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The unexpected global distribution of Earth's sediment sources and sinks

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ABSTRACT

Earth's landscapes, geochemical cycles, and sedimentary record are shaped by the source-to-sink transport of sediment. Sediment is sourced in erosional landscapes under the influence of climate and tectonics, transported through net bypass zones that can obscure forcing signals, and deposited in sinks to build the sedimentary record. Despite the importance of source-to-sink sediment transport in Earth science, the relative abundance of these domains remains unquantified, and the extent to which Earth's surface resembles classic conceptual models has not been tested. Here we produce a global database of Earth's source-to-sink systems. Results show that Earth's land area is mostly erosional (59%), with bypass (22%) and sink (19%) domains less common (18%, 6%, and 76%, respectively, including oceans and Antarctica). Higher elevations are likelier to be erosional, with the world's lowlands and large rivers disproportionately depositional. Large parts of the world are not described by the source-to-sink model; these areas are mostly deserts or shields without substantial rivers or sediment transport. Even in areas that do resemble the classic textbook progression, systems show exceptional source-to-sink domain variability between catchments and down the world's major rivers. While the source-to-sink paradigm remains useful, it cannot describe the sedimentologically inactive areas that make up much of the world.

INTRODUCTION

Open many introductory Earth science textbooks and you will see Earth's surface depicted as a source-to-sink profile (Fig. 1A; e.g., Tarbuck et al., 2019). This paradigm illustrates the first-order control of tectonics on surface processes, where sediment is generated from uplifting mountains (sources), moves downstream through tectonically stable regions (bypass), and deposits in subsiding basins, deltas, and the ocean (sinks; Meade, 1982). This paradigm has been used to understand petroleum reservoirs (Bhattacharya et al., 2016), carbon cycling (Leithold et al., 2016), geohazards (Driscoll and Nittrouer, 2000), landscape preservation in the rock record (Weissmann et al., 2015), and climate and tectonic signals in stratigraphy (Romans et al., 2016; Straub et al., 2020).

Despite the importance of source-to-sink sediment transport in Earth science, the framework has never been tested across the modern Earth surface. This has left basic knowledge gaps in sedimentology and Earth surface processes; we do not know Earth's relative abundance of sources, bypass zones, and sinks. Even more fundamentally, we have yet to test whether Earth's surface resembles classic source-to-sink depictions and conceptual models. If there are areas that do not fit the source-to-sink framework, it is unclear how they should appear and which criteria distinguish them from regions that do.

MAPPING GLOBAL SOURCE-TO-SINK DOMAINS

We harmonized a series of interpreted and remotely sensed data products to create a global database of Earth's sediment sources, bypass zones, and sinks (Figs. 1C, Supplemental Material S1[1]). Using the Global Islands data set (Sayre et al., 2023), which derived shorelines from Landsat images, we defined anything oceanward of the shoreline as a sink. While all oceanic deposits are definitionally below base level and thus within stratigraphic accommodation, accumulation, and preservation space (Jervey, 1988; Blum and Törnqvist, 2000), this definition is nonetheless a simplification of complex marine margin processes that deposit, resuspend, mix, and further transport sediment through subaqueous deltas (Steel et al., 2024). We did not map Antarctica due to a lack of data, but we assume it is erosional due to pervasive ice sheets (Nyberg and Howell, 2015). Elsewhere, we classified glacial or perennial ice areas as sources using the Pelletier et al. (2016) and GUM (Global Unconsolidated Sediments Map) databases (Börker et al., 2018). Areas identified by Nyberg and Howell (2015) as sedimentary basins were marked as sinks. These authors mapped modern basins as analogs for stratigraphic deposits by identifying broad, flat areas with recent surface deposits and using iterative rules and manual interpretation to include known subsiding basins and exclude known areas of erosion. We also classified 1.4 million lakes in the HydroLAKES data set (Messager et al., 2016) as sinks. In our scheme, any lowland that is not classified as a sedimentary basin must be a bypass zone. Thus, alluvial channel-belts that temporarily store sediment in their floodplains but are not in subsiding basins are considered bypass, not sinks, as they are unlikely to preserve sediment beyond $\sim 10^5$ yr time scales (Geyman et al., 2025). To distinguish between sources and bypass, we used the uplands and lowlands classifications, respectively, of Pelletier et al. (2016). These authors identified young or continuous sedimentary deposits as lowlands and older or discontinuous regions as uplands. They added bespoke rules for glaciated areas and a global inundation and flow-routing model that accumulated flow, assuming that areas above a depth threshold were lowlands. We found that some mountain regions were misclassified as lowlands (Fig. S2), which we fixed

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[1]Supplemental Material. Additional methodological details. Please visit https://doi.org/10.1130/GEOL.S.29448395 to access the supplemental material; contact editing@geosociety.org with any questions.

