

GEOMORPHOLOGY

Rapid changes to global river suspended sediment flux by humans

Evan N. Dethier^{1,2*}, Carl E. Renshaw¹, Francis J. Magilligan³

Rivers support indispensable ecological functions and human health and infrastructure. Yet limited river sampling hinders our understanding of consequential changes to river systems. Satellite-based estimates of suspended sediment concentration and flux for 414 major rivers reveal widespread global change that is directly attributable to human activity in the past half-century. Sediment trapping by dams in the global hydrologic north has contributed to global sediment flux declines to 49% of pre-dam conditions. Recently, intensive land-use change in the global hydrologic south has increased erosion, with river suspended sediment concentration on average $41 \pm 7\%$ greater than in the 1980s. This north-south divergence has rapidly reconfigured global patterns in sediment flux to the oceans, with the dominant sources of suspended sediment shifting from Asia to South America.

River basins globally are experiencing increasing threats to their key roles in physical and ecological processes, including increased erosion from land use changes, sediment trapping by dam building, and the cascading hydrological and sedimentological effects of climate change (1). In many basins, the past and ongoing relative impacts of each of these changes remain unknown because of insufficient monitoring, and future projections are hindered by nonstationary watershed behavior, including changes without recent or well-monitored precedents (2, 3). Given the divergent impacts of these different stressors—with land-use change dominantly increasing sediment flux, sediment trapping by dams dominantly decreasing sediment flux, and the effect of climate change on sediment flux uncertain—the temporal and global spatial variations in current and future net impacts are poorly constrained. We circumvented the global paucity of recent in situ river monitoring by using satellite analysis to investigate historic and ongoing changes in suspended sediment flux in 414 major rivers worldwide. We focused on sediment flux because of its essential role in maintaining riparian habitat and complexity, bolstering wetlands and deltas, delivering important nutrients to the oceans, and increasing coastal resilience to sea level rise. Because the major anthropogenic stresses to river functioning have both increased and decreased sediment flux, we found complex spatial and temporal variations in net impact on the world's major rivers, with major, global-scale reconfiguration in the past several decades.

We focused on 414 major rivers that flow into the oceans or major inland seas, are wider than ~90 m at their outlet, and have a drainage area of >20,000 km². Many of these rivers lack suspended sediment observations during the period of interest, and some have no published suspended sediment data at all. Recent advances in computational resources (4) and digital archives of hydrologic data allow for improved analysis of satellite image archives to monitor global water quality (5, 6). We capitalized on these advances to evaluate decadal changes to river suspended sediment concentration (SSC) and flux, using a suite of algorithms trained on more than 130,000 ground truth measurements from 340 diverse sites in North America, South America, and Taiwan (5). Applied to the entire Landsat 5 and 7 archive, these algorithms allow for estimates of SSC for each purely water river pixel on Earth for hundreds to thousands of days from 1984 to present (fig. S1). In constructing a monthly record of SSC for each major river over time, we have filled in many of the critical gaps in the global understanding of spatial and temporal variability in river suspended sediment transport. For each river outlet, we extended our analysis with unified time series of SSC and river discharge estimates (7) to quantify global patterns and changes in discharge-weighted average SSC and monthly sediment flux to the oceans from 1984 to the present (Fig. 1) (5).

Dam building dominant in 20th century

We found that global river sediment flux is rapidly changing. Temporal trends in suspended sediment flux over the four-decade satellite record were significant for 53% of rivers (220 of 414; $P < 0.05$) (Fig. 2). Most rivers have retained at least a semblance of their natural variability and seasonality in SSC as, for example, SSC increases with increasing discharge (fig. S4), and the timing of peak

SSC remains regionally consistent (Fig. 1 and fig. S4). However, our findings demonstrate in spatial and temporal detail the effects of direct human activity in altering suspended sediment transport, resulting in major changes to sediment transport in rivers and delivery of physical materials and nutrients to global estuaries and oceans. Decreasing sediment flux has been the prevailing global signal since the mid-20th century (Fig. 2), primarily because of dams (figs. S4 and S5), which are likely the dominant agent of riverine suspended sediment alteration in the past several centuries (8, 9). However, this global signal masks the strong spatial variation in impacts. Widespread dam building in the 20th and 21st centuries has led to systematic declines in suspended sediment flux from rivers in the global hydrologic north, defined here geographically as north of ~20°N. Yet dam building is, at present, less pervasive in the global hydrologic south, defined here as south of ~20°N. There, intensive land-use change is driving rapidly increasing sediment fluxes. This strong north-south divergence is drastically reshaping the pattern of sediment delivery to global oceans (Fig. 3). Until the 1990s, Asia was the leading continental exporter of suspended sediment to the oceans and, during the pre-dam peak, accounted for ~50% of all sediment exported to global oceans; now, rivers in Asia export only $27 \pm 1.9\%$ of the global total.

