and wetter. Li *et al*. present data showing that rivers originating in this region have experienced large increases in runoff and sediment fluxes over the past six decades, most dramatically since the mid-1990s. The authors project that sediment flux from those rivers could more than double by 2050 in the case of extreme climate change, with potentially serious impacts on the region's hydropower capacity, food security, and environment. —HJS