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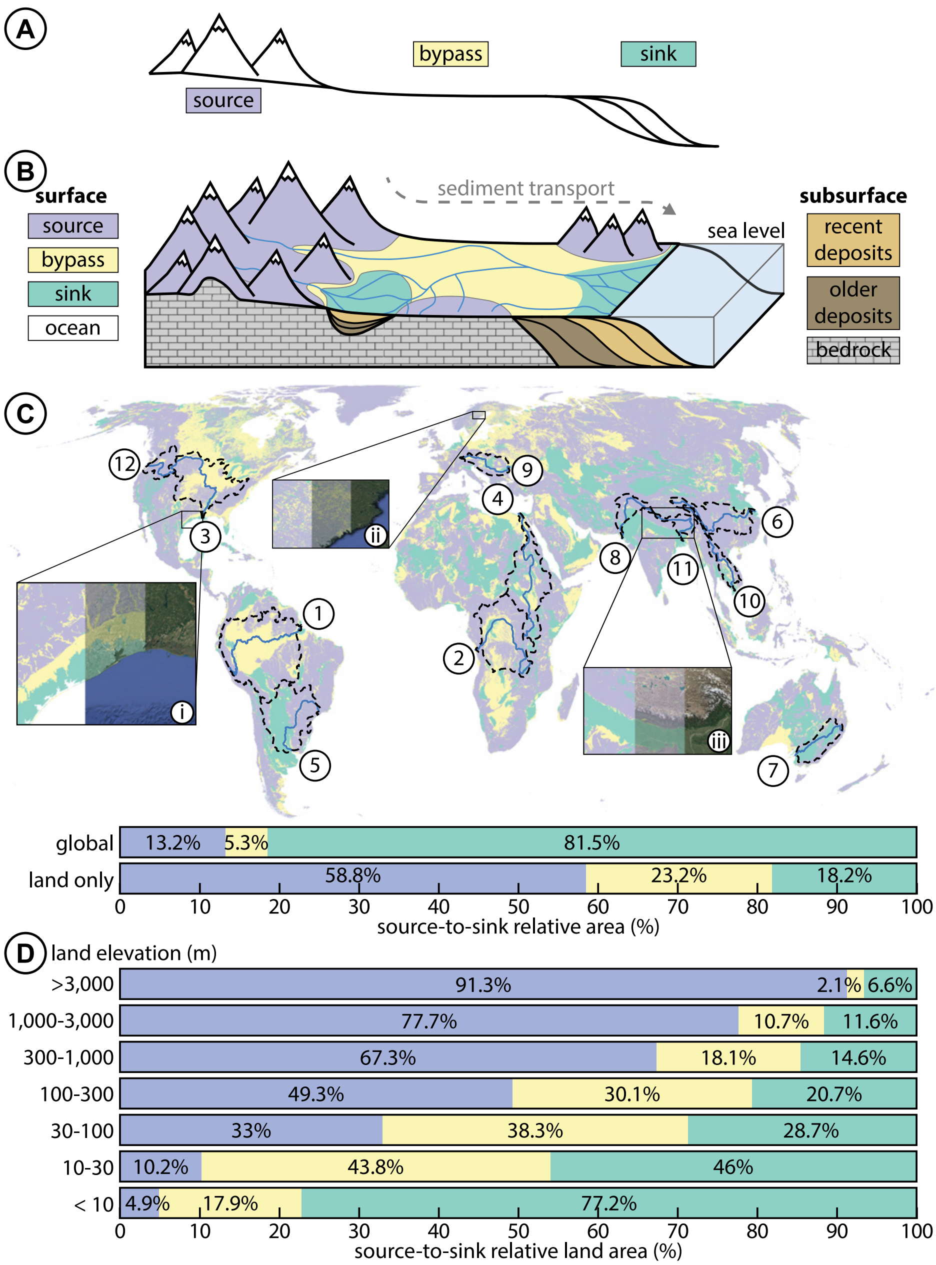

Figure 1. (A) 1-D source-to-sink diagram after Castelltort and Van Den Driessche (2003). (B) 2-D diagram adding complexity. (C) Global map of source-to-sink domains, with some major systems highlighted and numbered corresponding to Figure 4. Oceans shown in white for clarity. Relative global and land domain areas below. Inset satellite images © Google Satellite. (D) Relative land domain areas by binned elevation.

using Hammond's (1954, 1964) landscape classifications to reclassify all "lowland" mountain areas as sources (Karagulle et al., 2017). Finally, we infilled remaining no-data pixels <500 m from lakes or <250 m from intertidal zones (Murray et al., 2019) as sinks. About 0.3% of non-Antarctic land remained unclassified.