The major Northern Hemisphere shift toward sediment retention in dammed reservoirs occurred in the 20th century. Of the rivers in this study, 58% (240 of 414) have one or more major dams (Fig. 4) (10), and 78% of those rivers (187 of 240) have decreased sediment flux relative to pre-dam estimates largely made by Milliman and Farnsworth (11). These pre-dam data are from a range of years and reflect varying estimation and extrapolation approaches and sampling techniques and periods. However, although these metadata gaps can make constraint of uncertainty challenging, the estimates are by far the most comprehensive pre-dam inventory of suspended sediment flux made from direct measurements and are an essential point of comparison. In aggregate, we found that continental fluxes are reduced by $49 \pm 25\%$. The rivers with major dams are often comprehensively dammed. On average, reservoirs on dammed rivers have the capacity to retain 102% of annual river discharge (we refer to this normalized reservoir capacity simply as “reservoir capacity”). Continental sediment flux is decreased by $1.8 \pm 0.6\%$ per percent increase in reservoir capacity ($P = 0.043$) (Fig. 4), a negative trend that is also present and significant for individual rivers ($P = 0.002$) (fig. S10).

Dams have continued to reduce suspended sediment fluxes since 1984, although this effect has been strongly regional, focused where

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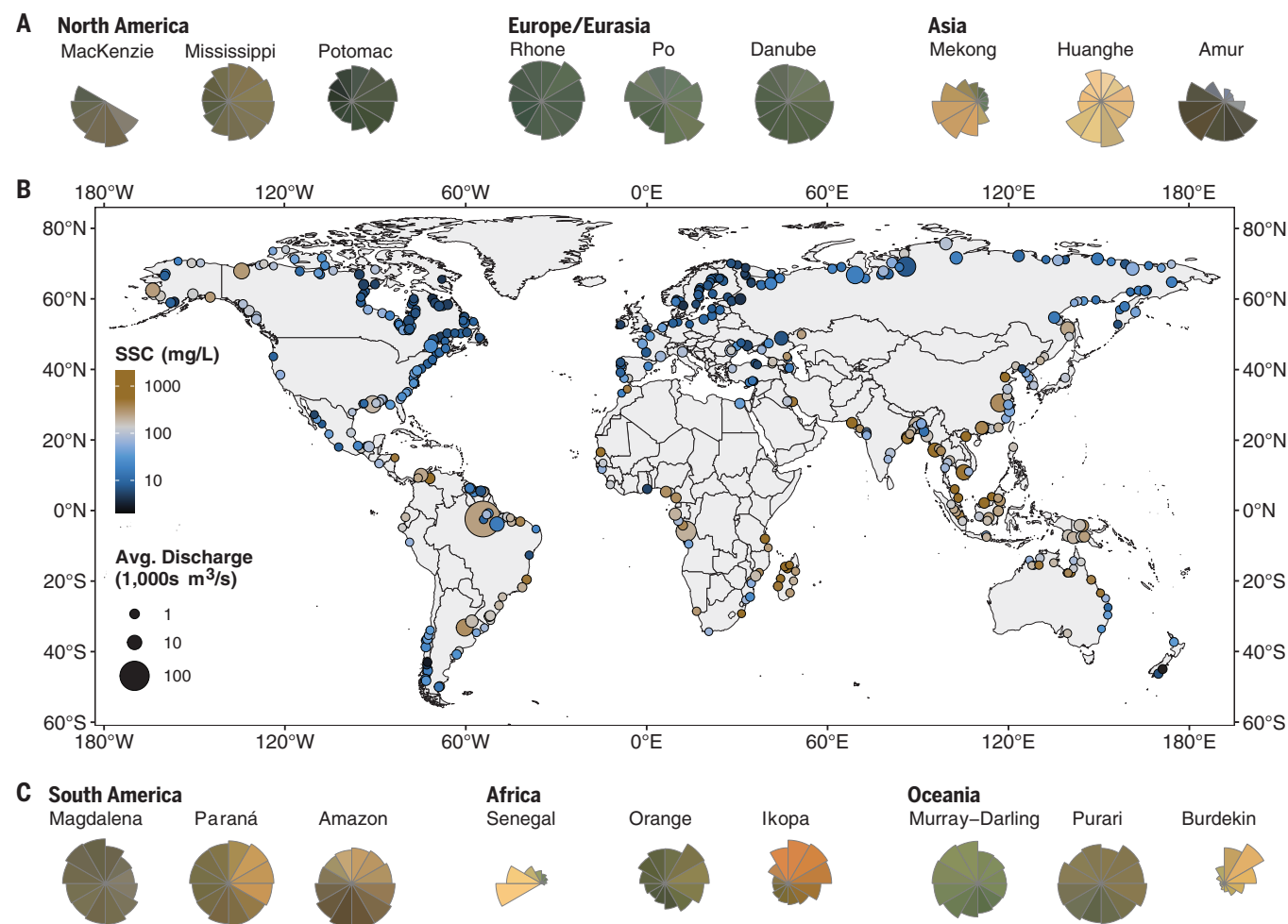


