Global extent of rivers and streams

George H. Allen*† and Tamlin M. Pavelsky

The turbulent surfaces of rivers and streams are natural hotspots of biogeochemical exchange with the atmosphere. At the global scale, the total river-atmosphere flux of trace gasses such as carbon dioxide depends on the proportion of Earth's surface that is covered by the fluvial network, yet the total surface area of rivers and streams is poorly constrained. We used a global database of planform river hydromorphology and a statistical approach to show that global river and stream surface area at mean annual discharge is 773,000 ± 79,000 square kilometers (0.58 ± 0.06%) of Earth's nonglaciated land surface, an area 44 ± 15% larger than previous spatial estimates. We found that rivers and streams likely play a greater role in controlling land-atmosphere fluxes than is currently represented in global carbon budgets.

Water interacts with the atmosphere in a series of complex biogeochemical processes at the water-atmosphere interface as it flows down Earth's rivers and streams (*1*–*5*). At this interface, equilibrium reactions drive mass and energy exchange, amounting to considerable material flux at the global scale (*4*–*6*). For example, estimated outgassing from rivers and streams introduces ~1.8 Pg of carbon per year as carbon dioxide to the atmosphere (*1*), roughly equivalent to one-fifth of combined emissions from fossil fuel combustion and cement production (*7*). Globally, the rates of these processes are partly controlled by the total river and stream surface area (RSSA), which acts as the medium of exchange between the fluvial network and the atmosphere (*1*, *2*, *4*–*6*). Despite the fact that RSSA is one of the principal parameters in large-scale evaluations of river-atmosphere biogeochemical and thermal flux (*1*, *2*, *5*, *6*), the field of large-scale river hydrology has primarily focused on quantifying the volume of water that rivers and streams transport to the ocean, rather than RSSA (*2*, *8*).

Only two studies have attempted to estimate global RSSA to date. In a pioneering effort, Downing *et al.* (*2*) developed stream-order scaling relationships between river width and length under the assumption that all rivers belong to a single branching river network. They made two global RSSA estimates: 485,000 km^2, based on an aggregate estimate of RSSA for rivers wider than 90 m, and 682,000 km^2, based on the length and width of the Amazon trunk river. Raymond *et al.* (*1*) remain the only group to estimate the spatial variability of RSSA globally. They arrived at a total RSSA estimate of 536,000 km^2 (excluding Greenland, Antarctica, and the seasonal effects of freezing rivers on RSSA) by applying a flow-routing algorithm to digital topography and assuming globally constant hydraulic geometry relationships between river width and discharge (*9*). Both of these previous studies are limited by the lack of direct observations of RSSA, quantification of statistical uncertainty, and consideration of regional variability in hydraulic geometry. We used satellite observations of rivers and a statistical approach to produce a direct estimate of river and stream coverage at the global scale.

We built the Global River Widths from Landsat (GRWL) Database to characterize the global coverage of rivers and streams. The GRWL Database is the first global compilation of river planform geometry at a constant-frequency discharge (Fig. 1). We used a global database of 3693 gauge stations (*10*) to determine months that rivers were commonly near mean discharge (fig. S1). Then we acquired 7376 Landsat TM (Thematic Mapper), ETM+ (Enhanced Thematic Mapper Plus), and OLI (Operational Land Imager) scenes captured during these months. We applied previously published image processing techniques (*11*, *12*) to classify rivers and measure their location, width, and braiding index. The GRWL Database contains planform measurements of >2.1 million km (>58 million measurements) of rivers ≥30 m wide at mean annual discharge. It also contains >7.6 million flagged measurements of lakes, reservoirs, and canals connected to the fluvial network. We validated the Landsat-derived width data by using in situ river width measurements from the U.S. Geological Survey and the Water Survey of Canada taken at 1250 gauge stations (Fig. 2) (*13*). We found that GRWL width data are most accurate and complete at widths wider than 90 m (about three Landsat pixels), and thus we considered only rivers wider than this width to assess the statistical distributions of RSSA (*11*, *12*, *14*).