To evaluate uncertainty, we compared our global map against previously published data sets of features that we correlated to surface elements of source to sink systems, including distributive fluvial systems, avulsions, and a detailed map of surficial geology across 753,220 km^2 of the southern USA (see "validation and uncertainty" in the Supplemental Material). Our global map agreed with 73%–95% of local observations in each data set (Figs. S3 and S4).

GLOBAL MAP RESULTS

We created a spatially continuous high-resolution (250 m) global map of source, bypass, and sink domains (Martin and Lamb, 2025). Our map indicates that more than half of Earth's land surface is erosional (59%), with the remainder split between bypass (22%) and sink (19%; Fig. 1C). Including oceans and Antarctica changes the distribution to 18% source, 6% bypass, and 76% sink. All domains appear in all climate settings and at all mapped latitudes (Fig. S5). The major mountain chains of the world appear as contiguous strips of sediment source areas with isolated, coaligned pockets of extensional or strike-slip sinks (e.g., western USA). These higher elevations are dominated by sources (Fig. 1D). The largest contiguous bypass regions are infilled sedimentary basins (e.g., Amazon River basin). Sinks are the smallest areal component of the land surface. They mostly represent subaerial subsiding deltas, isolated mountainous endorheic basins, lakes, and inland distributive fluvial systems (Weissmann et al., 2015). More than three quarters of the land below 10 m elevation is a sink and thus has potential to be preserved in the rock record (Fig. 1D).

Knowing the location of sediment sources, bypass, and sinks allows for quantitative tests of stratigraphic community hypotheses. As an example, it has long been recognized that some types of rivers will be preferentially preserved in the stratigraphic record over others (Friend, 1978), but we have an opportunity to systematically test this idea. To do so, we chose to evaluate rivers by Strahler stream order as a proxy for size. As a caveat, while global mean water discharge monotonically increases with Strahler order (Fig. 2), the sizes of rivers in distributive systems are not represented well by Strahler classification, as progressively smaller channels inherit the higher Strahler order of their upstream channels, exaggerating their order relative to their size (Sah and Das, 2017). Nonetheless, we evaluated all pixels containing the 2,705,080 reaches (total length = 1.06×10^7 km) in the HydroRIVER (Lehner and Grill, 2013) global data set of topography-derived river locations with a modeled water discharge >0.75 m^3/s (Fig. S6). We found that headwater channels (lower-order, proximal) are disproportionately located in sources, while trunk channels (larger-order, distal) disproportionately occur in sinks (Fig. 2). Rivers of stream order ≤ 3 are less likely to be preserved in the rock record than the global land average, while those ≥ 4 are disproportionately likely to be preserved. This trend holds globally despite not controlling for climate, tectonics, lithological setting, or any other variables and suggests that the world's largest rivers are likely to be preserved.

If we assumed the source-to-sink diagram of Figure 1A applied to the entire Earth as a null hypothesis, we should expect to see concentric bands of sink, bypass, and source ringing coastlines. Some areas with ample relief and substantial rivers do resemble this assumption, especially passive margins like the eastern U.S. seaboard where source-to-sink theories were first formalized (Meade, 1972, 1982) or the Gulf Coastal Plains of North America ("i" in Fig. 1C). Most of the world, however, is a

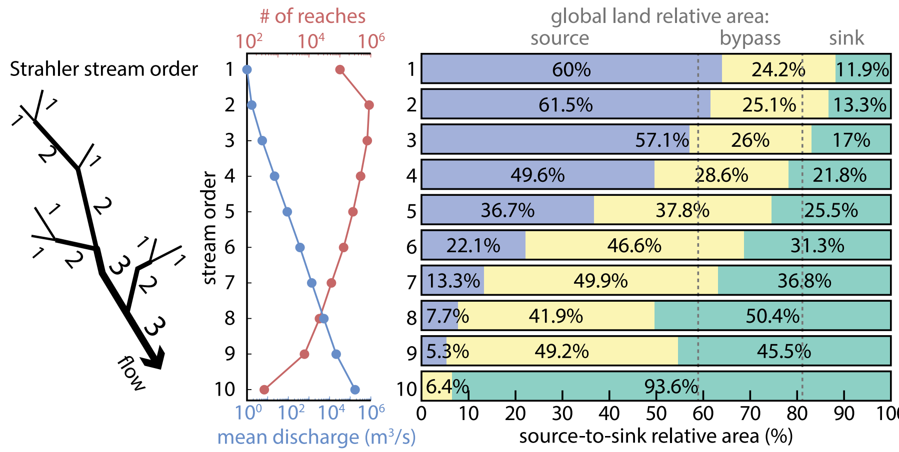

Figure 2. Discharge, count, and source-to-sink distribution of global rivers, classified by Strahler stream order, with discharge >0.75 m³/s. For context, gray dashed lines show the global non-river source-to-sink relative areas.