Fig. 1. Global variations in SSC, as estimated from satellite imagery from 1984 to 2021. (A and C) Variation in suspended sediment is shown with color wheels for select rivers from each primary landmass. Each wheel displays the monthly patterns in average river true color in Landsat imagery, by using the average red-green-blue (RGB) reflectance at the river outlet (supplementary materials, materials

and methods). 1 January is at the top of each wheel, and each section of the wheel is scaled by monthly average discharge normalized by average peak monthly discharge for that river. Missing sections indicate ice-in season for high-latitude rivers. (B) Global map of average discharge-weighted SSC for 414 major rivers shows global patterns in SSC. Symbols are scaled by average annual discharge.

continued dam construction has occurred in Eurasia and Asia. Since 1984, approximately two-thirds (68%) of rivers with significant trends have decreased significantly (36% of all rivers), compared with increases at approximately one-third (32%) of rivers with significant trends (17% of all rivers). Reductions since 1984 have primarily occurred in Asia ($-34 \pm 7\%$) and Europe/Eurasia ($-19 \pm 12\%$) (Figs. 2A and 4B), where dam building on important undammed river reaches and tributaries continued through the mid-2000s (Fig. 4A).

However, in many ways our findings illustrate the diminishing additional impact of new dams on sediment flux to the global oceans. New dams and changing land-use practices continue to reduce sediment export from rivers in the global hydrologic north, primarily in Eurasia and Asia (Fig. 2, A and B, and, for example, fig. S8). However, fluxes from these rivers

have on average only declined $7.5 \pm 3.5\%$ since the 1980s (Fig. 3C, top), a fraction of the 60 to 80% decline we documented relative to their pre-dam condition (Fig. 4B). Of the 146 rivers with post-1984 dams, about half (52%) have no statistically significant decline in suspended sediment flux, which possibly reflects increases in erosion from these watersheds but likely is primarily because previously built dams in those watersheds were already trapping substantial amounts of sediment. Indeed, rivers with post-1984 dams were widely dammed before 1984. On average, pre-1984 reservoir capacity for rivers with dams was $88 \pm 8.2\%$ of annual discharge, compared with $102 \pm 10\%$ today. With sediment retention already so high before the period of satellite observation, potential sediment flux reductions in the satellite period were comparatively limited. As a result, the post-1984

reductions were largely continuations of reductions owing to the initial wave of dam building in the mid-20th century. Of the rivers with post-1984 dams, only 7.5% (11 of 146) were built on rivers without at least one preexisting major dam.

