Substantial increases in riverine sediment loads in a warmer and wetter Third Pole

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WMO UNEP

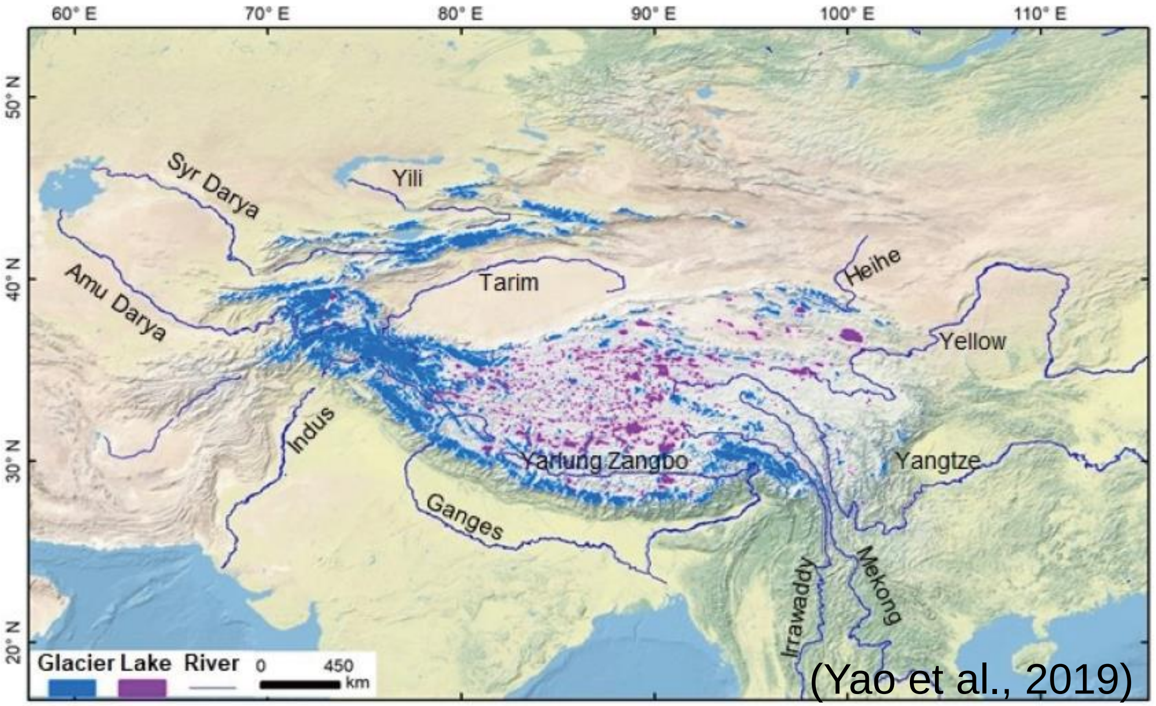




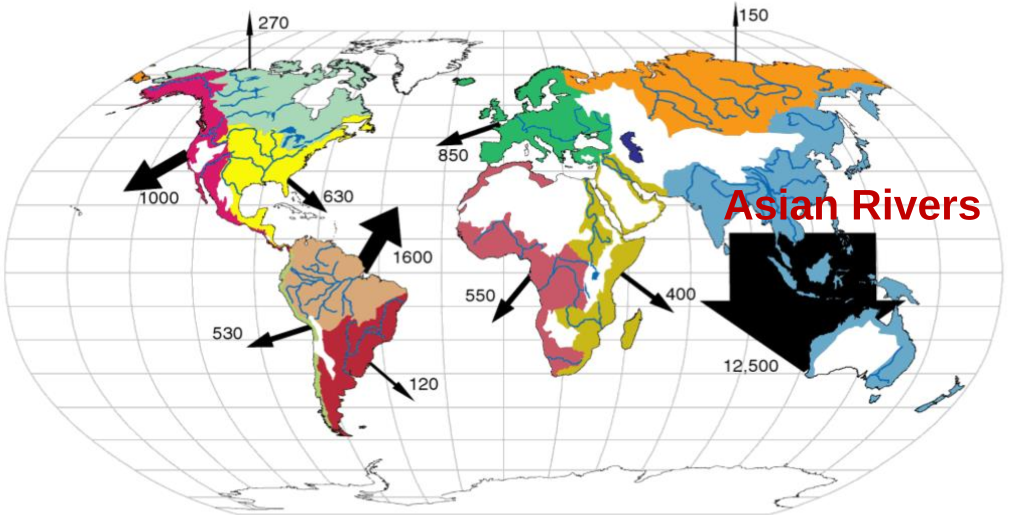
01 Introduction

Third Pole

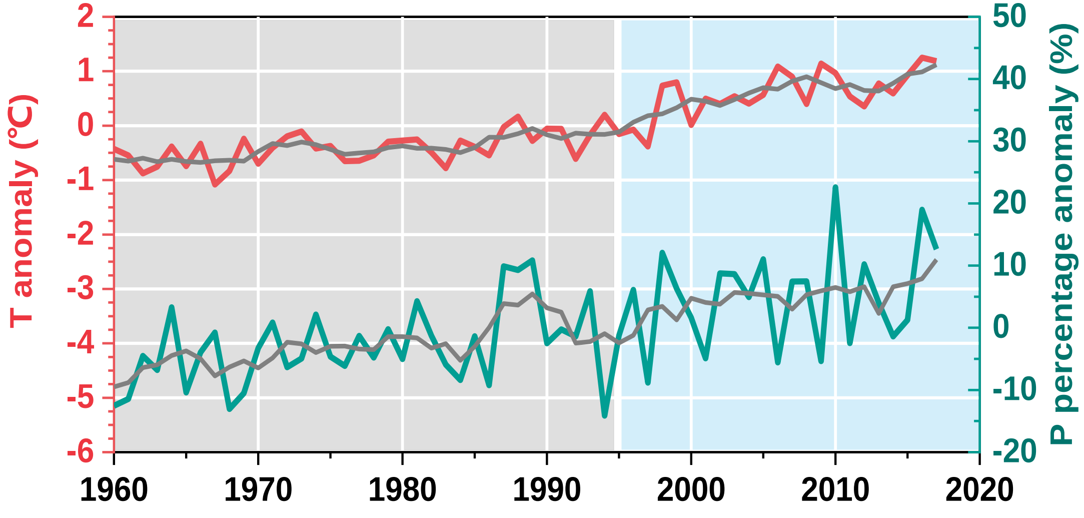
- **"Third Pole" "Roof of the World"** (Yao et al., 2019)
- **"Asian Water Towers"** (Immerzeel et al., 2010; 2020)
- **Important sediment sources**



(Yao et al., 2019)