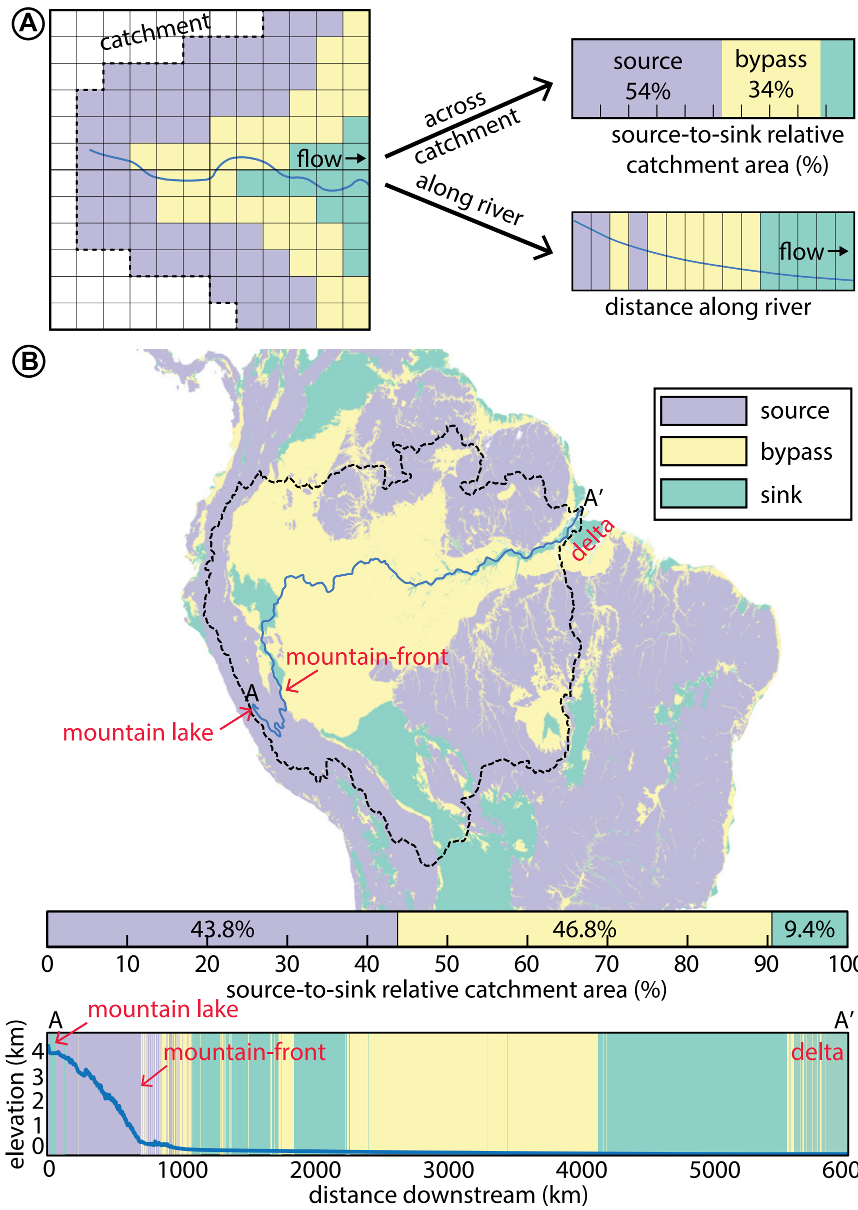

Figure 3. (A) Schematic example of how we calculated source-to-sink abundances across catchments and along rivers. (B) Example application to the Amazon River.

mosaic where all three domains can abut the ocean. Large regions are not well-described by the source-to-sink paradigm, such as very-low-relief areas like shields or recently glaciated terrains (e.g., Baltic Shield; "ii" in Fig. 1C). These anomalies exist perhaps because flat crystalline basement rocks yield little sediment, and glaciated landscapes are too pockmarked by small lakes to form large drainage areas. Regions with predominantly aeolian sediment transport also do not fit the typical progression (e.g., Sahel and Sahara; Fig. 1C). Finally, endorheic mountain ranges are mosaics of sources with scattered extensional, strike-slip, or anthropogenic dammed reservoir sinks (Fig. S7) and no clear overall sediment transport direction (e.g., North American Basin and Range Province, Tibetan Plateau; top of "iii" in Fig. 1C).