Recent sediment flux increases in the global hydrologic south

Contrary to the northern trend of decreasing sediment flux, sediment fluxes from rivers in the global hydrologic south are rapidly and systematically increasing because of intensive land-use changes, particularly in watersheds within 20° of the Equator. About one-third (36%) of the 146 rivers in the global hydrologic south are transporting significantly more sediment than in 1984 (Fig. 3B). This rate of increase is significantly higher than for rivers in the global hydrologic north, where only 7%

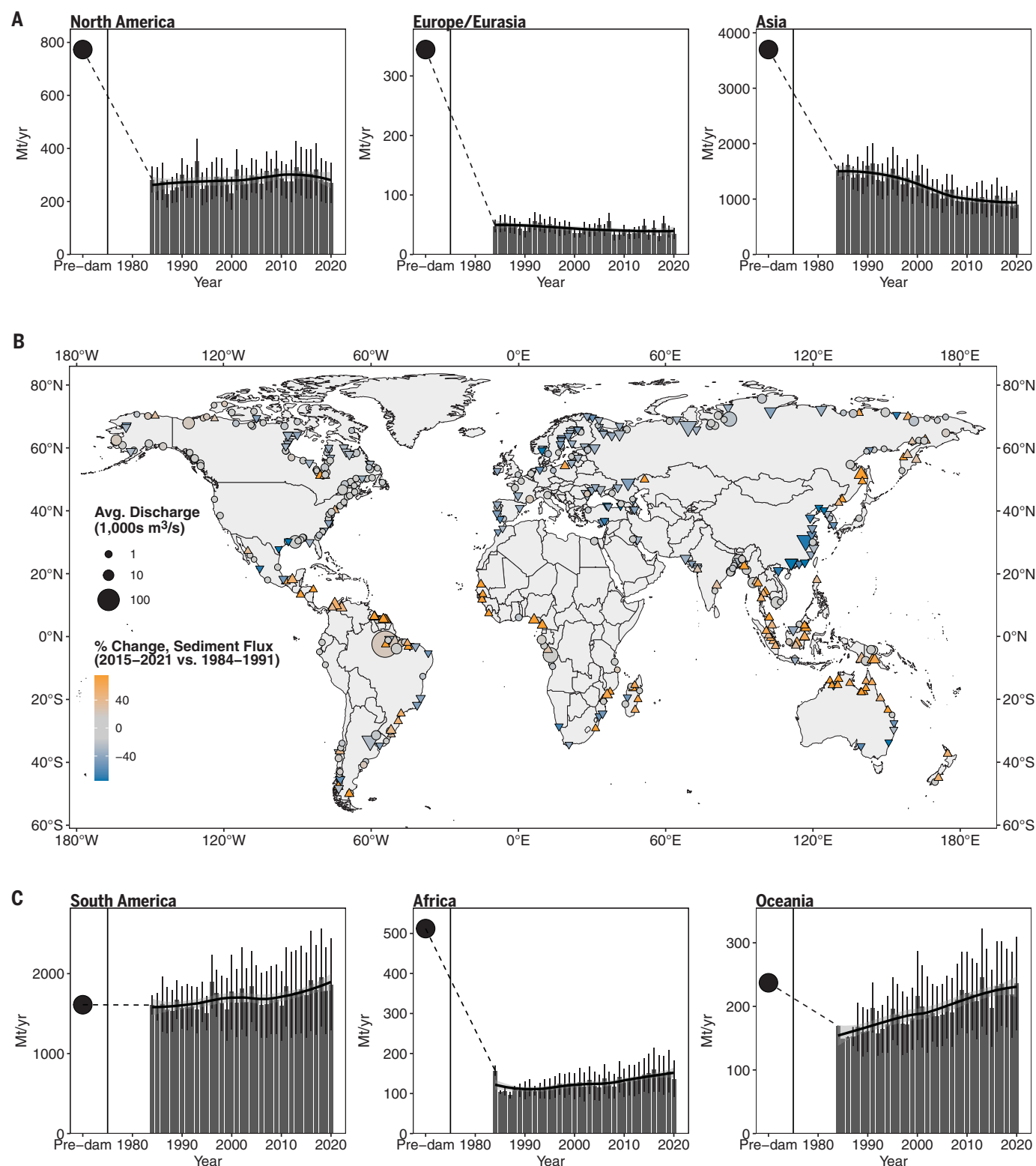


Fig. 2. Changes in suspended sediment flux for 414 major rivers on the six major global landmasses. (A) Changes for northern rivers relative to pre-dam fluxes estimated for those rivers (11). Annual estimates of suspended sediment flux show decrease or no change north of 20°N latitude, which is likely the result of continued dam building. (B) Rivers with increasing suspended sediment flux (upward-pointing triangles), rivers with

declining suspended sediment flux (downward-pointing triangles), and rivers with no statistically significant change (circles). (C) Suspended sediment flux has increased south of 20°N over the same period owing to ongoing land-use change and intensification of the hydrological cycle. Scales for the y axes in (A) and (C) vary, and this analysis does not include every river on each landmass.