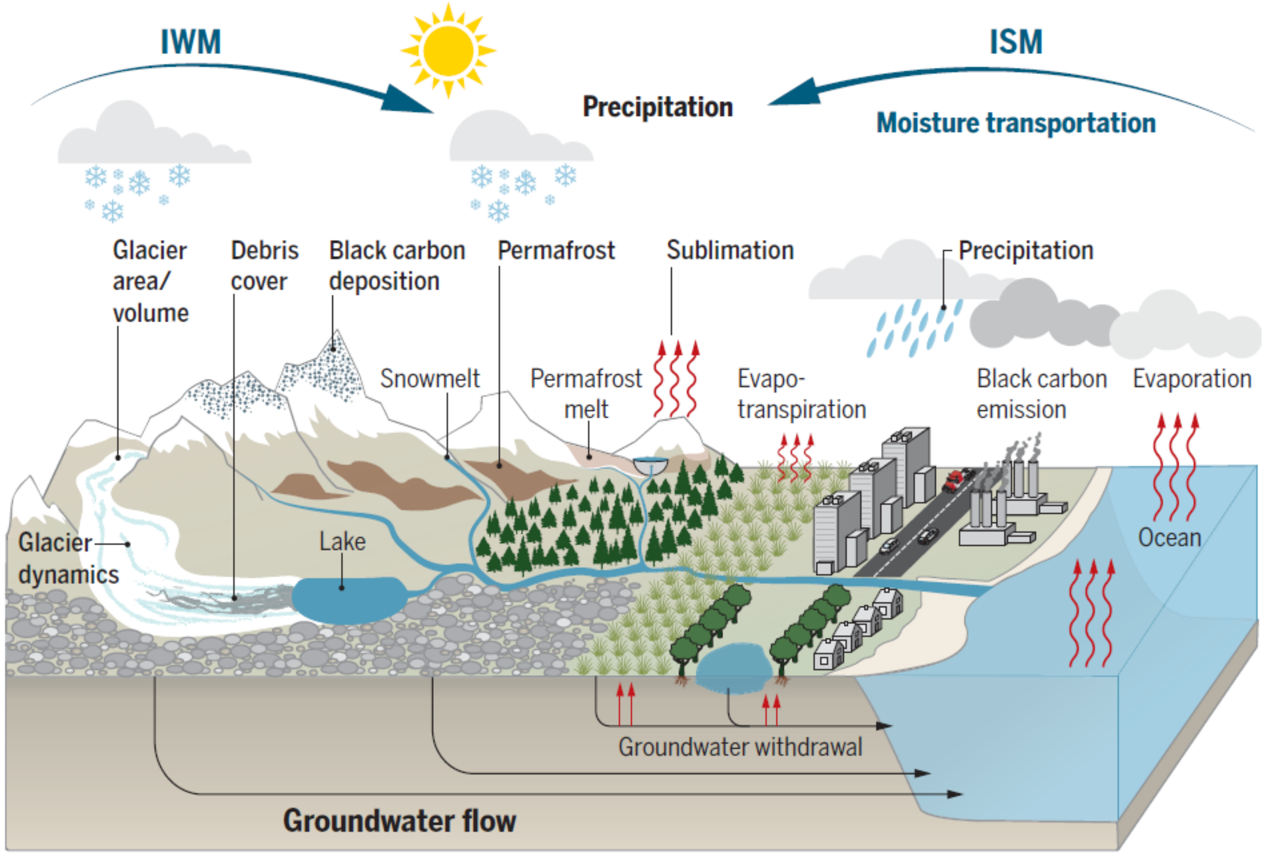


(Milliman & Farnsworth, 2011)



(Li et al., 2021, Science)

□ Glacier retreat, snow melt, permafrost thawing, water cycle……



(Azam et al., 2021, Science)

How does modern climate change affect the riverine sediment loads in Third Pole?

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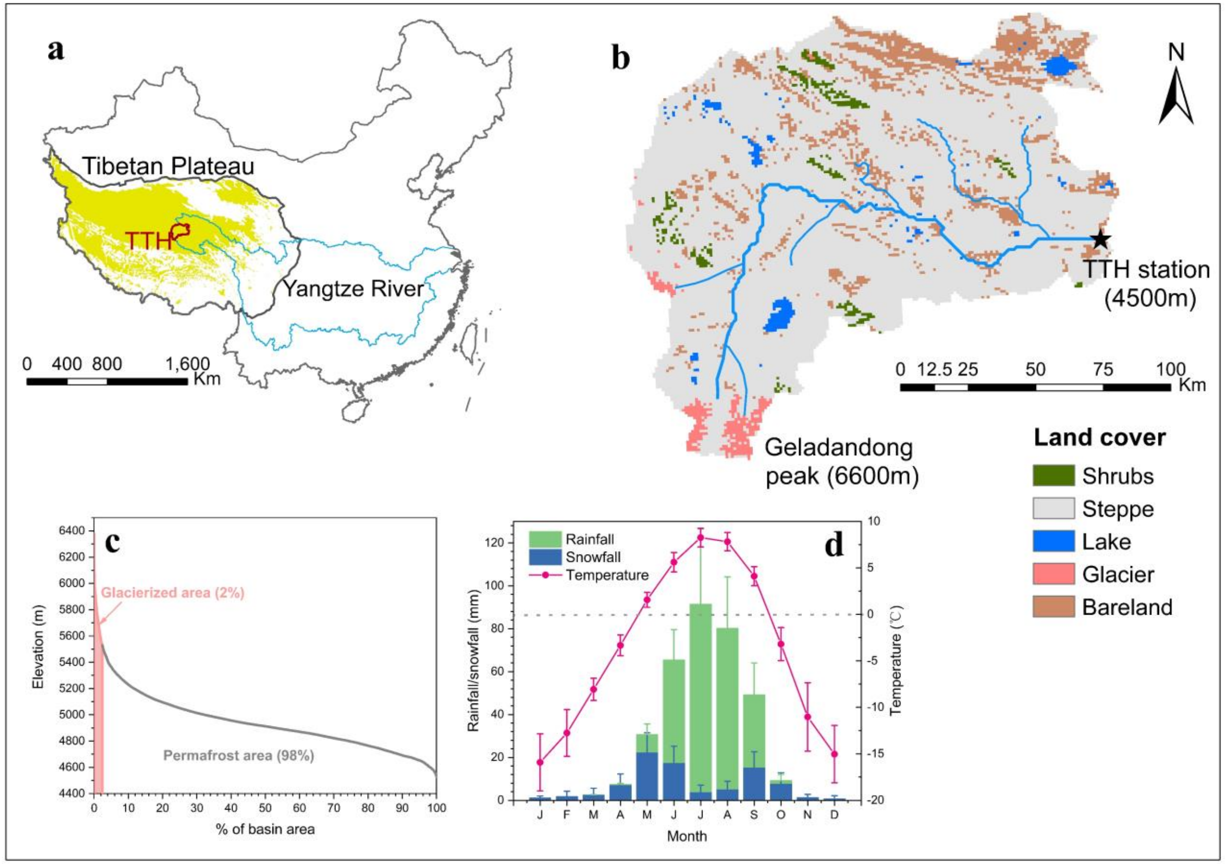
02 Long-term hydrological data

A case: headwater of the Yangtze

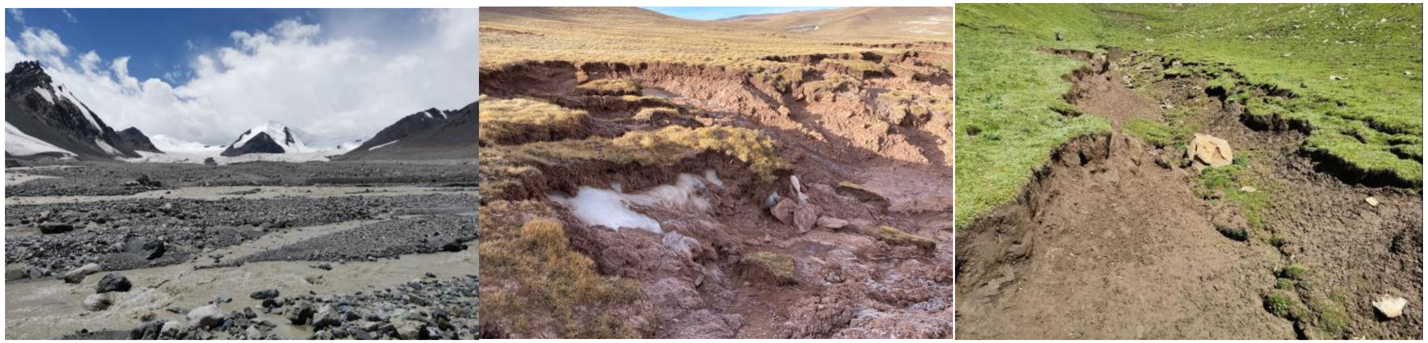
- **Tuotuohe (TTH) – headwater of the Yangtze**
- **4500-6600 m a.s.l.**
- **2% glacier vs 98% permafrost**
- **Pristine river (no human activities)**
- **>6000 sediment samplings (1985-2017)**



<u>Li, D.,</u> Li, Z., Zhou, Y., & Lu, X. (2020). Substantial increases in the water and sediment fluxes in the headwater region of the Tibetan Plateau in response to global warming. *Geophysical Research Letters*, *47*(11), e2020GL087745.