RIVER AND CATCHMENT ANALYSIS

We also compared individual source-to-sink systems ("sediment routing systems" sensu Allen, 2017) to the conceptual model by analyzing rivers and their catchments. Rivers carry most of the world's sediment, organic carbon, and nutrients from land to oceans (Paola et al., 2006), and their spatially discrete and contiguous catchments sample most of Earth's surface.

We analyzed 12 of the world's largest rivers and their catchments (Table S1; Best, 2019). These rivers sample a wide range of tectonic and climatic zones (Figs. S5 and S7), collectively drain 17% of Earth's land area, and represent 30% of annual global river discharge (Collins et al., 2024) and 12% of sediment flux to oceans (Milliman and Farnsworth, 2011). We extracted the series of pixels that each river intersects from its headwater to its terminus and plotted it as a background color along-stream (Fig. 3A). For example, following the Amazon River downstream shows a broad source-to-sink trend with local complexity from features like Lake Junin (Fig. 3B). We also analyzed each river catchment by summing the source, bypass, and sink pixels in its drainage area (Fig. 3A). Thus, the relative abundance of source, bypass, and sink along a river can be different from across its catchment.

The major river analyses show that rivers frequently encounter and re-encounter many intermediate sinks and even sources as they move downstream (Fig. 4). Downstream transitions from sinks to sources or bypass are common, despite violating the schematic generalized trend. There is also considerable variability between rivers. Some, such as the Murray-Darling, follow large terrestrial sinks with little source or bypass, while others, such as the Yangtze, are dominated by sources. Catchments have widely variable relative abundances of source, bypass, and sinks between the 12 systems, but systematically contain proportionally more source and less sink than their rivers encounter (Figs. 3B and 4).