(18 of 268 rivers) have increasing sediment flux, despite increasing precipitation in several regions (fig. S7). Increases show heterogeneity in timing and magnitude, but discharge-weighted SSC has on average increased in southern rivers by $41 \pm 7\%$ (Fig. 3C, bottom). We attribute this increase in suspended sediment runoff from the global hydrologic south primarily to direct human influence. Suspended sediment flux increased after major land-use change in 58 of 70 total rivers with significant increasing trends (table S1), with most activities associated with widespread and/or acute

deforestation in those watersheds (figs. S11 and S12) (12). In many cases, these land-use changes result in pronounced, point-source sediment inputs. Of particular note are alluvial mining, sand mining, and palm oil plantations (for example, fig. S12), which respectively appear to be primary drivers of increased erosion in 34, 19, and 17% of watersheds with increasing suspended sediment flux. Although sand mining is generally thought to reduce downstream bedload sediment flux, channel disruption and bank instability resulting from this practice could lead to increased suspended

sediment load (13). These landscape-altering activities have become pervasive in tropical and subtropical watersheds in the past 20 years, often in or adjacent to rivers, without widespread recognition or documentation of their effects on rivers (fig. S5) (1, 13–15).

We are unable to detect whether climate change and attendant changes to the hydrologic cycle have demonstrably contributed to changes in sediment supply. Some watersheds have experienced increased precipitation (16) or temperature-related erosion (3) during this period (fig. S6). However, although we observed