02 Sediment sources in cold environments

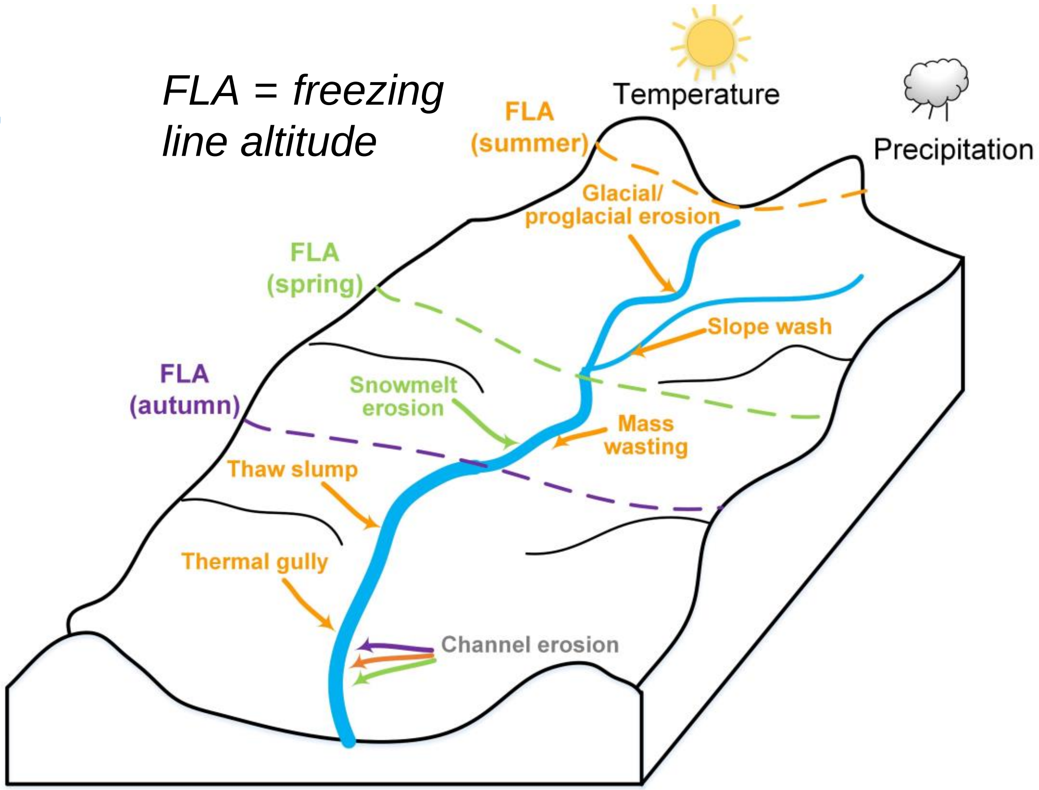
- **Temperature-driven sediment sources:** glacial erosion, permafrost thaw slumps, thermal erosional gully



- **Precipitation-driven sediment sources :** slope wash, mass wasting, riverbank erosion

© *X. Li, C. Song*

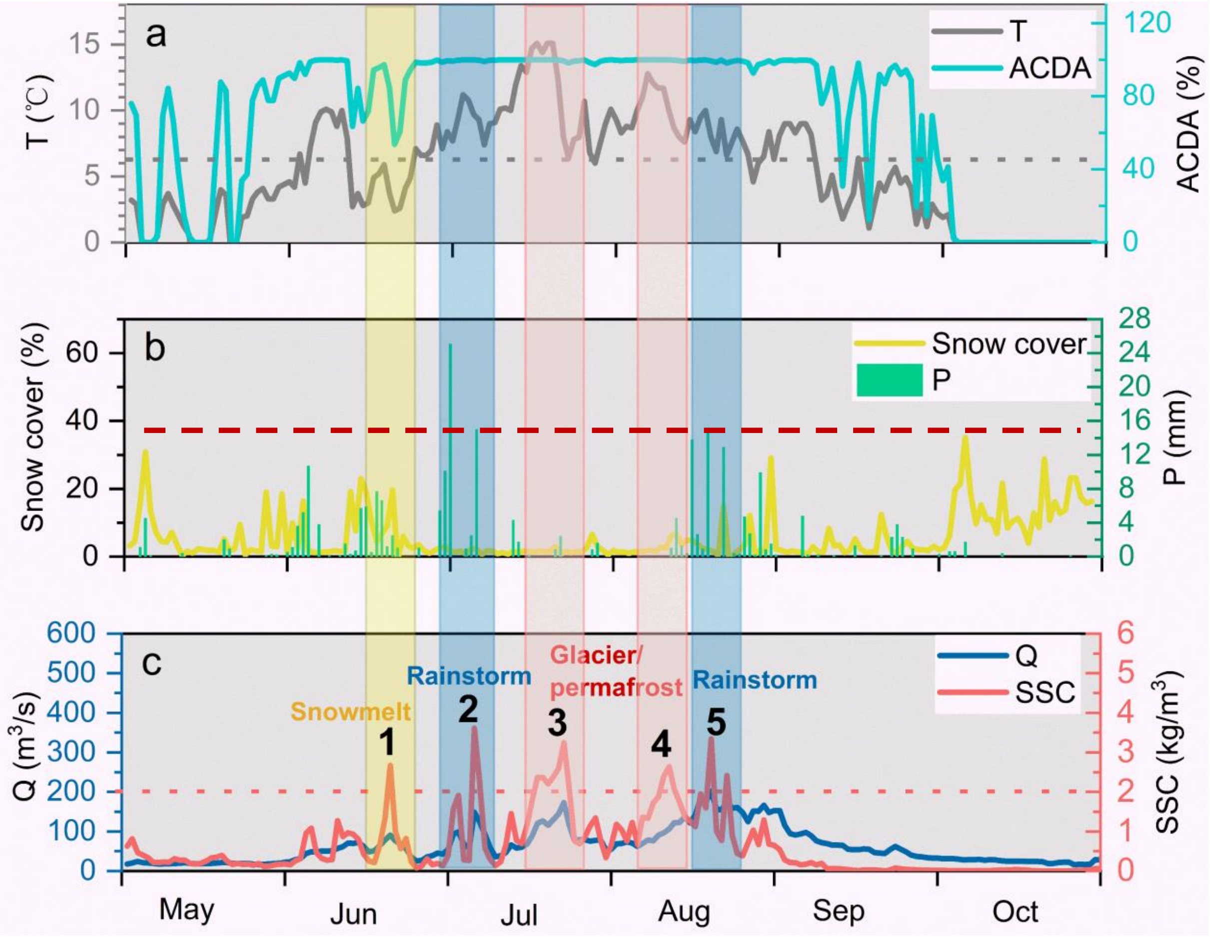
FLA = freezing line altitude

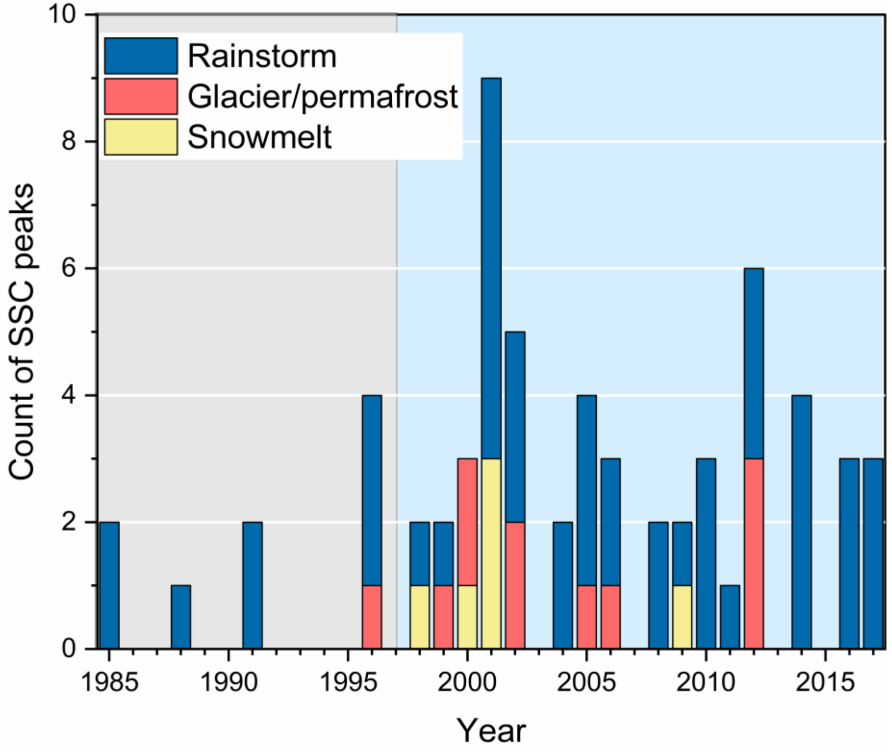


Li, D., Overeem, I., Kettner, A. J., & Lu, X. (2021). Air temperature regulates erodible landscape, water and sediment fluxes in the permafrost-dominated catchment on the Tibetan Plateau. *Water Resources Research*, *56*, e2020WR028193.