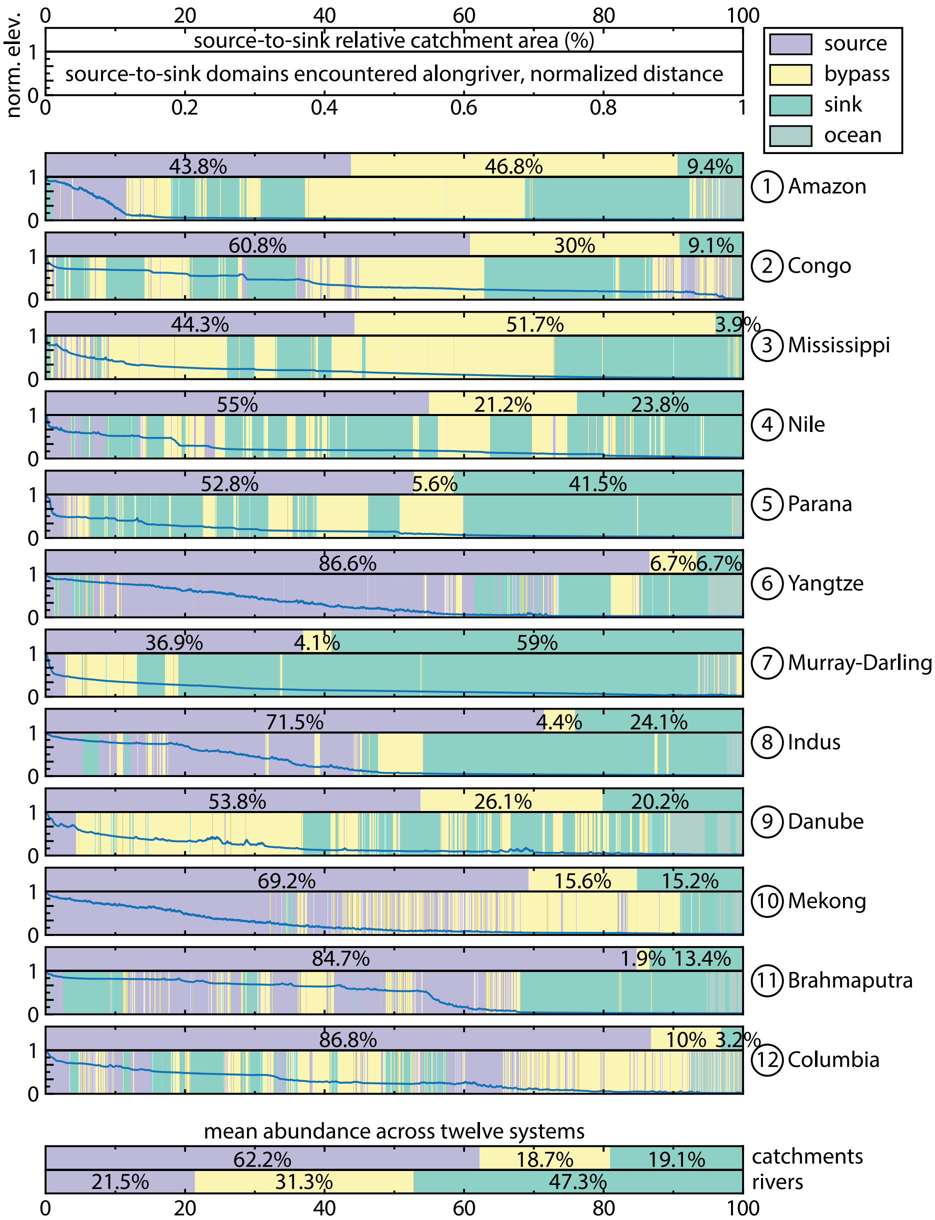

Figure 4. Source-to-sink analyses for the catchments and rivers of 12 major source-to-sink systems. Normalized river elevation profiles shown in blue. Below is the mean catchment and along-river abundance across the 12 systems.

DISCUSSION

Earth's land is mostly eroding. The sources that feed the source-to-sink cycle, however, are a small areal fraction of the planet when oceans are also considered. Further, not all sources are made alike. Our criteria included both quickly eroding steep mountains and slowly eroding flat shields as sources despite their vastly different impacts on the global sediment cycle. Similarly, bypass zones can include tectonically inactive areas far away from the influence of rivers, glaciers, or aeolian processes. Despite the dominance of the source-to-sink paradigm in Earth science, much of the world is made up of these understudied, low-elevation, flat sources or distal bypass regions that are not represented by the source-to-sink framework as they do not substantially participate in source-to-sink systems. We propose that the source-to-sink framework requires a fourth category for sedimentologically "inactive" landscapes, defined by choosing threshold time scales and elevation change rates of interest, before it can be used to understand the full suite of Earth surface processes.

One common factor of inactive areas is that they generally lack substantial rivers. This suggests that rivers are the key component of source-to-sink systems as classically conceptualized. Among parts of Earth that do resemble textbook source-to-sink systems, there is considerable variability between systems in the relative abundance and sequences of source, bypass, and sink domains along rivers. This variability does not obviously scale with catchment area, river discharge, or sediment flux (Figs. S8–S10), but differences in bypass abundance between systems do imply different abilities to record climate or tectonic signals as they propagate from sources where they are generated to sinks where they are recorded. This is because bypass regions temporarily store sediment through lateral, not vertical, aggradation, leaving deposits susceptible to reworking (Durkin et al., 2018) that delays or obscures signals (Straub et al., 2020). More specifically, a system's ability to accurately record climate and tectonic signals should vary with the distance between source and sink and the relative length of any bypass regions that separate them. While it is not always easy to measure these distances in ancient systems, studying modern systems through the source-to-sink lens helps contextualize stratigraphic paleogeographic interpretations and the extent to which ancient systems could record useful environmental signals.

Our analysis was necessarily limited to the current Earth surface and thus represents one snapshot in time. In deep time, however, plate tectonics have shaped and reshaped continents and could thus have led to shifts in relative abundances of each domain across Earth's history. Periods such as the Cretaceous lacked significant mountain-building continent-continent collisions (Scotese et al., 2025), causing lower and more easily flooded continents and likely driving an overall shift from sources to sinks. Discerning these preservation biases over geologic time will require more fully coupled modeling of continental evolution and source-to-sink transport (e.g., Salles et al., 2023).

CONCLUSIONS

We classified Earth's surface according to the source-to-sink framework. The data set is online at https://sourcetosink.mapsof.rocks. We demonstrated that source, bypass, and sink are 59%, 22%, and 19% of the land, respectively, or 18%, 6%, and 76% of the globe. Erosional areas are a large part of the land but a small fraction of the world. There are relatively few regions that resemble "typical" source-to-sink diagrams. These areas are usually passive margins with substantial rivers. Large regions of Earth do not fit the source-to-sink paradigm well. These areas are usually flat, sedimentologically inactive, and lack substantial rivers. These areas are understudied but represent much of Earth's surface. Rivers with Strahler order ≤ 3 are less likely to be preserved than the global land average, while those ≥ 4 are disproportionately likely to be preserved. We analyzed 12 major rivers, finding exceptional variability in the abundance and order of source-to-sink domains between and along rivers and their catchments. The cause for the variability between systems is not clear but may reflect differences between large-scale tectonic domains. Though sedimentologically inactive areas evolve slowly and do not participate in larger-scale source-to-sink systems, they make up much of Earth and deserve both recognition and further study.