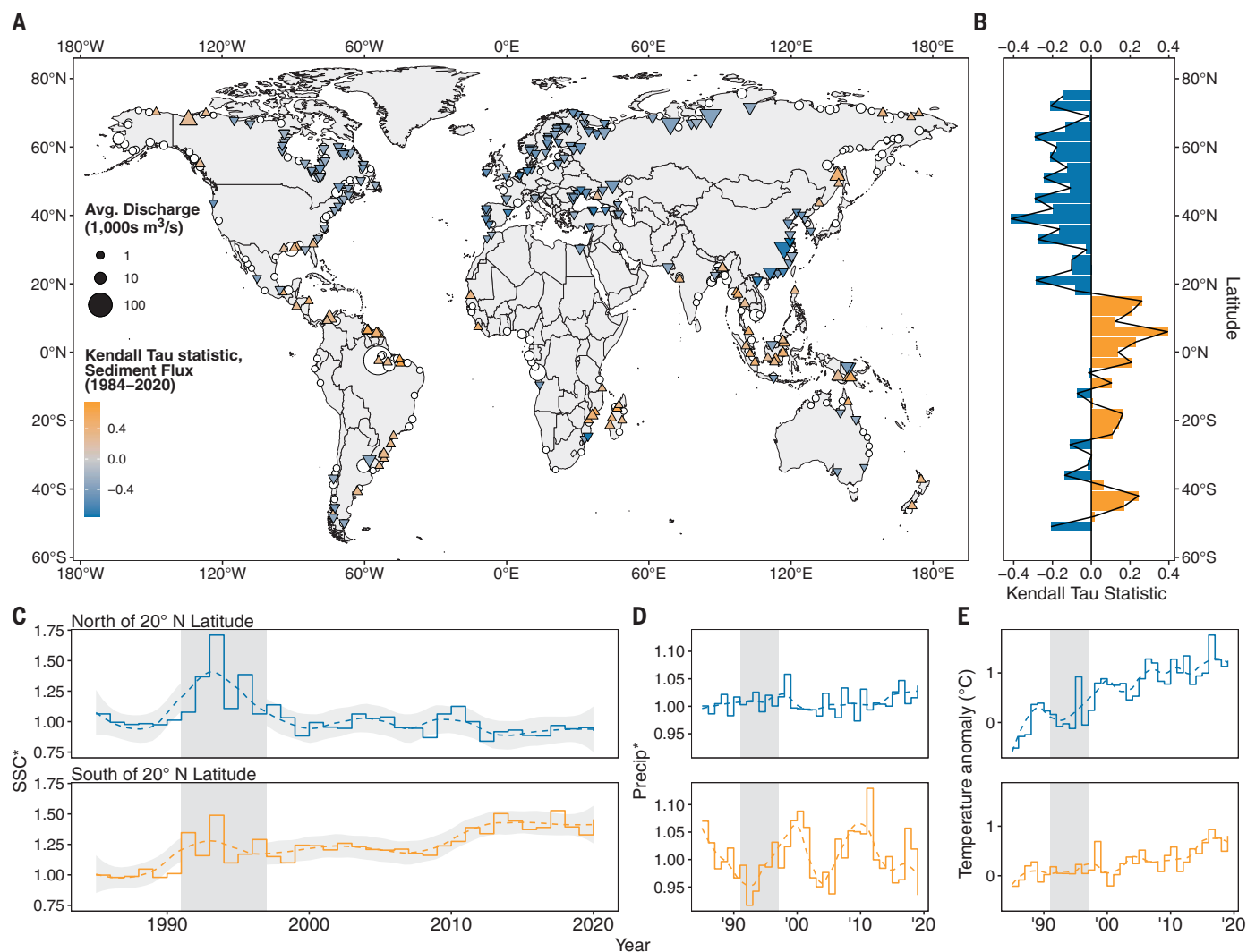


Fig. 3. Changes in suspended sediment flux from 1984 to 2020 at 414 major rivers. (A) Changes in river suspended sediment flux for each river, as determined with the Mann-Kendall nonparametric trend test. (B) Latitudinal variation in sediment flux trends, with the Mann-Kendall Tau statistic averaged for every river within 3° latitude bins, show a global divergence, with major increases south of 20°N and decreases north of 20°N. (C) Changes in SSC normalized by the 1984–1990 period (SSC*), with the Pinatubo eruption period removed, show a $7.5 \pm 3.5\%$ decline for northern rivers and a $41 \pm 7\%$ increase for southern rivers, which are likely driven by accelerating

intensive land-use changes. (D) Changes in precipitation normalized by the 1984–1990 period (Precip*) do not show a significant relationship with trends in SSC*. (E) Changes in temperature relative to the 1984–1990 baseline show faster warming in northern watersheds, countering the hypothesis that increasing SSC for southern watersheds is the result of increased temperature. The gray bands in (C) and (D) indicate the standard error in the estimate for each year. Gray shading in (C) to (E) indicates years when the eruption of Mt. Pinatubo affected regional climates and satellite measurements of some rivers, particularly the upward excursion in SSC* for northern rivers.

cyclical changes in precipitation in southern-latitude watersheds, we found no correlation with the systematic change in SSC ($P = 0.80$) (Fig. 3D). Temperature, another potential explanatory variable because of its connection to rates of weathering and soil erosion (fig. S13) (17), has warmed more slowly in southern watersheds ($\sim 0.5^{\circ}\text{C}$) than in northern watersheds ($\sim 1.6^{\circ}\text{C}$) (Fig. 3E), where we observed stable or declining SSC. These potential or

incipient effects of climate change on rivers do not yet pose a threat comparable with that of direct anthropogenic impacts. Yet they have been the major focus of international attention, including in the recent Intergovernmental Panel on Climate Change (IPCC) reports (18), possibly in part because of the lack of monitoring on tropical and subtropical rivers that account for many of the pronounced recent changes. The immediate consequences of di-

rect land-use change, which are far greater in the present and near future, thus risk being overlooked.

Continued threats to rivers in the 21st century

In addition to being hotspots for intensive land-use change, for now the regions with increasing sediment fluxes remain notable exceptions to the global proliferation of dams and consequent decline in suspended sediment