02 Seasonal water and sediment dynamics

The role of temperature and precipitation





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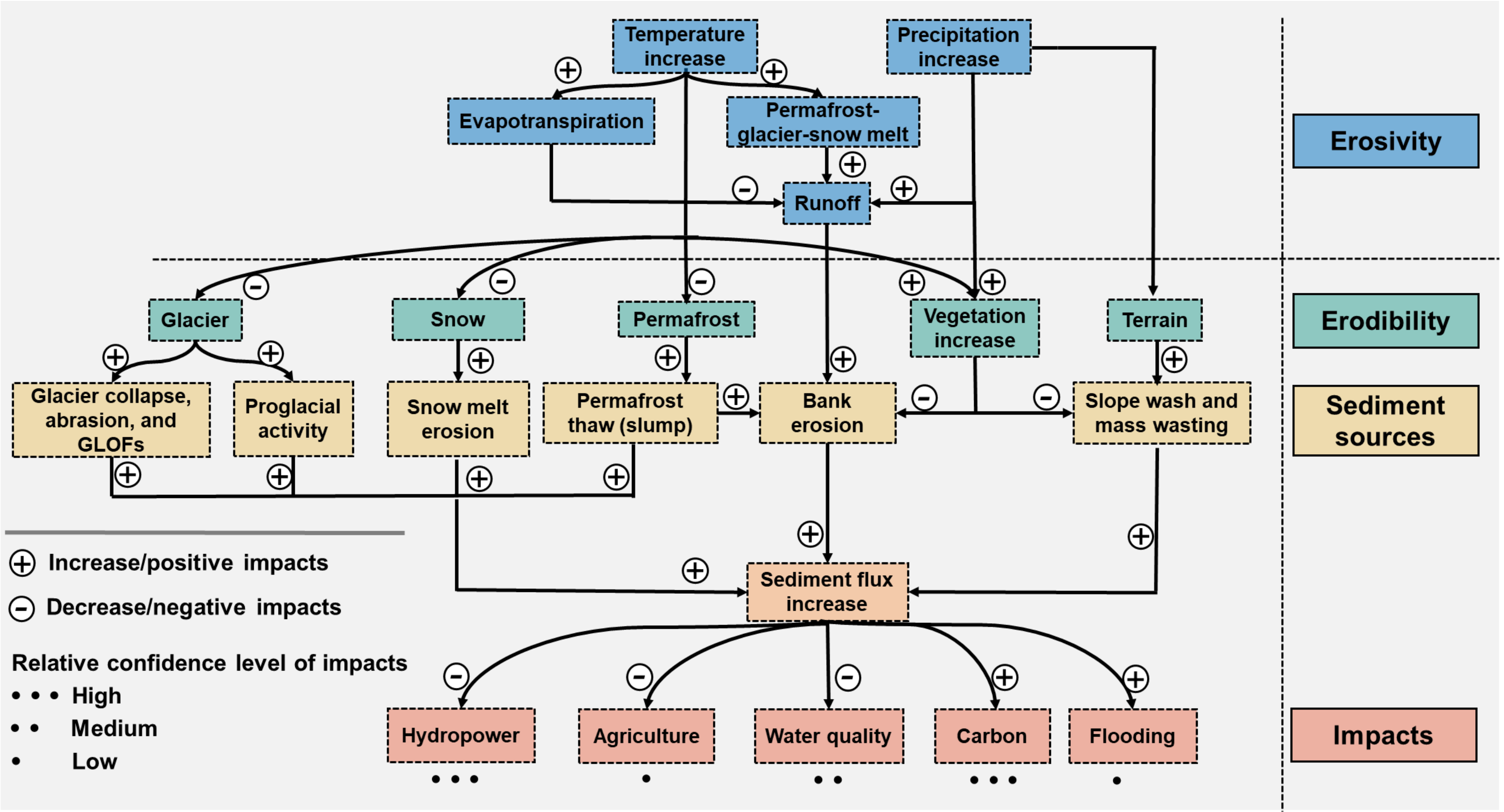
The conceptual framework of the sediment response to climate change



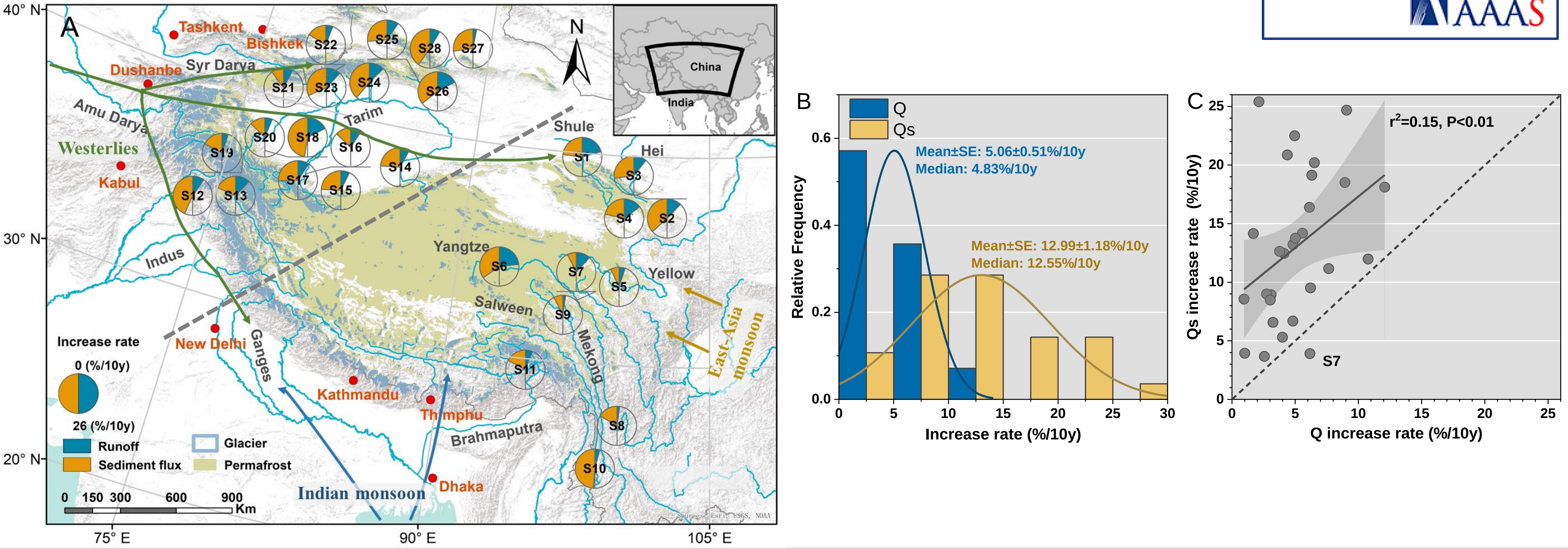
- Temperature and precipitation are the two primary driven factors
- Sediment research is much more complicated than runoff research

Li, D., Li, Z., Zhou, Y., & Lu, X. (2020). Substantial increases in the water and sediment fluxes in the headwater region of the Tibetan Plateau in response to global warming. *Geophysical Research Letters*, *47*(11), e2020GL087745.

03 Rising fluvial sediment loads

☐ Rising river runoff and sediment loads (1950s-2010s)

- **28 quasi-pristine headwater rivers (1,000-200,000 km²)**



Li, D., Lu X., Overeem, I., Walling, D., Syvitski J., Kettner, A. J., Bookhagen B., Zhou, Y., & Zhang, T. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, 374(6567), 599-603.