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REFERENCES CITED

Allen, P.A., 2017, Sediment Routing Systems: The Fate of Sediment from Source to Sink: Cambridge, UK, Cambridge University Press, 407 p., https://doi.org/10.1017/9781316135754.

Best, J., 2019, Anthropogenic stresses on the world's big rivers: Nature Geoscience, v. 12, p. 7–21, https://doi.org/10.1038/s41561-018-0262-x; erratum available at https://doi.org/10.1038/s41561-018-0295-1.

Bhattacharya, J.P., Copeland, P., Lawton, T.F., and Holbrook, J., 2016, Estimation of source area, river paleo-discharge, paleoslope, and sediment budgets of linked deep-time depositional systems and implications for hydrocarbon potential: Earth-Science Reviews, v. 153, p. 77–110, https://doi.org/10.1016/j.earscirev.2015.10.013.

Blum, M.D., and Törnqvist, T.E., 2000, Fluvial responses to climate and sea-level change: A review and look forward: Sedimentology, v. 47, p. 2–48, https://doi.org/10.1046/j.1365-3091.2000.00008.x.

Börker, J., Hartmann, J., Amann, T., and Romero-Mujalli, G., 2018, Terrestrial sediments of the earth: development of a Global Unconsolidated Sediments Map database (GUM): Geochemistry, Geophysics, Geosystems, v. 19, p. 997–1024, https://doi.org/10.1002/2017GC007273.

Castelltort, S., and Van Den Driessche, J., 2003, How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record?: Sedimentary Geology, v. 157, p. 3–13, https://doi.org/10.1016/S0037-0738(03)00066-6.

Collins, E.L., David, C.H., Riggs, R., Allen, G.H., Pavelsky, T.M., Lin, P., Pan, M., Yamazaki, D., Meentemeyer, R.K., and Sanchez, G.M., 2024, Global patterns in river water storage dependent on residence time: Nature Geoscience, v. 17, p. 433–439, https://doi.org/10.1038/s41561-024-01421-5.

Driscoll, N., and Nittrouer, C., 2000, Source to sink studies: Margins, newsletter no. 5, workshop report, p. 1–3.

Durkin, P.R., Hubbard, S.M., Holbrook, J., and Boyd, R., 2018, Evolution of fluvial meander-belt deposits and implications for the completeness of the stratigraphic record: Geological Society of America Bulletin, v. 130, p. 721–739, https://doi.org/10.1130/B31699.1.

Friend, P.F., 1978, Distinctive features of some ancient river systems, *in* Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 531–542.

Geyman, E.C., Ke, Y., Magyar, J.S., Reahl, J.N., Soldano, V., Brown, N.D., West, A.J., Fischer, W.W., and Lamb, M.P., 2025, Scaling laws for sediment storage and turnover in river floodplains: Science Advances, v. 11, https://doi.org/10.1126/sciadv.adu8574.

Hammond, E.H., 1954, Small-scale continental landform maps: Annals of the Association of American Geographers, v. 44, p. 33–42, https://doi.org/10.1080/00045605409352120.

Hammond, E.H., 1964, Analysis of properties in land form geography: An application to broad-scale land form mapping: Annals of the Association of American Geographers, v. 54, p. 11–19, https://doi.org/10.1111/j.1467-8306.1964.tb00470.x.

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, *in* Wilgus, C.K., Hastings, B.S., Posamentier, H., Van Wagoner, J., Ross, C.A., and Kendall, C.G.St.C., eds., Sea Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 47–69, https://doi.org/10.2110/pec.88.01.0047.

Karagulle, D., Frye, C., Sayre, R., Breyer, S., Aniello, P., Vaughan, R., and Wright, D., 2017, Modeling global Hammond landform regions from 250-m elevation data: Transactions in GIS, v. 21, p. 1040–1060, https://doi.org/10.1111/tgis.12265.

Lehner, B., and Grill, G., 2013, Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems: Hydrological Processes, v. 27, p. 2171–2186, https://doi.org/10.1002/hyp.9740.

Leithold, E.L., Blair, N.E., and Wegmann, K.W., 2016, Source-to-sink sedimentary systems and global carbon burial: A river runs through it: Earth-Science Reviews, v. 153, p. 30–42, https://doi.org/10.1016/j.earscirev.2015.10.011.

Martin, H.K., and Lamb, M.P., 2025, Global Source-to-sink Domain Map: Figshare, https://doi.org/10.6084/m9.figshare.28432280.

Meade, R.H., 1972, Transport and deposition of sediments in estuaries, *in* Swift, D.J.P., Duane, D.B., and Pilkey, O.H., eds., Shelf sediment transport: process and pattern: Stroudsburg, Pennsylvania, Dowden, Hutchinson & Ross, Inc., p. 249–262.