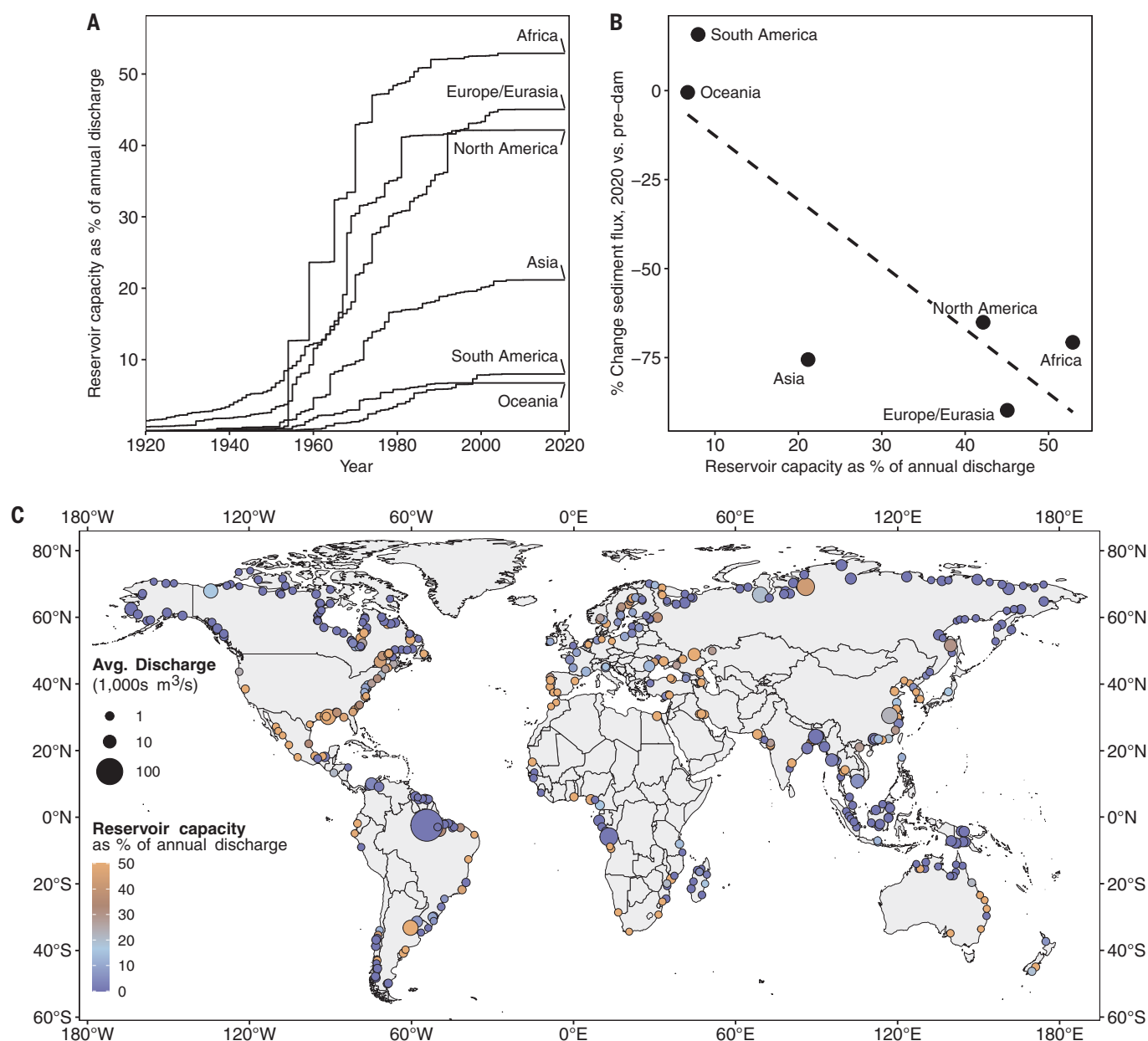


Fig. 4. Increases in reservoir capacity as a percent of annual discharge (RCI). (A) Dam building in Africa, North America, and Europe/Eurasia have capacity for ~40 to 50% of annual river flow, which is far greater than capacity in Asia (~20%), South America (~8%), and Oceania (~6%). (B) RCI is significantly negatively correlated with the change in suspended sediment flux relative to pre-

dam ($P = 0.043$). Departure below the best-fit line in Asia is likely partially the consequence of a national soil conservation project and recent major dams missing from global dam inventories. (C) Map of RCI indicates the remaining undammed or minimally dammed rivers in dark blue, which are concentrated in the arctic and near the equator.

flux. South America and Oceania have the lowest reservoir capacity of all the continents. Reservoirs on those landmasses are capable of containing <10% of total river flow (Fig. 4), which is only a fraction of the reservoir capacity on other continents. Before global dam building, South America transported ~20% of the sediment from rivers in our study. Sediment fluxes from this continent have increased, in both relative and absolute terms, as declines have occurred in the Northern Hemisphere. South American rivers represent $52 \pm 2.6\%$ of the global total and, despite increases in river headwater sediment fluxes in Asia (3), are now the leading exporters of sediment to the oceans.