03 Rising fluvial sediment loads

□ The increases accelerated after 1995

- **Increasing glacier melt**

Photo by Z. Li and Tie Gai for GreenPeace

- **Increasing thaw slumps**

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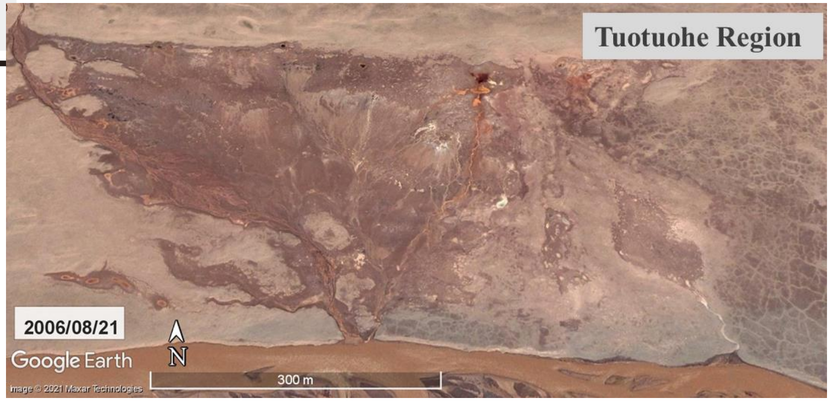
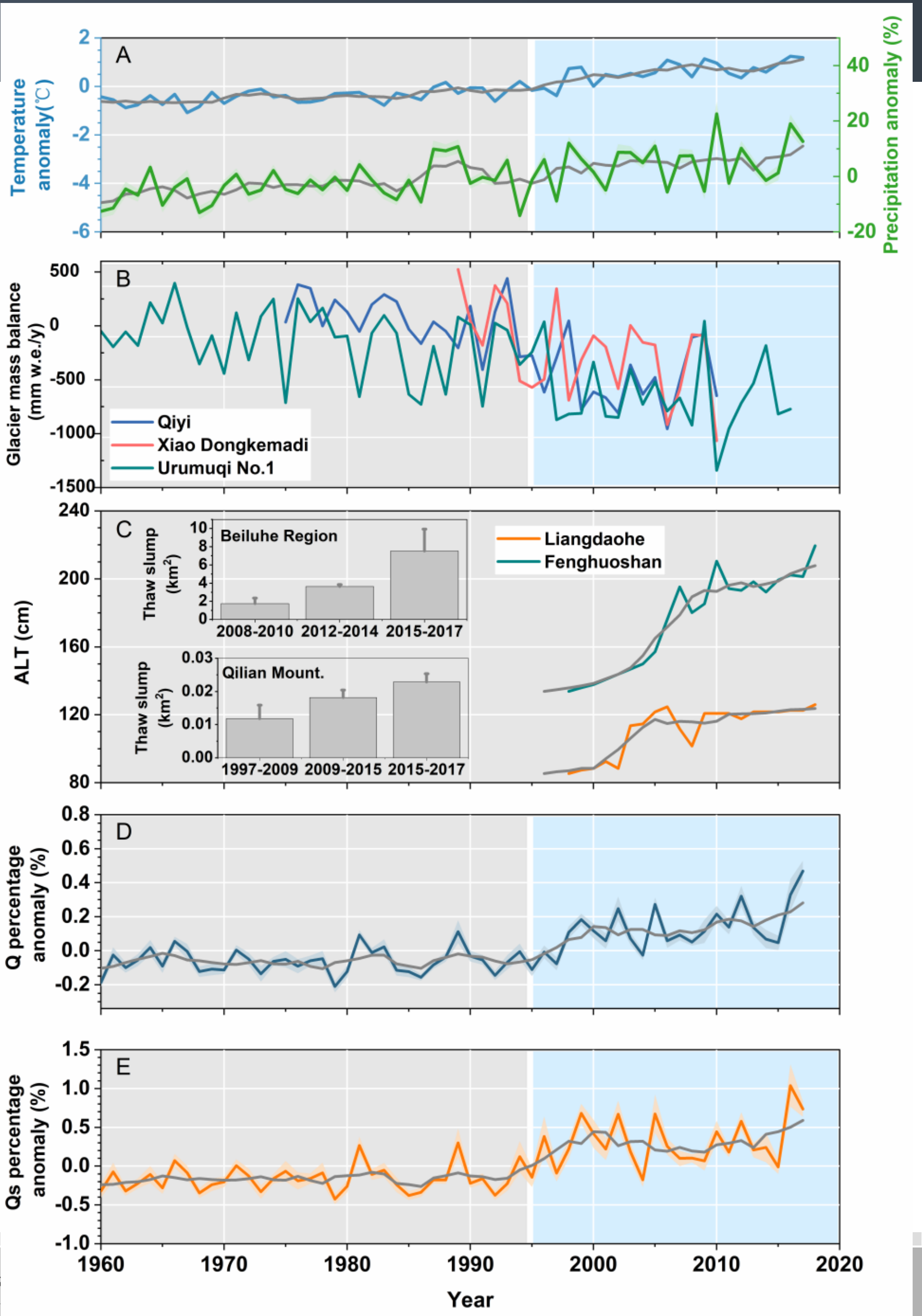
Geomorphology
journal homepage: www.elsevier.com/locate/geomorph

Recent acceleration of thaw slumping in permafrost terrain of Qinghai-Tibet Plateau: An example from the Beiluhe Region

Jing Luo ⁎, Fujun Niu ⁎, Zhanju Lin, Minghao Liu, Guoan Yin
State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China





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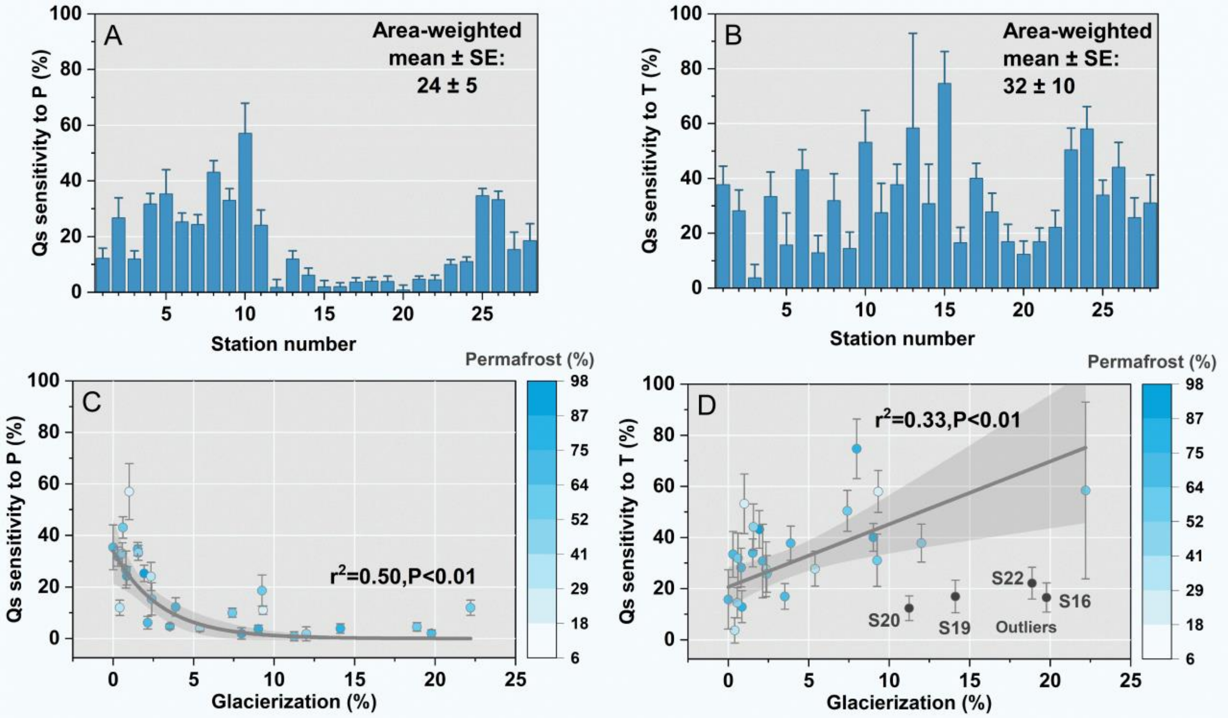
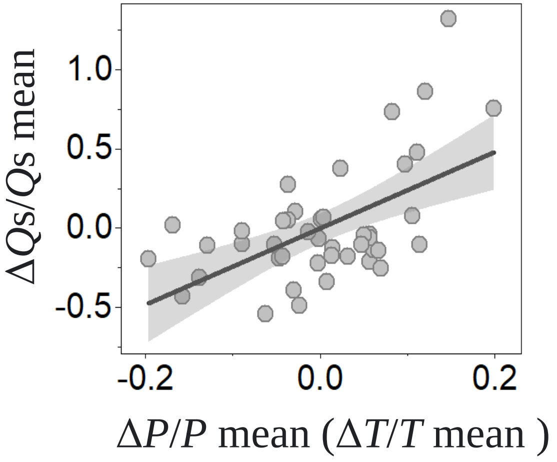
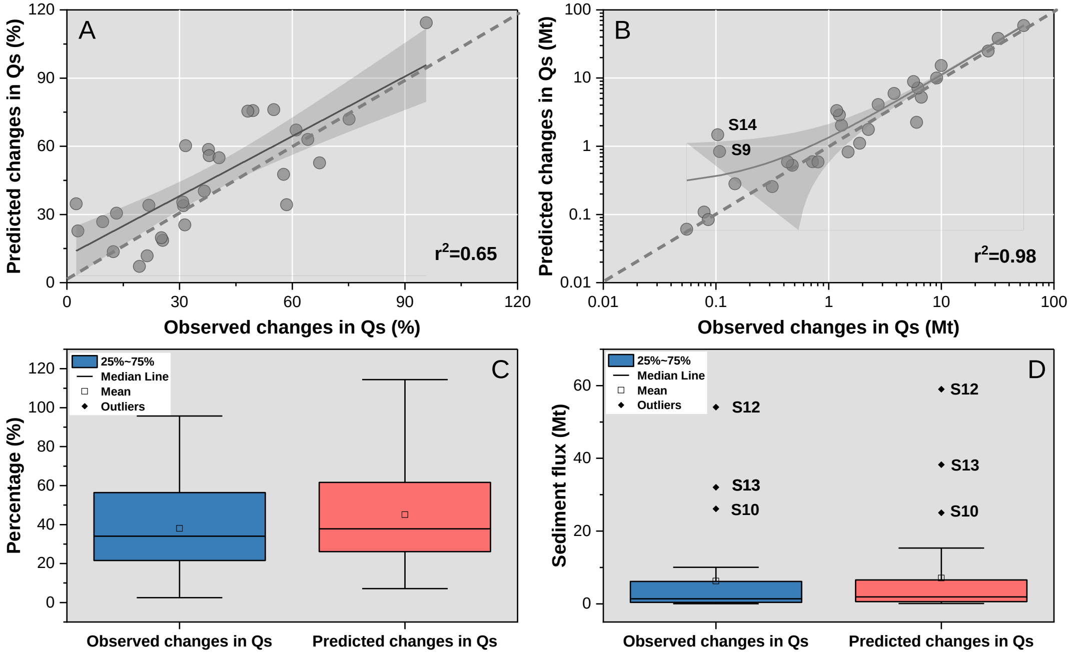
fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, 374(6567), 599-603.