Meade, R.H., 1982, Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States: The Journal of Geology, v. 90, p. 235–252, https://doi.org/10.1086/628677.

Messager, M.L., Lehner, B., Grill, G., Nedeva, I., and Schmitt, O., 2016, Estimating the volume and age of water stored in global lakes using a geo-statistical approach: Nature Communications, v. 7, https://doi.org/10.1038/ncomms13603.

Milliman, J.D., and Farnsworth, K.L., 2011, River Discharge to the Coastal Ocean: A Global Synthesis: Cambridge, United Kingdom, Cambridge University Press, 384 p, https://doi.org/10.1017/CBO9780511781247.

Murray, N.J., Phinn, S.R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M.B., Clinton, N., Thau, D., and Fuller, R.A., 2019, The global distribution and trajectory of tidal flats: Nature, v. 565, p. 222–225, https://doi.org/10.1038/s41586-018-0805-8.

Nyberg, B., and Howell, J.A., 2015, Is the present the key to the past? A global characterization of modern sedimentary basins: Geology, v. 43, p. 643–646, https://doi.org/10.1130/G36669.1.

Paola, C., Foufoula-Georgiou, E., Dietrich, W.E., Hondzo, M., Mohrig, D., Parker, G., Power, M.E., Rodriguez-Iturbe, I., Voller, V., and Wilcock, P., 2006, Toward a unified science of the Earth's surface: Opportunities for synthesis among hydrology, geomorphology, geochemistry, and ecology: Water Resources Research, v. 42, W03S10, https://doi.org/10.1029/2005WR004336.

Pelletier, J.D., Broxton, P.D., Hazenberg, P., Zeng, X., Troch, P.A., Niu, G.-Y., Williams, Z., Brunke, M.A., and Gochis, D., 2016, A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling: Journal of Advances in Modeling Earth Systems, v. 8, p. 41–65, https://doi.org/10.1002/2015MS000526.

Romans, B.W., Castelltort, S., Covault, J.A., Fildani, A., and Walsh, J.P., 2016, Environmental signal propagation in sedimentary systems across timescales: Earth-Science Reviews, v. 153, p. 7–29, https://doi.org/10.1016/j.earscirev.2015.07.012.

Sah, K.S., and Das, A.K., 2017, Minimizing ambiguities in stream classification of complex drainage structures: Journal of Hydrology (Amsterdam), v. 553, p. 224–230, https://doi.org/10.1016/j.jhydrol.2017.07.047.

Salles, T., Husson, L., Rey, P., Mallard, C., Zahirovic, S., Boggiani, B.H., Coltice, N., and Arnould, M., 2023, Hundred million years of landscape dynamics from catchment to global scale: Science, v. 379, p. 918–923, https://doi.org/10.1126/science.add2541.

Sayre, R., 2023, Global Islands: U.S. Geological Survey data release, https://doi.org/10.5066/P91ZCSGM.

Scotese, C.R., Vérard, C., Burgener, L., Elling, R.P., and Kocsis, A.T., 2025, The Cretaceous world: Plate tectonics, palaeogeography and palaeoclimate, *in* Hart, M.B., et al., eds., Cretaceous Project 200 Volume 1: The Cretaceous World: Geological Society, London, Special Publication 544, p. 31–202, https://doi.org/10.1144/SP544-2024-28.

Steel, R., Osman, A., Rossi, V.M., Alabdullatif, J., Olariu, C., Peng, Y., and Rey, F., 2024, Subaqueous deltas in the stratigraphic record: Catching up with the marine geologists: Earth-Science Reviews, v. 256, https://doi.org/10.1016/j.earscirev.2024.104879.

Straub, K.M., Duller, R.A., Foreman, B.Z., and Hajek, E.A., 2020, Buffered, incomplete, and shredded: The challenges of reading an imperfect stratigraphic record: Journal of Geophysical Research: Earth Surface, v. 125, https://doi.org/10.1029/2019JF005079.

Tarbuck, E.J., Lutgens, F.K., Tasa, D.G., and Linneman, S., 2019, Earth: An Introduction to Physical Geology: London, England, Pearson Publishing, 13th edition, 784 p.

Weissmann, G.S., Hartley, A.J., Scuderi, L.A., Nichols, G.J., Owen, A., Wright, S., Felicia, A.L., Holland, F., and Anaya, F.M.L., 2015, Fluvial geomorphic elements in modern sedimentary basins and their potential preservation in the rock record: A review: Geomorphology, v. 250, p. 187–219, https://doi.org/10.1016/j.geomorph.2015.09.005.

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