Because of ongoing and imminent dam building, the stable or increasing sediment fluxes to the ocean from South America and Oceania may not persist. To this point, dams have not wholly insulated river outlets from these changes; 40% of the southern rivers with increasing suspended sediment flux have at least one major dam, including 13% with dams built since 1984. However, more than 300 large dams are planned for the Amazon River, and more are planned for other rivers in South America and Oceania that are similarly unregulated (19, 20). The Amazon, which exports two-thirds of the sediment from South America and more sediment than any other global river, is home to globally unrivaled channel, floodplain, and estuary biodiversity (21) and transfers essential nutrients to coastal waters (22). The planned dam projects there and on other unregulated rivers are particularly impactful because the current absence of dams allows virtually unchecked river transport of sediment, conditions that persist along few major rivers.

Elsewhere, dams are increasingly overprinted on systems that already face acute anthropogenic pressures, extending threats to critical human use and ecosystem services (1). Particularly in tropical and subtropical regions, losses of riverine function have accelerated because of morphological alteration (13, 15) and physical and contaminant pollution (15, 23, 24). Planned dam projects on major rivers with existing dams—for example, more than 100 dams on the Mekong alone (25, 26), as well as many on the Ganges/Brahmaputra, Yangtze, Danube, La Plata, and Uruguay Rivers, and dozens on other systems (27)—may have diminishing sediment trapping effects because those systems already have numerous major dams. In those cases, although successive dams might have less impact on global sediment export to the oceans, the upper- and middle-river channels and floodplains of these systems will nonetheless experience continued sediment reduction. Additionally, although sand mining has the potential to liberate sediment from channel beds, banks, and flood-

plains, the comprehensive removal of these materials for industrial uses may ultimately contribute to reduced suspended sediment loads (13, 28). In reaches not affected by intensive land-use change, diminished sediment fluxes may alter channel migration rates (29), critical floodplain exchange (30), channel morphology (31), and in-channel habitat and biodiversity (32). Sediment retention in dam reservoirs can contribute to increases in downstream erosion (33), with potential consequences for downstream communities and estuaries.

Summary

We offer both a retrospective and current assessment of the global state of large rivers. We highlight the various pressing threats to these vital systems, especially the southward shift in the global center of mass of suspended sediment export to the oceans. The preponderance of both dams and rapid land-use change along the world's rivers continues their fundamental alteration through direct human action, so far outpacing the growing threats from climate change. As nations plan more dam projects, alter land-use practice, or reexamine current infrastructure and policy, stakeholders involved in planning decisions in the riparian corridor or coastal zone—for example, dam emplacement and removal, wetland resiliency, land-use management, and climate change adaptation—have historically made decisions with inadequate data (19). We have demonstrated the value of our satellite remote-sensing approach for estimating SSC and suspended sediment flux. Validated with 130,000 ground truth measurements, this technique can be updated and refined as additional in situ measurements are added to the calibration datasets and new satellites improve our monitoring coverage of Earth's surface (34). The real-time assessment of sediment transport by rivers can help inform policy decisions through direct observation of extant and historical conditions. Critically, we also provide the tools to evaluate the success of policy actions and interventions intended to improve conservation or public safety efforts. Our approach, as presented here and in the hands of other researchers and stakeholders, may help provide a robust means of impact assessment and assist in future planning, early detection, and mitigation efforts.

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Competing interests: The authors declare that they have no competing interests. **Data and materials availability:** All data used in this analysis are publicly available. Data and code used to generate all analysis, figures, and tables can be found at <https://www.github.com/evandethier/satellite-ssc>, with release archived at (35). **License information:** Copyright © 2022 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. <https://www.science.org/about/science-licenses-journal-article-reuse>

SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S13
Table S1
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Rapid changes to global river suspended sediment flux by humans

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Sediment traps and drains

Humans dramatically change the amount of sediment that makes it to the oceans and seas by damming rivers or through land-use changes. Dethier *et al.* used satellite imagery from the mid-1980s onward, ground truthed with over 100,000 measurements, to estimate the sediment flux from 414 rivers worldwide (see the Perspective by Zarfl and Dunn). Dams have substantially reduced sediment flux in the global north, whereas land-use changes have increased sediment flux in the global south. These observations can help to guide policy decisions regarding critical water resources. —BG

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