Qs sensitivities to climate change

- **Thermal and pluvial-driven erosional processes**
- **Climate elasticity model** (Schaake, J C, 1990)







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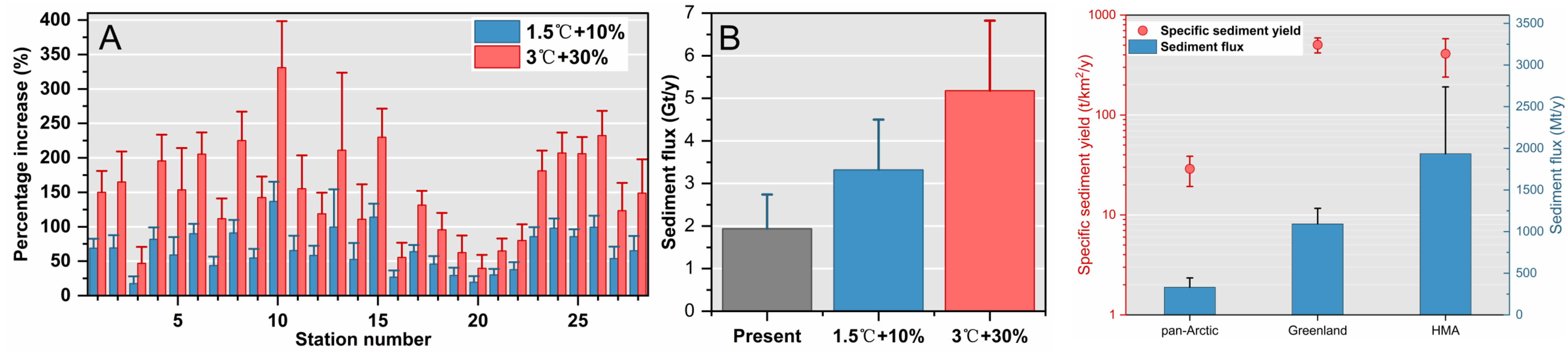
03 Rising fluvial sediment loads

Future rising sediment fluxes



- **Extreme scenario: from present-day 1.94 ± 0.80 Gt/y (1995-2015) to 5.18 ± 1.64 Gt/y by 2050**
- **Net increase of 3.24 Gt/y**

✓ **Larger than the present-day sediment fluxes from Pan-Arctic** (Holmes et al., 2002) **and Greenland** (Overeem et al., 2017)

✓ **Equivalent to ~23% of the current global land-ocean sediment flux** (14.18 Gt/y; Syvitski and Kettner, 2011)

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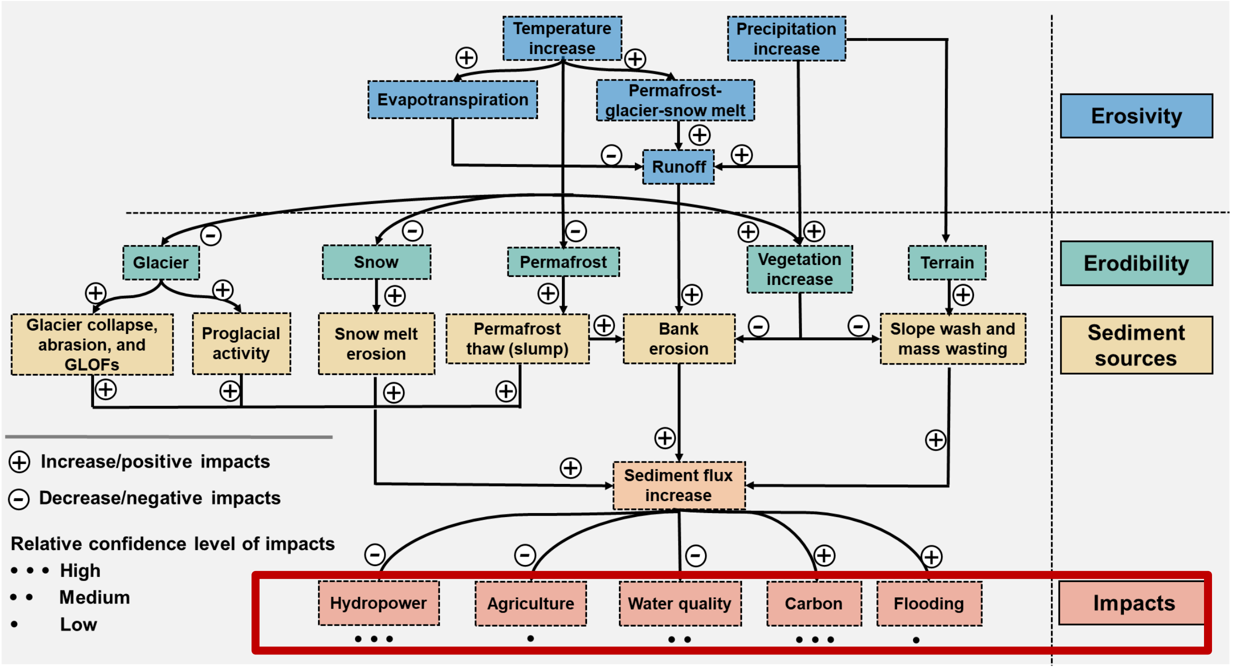
The conceptual framework of the sediment response to climate change



https://science.altmetric.com/details/115914305/news

NUS NEWS
Climate change increases fluvial sediment in the high mountains of Asia
National University of Singapore News, 29 Oct 2021

SCIENTIFIC AMERICAN
Water Muddier Rivers Are Jeopardizing Dams and Water Quality for Millions
Scientific American, 28 Oct 2021

EurekAlert! AAAS
Increasing sediment flux from rivers in High Mountain Asia poses regional risks
EurekAlert!, 28 Oct 2021

ScienceDaily
Runoff, sediment flux in High Mountain Asia could limit food, energy for millions
Science Daily, 29 Oct 2021

ENN ENVIRONMENTAL NEWS NETWORK
Runoff, Sediment Flux in High Mountain Asia Could Limit Food, Energy for Millions
Environmental News Network, 29 Oct 2021

AZO CLEANTECH
Climate Change Increases Fluvial Sediment in High Mountain Asia, Study Reveals
Azocleantech.com, 01 Nov 2021

Li, D., Lu X., Overeem, I., Walling, D., Syvitski J., Kettner, A. J., Bookhagen B., Zhou, Y., & Zhang, T. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science*, 374(6567), 599-603.

04 Impacts

nature geoscience

Hydropower systems

Contents lists available at ScienceDirect
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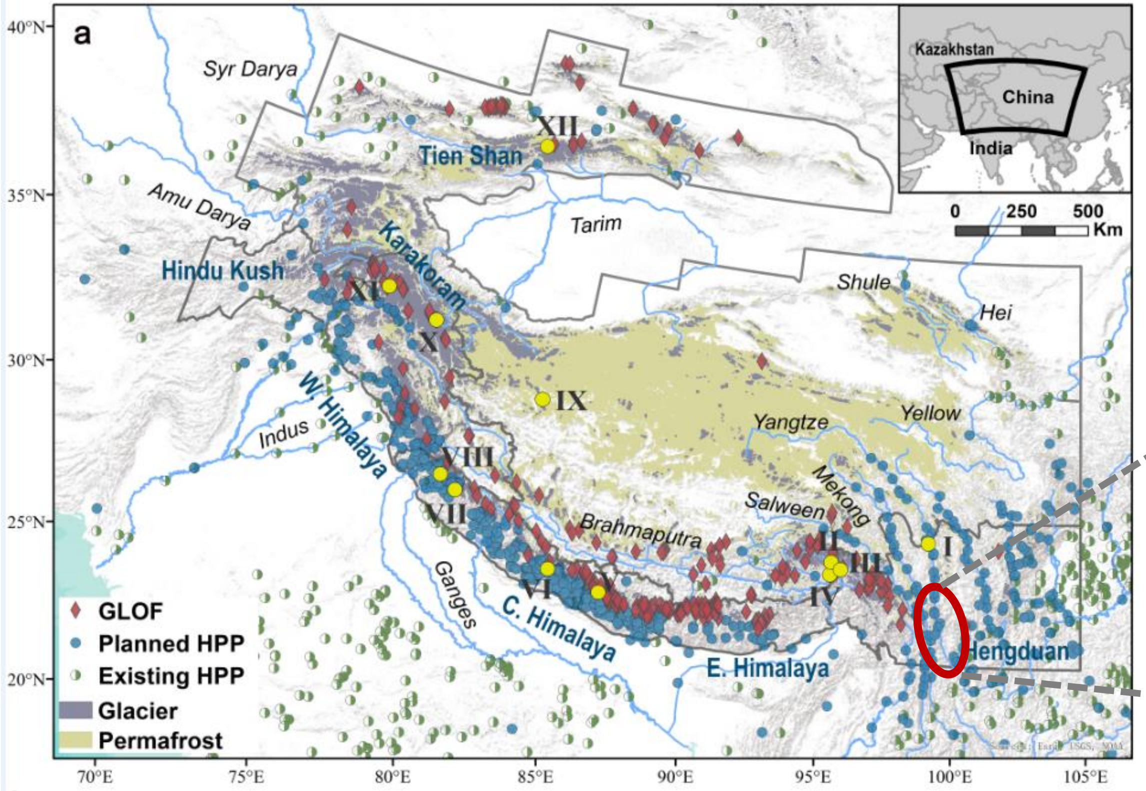
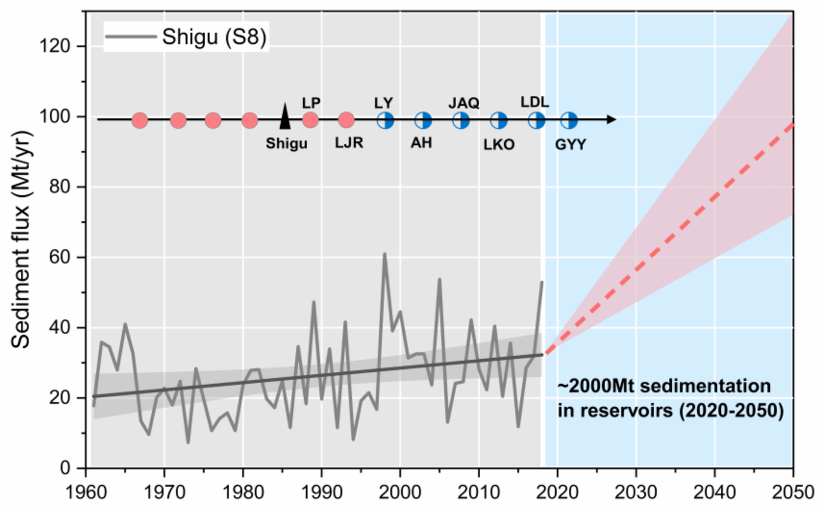
Sediment load responses to climate variation and cascade reservoirs in the Yangtze River: A case study of the Jinsha River

Dongfeng Li [a], Xi Xi Lu [a,b,*], Xiankun Yang [c], Li Chen [d], Lin Lin [a]



- **Sediment trapping efficiency of over 80% in Jinsha River**



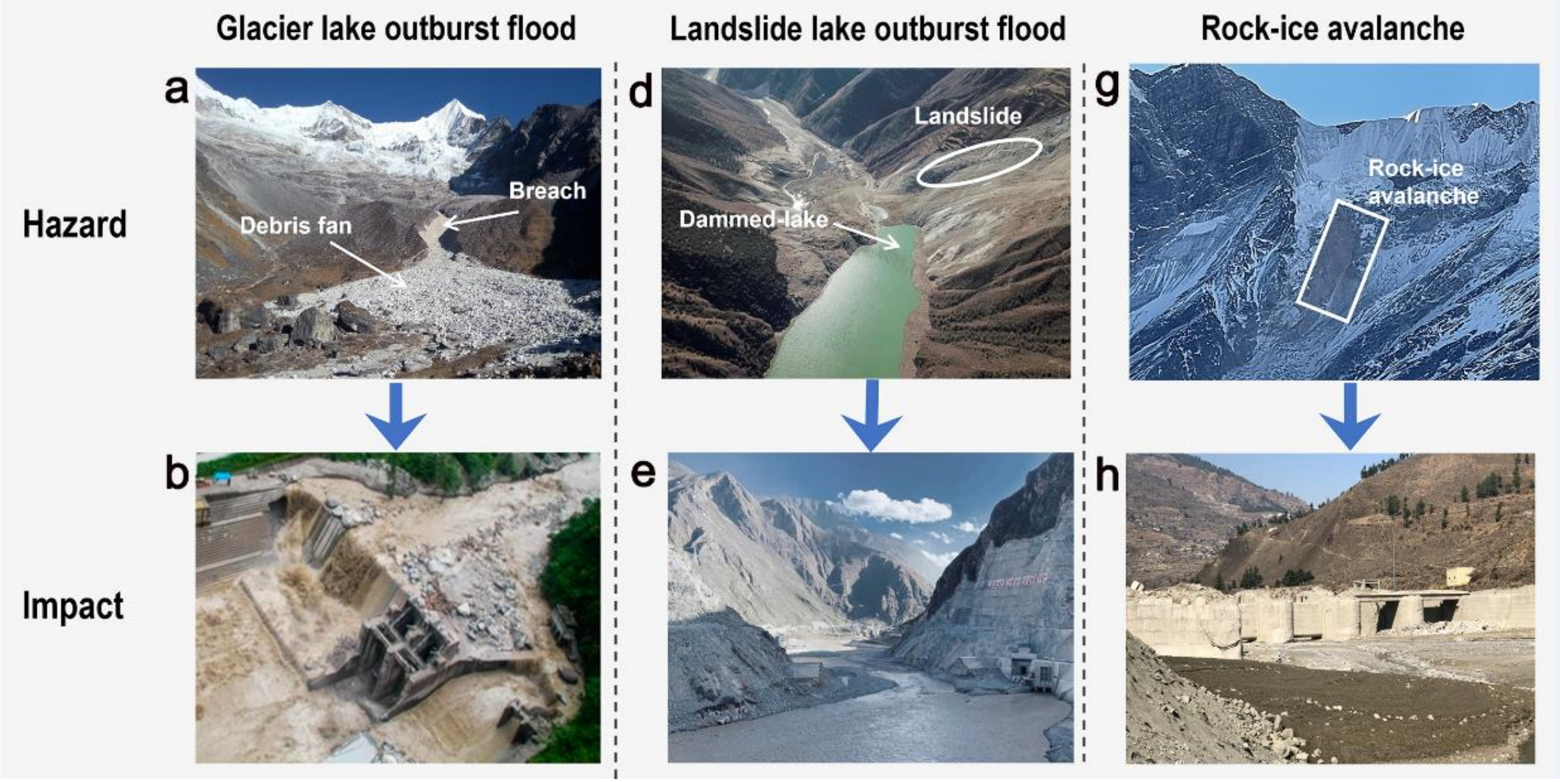
- **~2 Gt sedimentation over 2020-2050 under the extreme climate change scenario**
- **~2 times the designed storage capacity of the downstream Liyuan Reservoir** (assuming sediment bulk density of 1.3 t/m³)

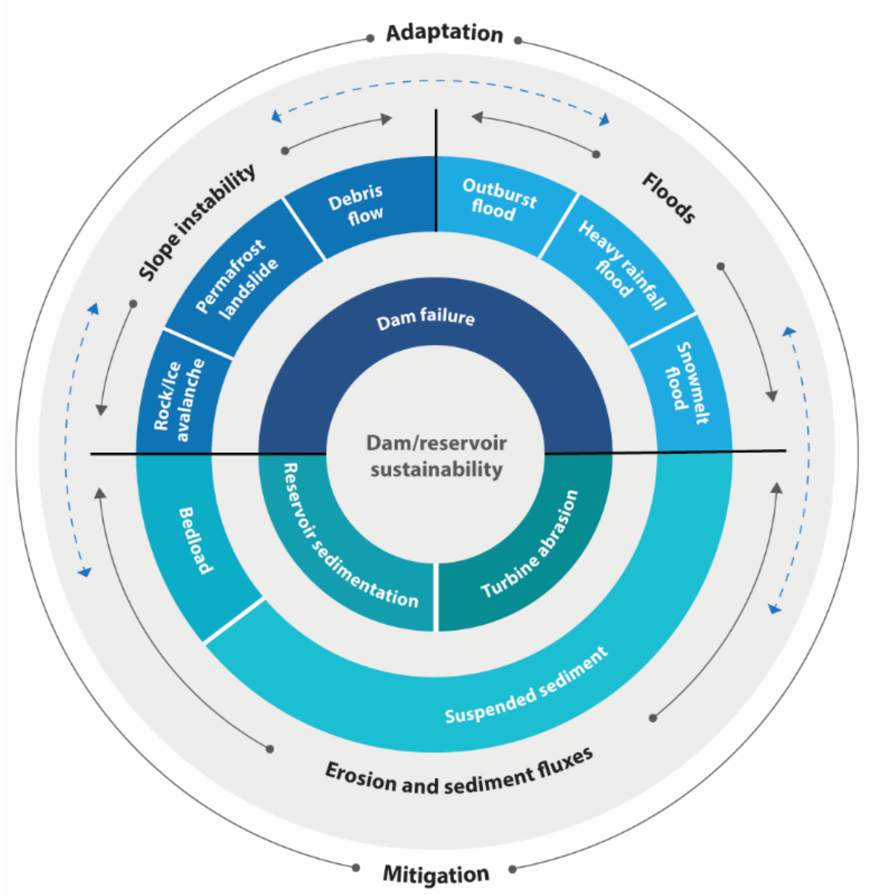
Li, D., Lu X., Walling, D., Zhang, T., Steiner J. K., Wasson, R. J., Harrison S., Nepal S., Nie, Y., Immerzeel, W. W., Shugar, D., Koppes, M., Lane, S., Zeng, Z., Sun, X., Yegorov A. & Bolch, T. (2021). High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nature Geoscience. (accepted).

nature geoscience

Hydropower systems

- **Mountain landscape instabilities** (slope instability, floods, and erosion)





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05 Take-home messages

- **Sediment sources: glacial erosion, thaw slumps, thermal gully, bank erosion, slope wash and mass wasting**
- **Temperature and precipitation regulate seasonal patterns of discharge and sediment dynamics by controlling erodible landscapes and multiple thermal/pluvial processes**
- **Water and sediment fluxes increased substantially, with accelerations after mid-1990s**
- **In a warmer and wetter future, sediment fluxes will likely more than double by 2050**
- **Increasing sediment loads (and cascading hazards) have important implications for the region's hydropower systems**

Increasing riverine sediment loads in Third Pole

Science   Contents   News   Careers   Journals

RESEARCH

SEDIMENT TRANSPORT

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

Dongfeng Li[1]*, Xixi Lu[1]*, Irina Overeem[2], Desmond E. Walling[3], Jaia Syvitski[2], Albert J. Kettner[2], Bodo Bookhagen[4], Yinjun Zhou[5], Ting Zhang[1]

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.

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

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

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL087745

Substantial Increases in the Water and Sediment Fluxes in the Headwater Region of the Tibetan Plateau in Response to Global Warming

Dongfeng Li[1], Zhiwei Li[2], Yinjun Zhou[3], and Xixi Lu[1,4]

[1]Department of Geography, National University of Singapore, Singapore, [2]State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China, [3]Changjiang River Scientific Research Institute, Wuhan, China, [4]Inner Mongolia Key Lab of River and Lake Ecology, School of Ecology and Environment, University of Inner Mongolia, Hohhot, China

Key Points:

- Runoff and sediment fluxes and their interannual variabilities increased substantially in this undisturbed cold environment
- Climate warming is likely the primary reason for the increased sediment fluxes and enhanced precipitation plays a secondary role
- The substantially increased

Water Resources Research

RESEARCH ARTICLE
10.1029/2020WR028193

Air Temperature Regulates Erodible Landscape, Water, and Sediment Fluxes in the Permafrost-Dominated Catchment on the Tibetan Plateau

Dongfeng Li[1], Irina Overeem[2], Albert J. Kettner[2], Yinjun Zhou[3], and Xixi Lu[1,4]

[1]Department of Geography, National University of Singapore, Kent Ridge, Singapore, [2]CSDMS, Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO, USA, [3]Changjiang River Scientific Research Institute, Wuhan, China, [4]Inner Mongolian Key Lab of River and Lake Ecology, School of Ecology and Environment, University of Inner Mongolia, Hohhot, China

Key Points:

- Climate warming expands the erodible landscape and increases fluvial water and sediment fluxes on the Tibetan Plateau
- Air temperature regulates seasonal discharge and sediment dynamics by controlling glacier-snow melt and permafrost processes

Water Resources Research

RESEARCH ARTICLE
10.1029/2021WR030690

Constraining Dynamic Sediment-Discharge Relationships in Cold Environments: The Sediment-Availability-Transport (SAT) Model

Ting Zhang[1], Dongfeng Li[1], Albert J. Kettner[2], Yinjun Zhou[3], and Xixi Lu[1,4]

[1]Department of Geography, National University of Singapore, Singapore, Singapore, [2]CSDMS, University of Colorado Boulder, Institute of Arctic and Alpine Research, Boulder, CO, USA, [3]Changjiang River Scientific Research Institute, Wuhan, China, [4]Inner Mongolian Key Lab of River and Lake Ecology, School of Ecology and Environment, University of Inner Mongolia, Hohhot, China

Key Points:

- Glacier-snow-permafrost melting elevates sediment availability by enlarging erodible landscapes and enhancing channel-slope connectivity
- A sediment-availability-transport (SAT)-model is developed to simulate dynamic suspended sediment concentration (SSC)-

Thanks!

Co-authors: Des Walling, Jaia Syvitski, Irina Overeem, Albert Kettner, Bodo Bookhagen, Ting Zhang, Zhiwei Li, Yinjun Zhou, **Xixi Lu**

Collaborators: Jim Best, Tom Dunne, Achim Beylich, Michele Koppes, Stuart Lane, Zhenzhong Zeng, Bob Wasson

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