The freely available GRWL vector product and water mask have considerable potential to improve the representation of large-scale fluvial processes and understanding of river resources (*15*). Although other empirical datasets of river width exist, their coverage is not global, or their coarse spatial resolution limits their usefulness for river system models (*11*, *14*, *16*). Subsets of the GRWL data are already being used to improve hydrologic models (*17*), organize remotely sensed surface-water observations (*18*), and improve biogeochemical efflux estimates (*11*). The database will also be used to identify river segments observable by the NASA and Centre National d'Etudes Spatiales SWOT (Surface Water and Ocean Topography) satellite, scheduled to launch in 2021 (*19*). Further, the GRWL Database has applications for fluvial geomorphology (e.g., studies of river sinuosity), determining spatiotemporal variations in river discharge

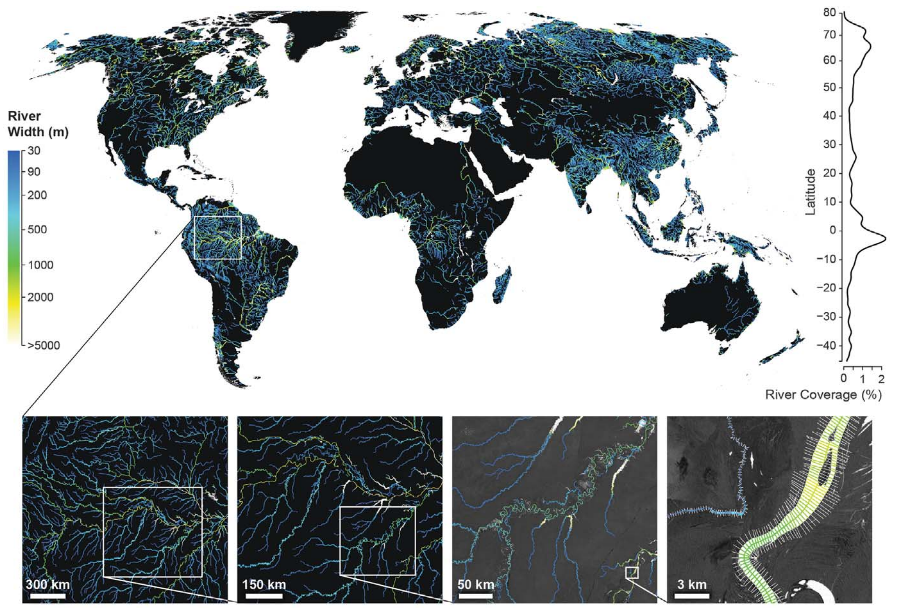

Fig. 1. The Global River Widths from Landsat (GRWL) Database contains more than 58 million measurements of planform river geometry. The line plot on the right shows observed river coverage as a percentage of land area by latitude, and the bottom insets show GRWL at increasing zoom. The rightmost inset shows GRWL orthogonals over which river width was calculated, with only every eighth orthogonal shown for clarity.

Department of Geological Sciences, University of North Carolina, Chapel Hill, NC, USA.
*Present address: Department of Geography, Texas A&M University, College Station, TX, USA.
†Corresponding author. Email: georgehenryallen@gmail.com

at the global scale (*20*), and organizing large multitemporal datasets of surface-water dynamics (*21*).

This newly assembled database of river hydromorphology allows direct quantification of RSSA for large, observable rivers. By summing the product of each river width measurement and its corresponding downstream pixel length (Fig. 3A), the total observed area of rivers measured by the GRWL Database is 468,000 km^2, or 0.35% of Earth's nonglaciated land surface. We excluded reservoirs, lakes, canals, Antarctica, Greenland, and any water bodies measured at mean sea level (*22*) from this analysis to make it comparable to previous studies. The total surface area of rivers wider than 90 m, where GRWL data are most complete and accurate, is 404,000 km^2, which exceeds a previous aggregate estimate of 360,000 km^2 (*2*).

To estimate the surface area of streams and rivers too narrow to accurately observe from Landsat imagery (widths < 90 m), we split GRWL measurements into major global drainage basins (*22*) and grouped these drainage basins into three categories: basins that contain >250,000 measurements (class A), basins that contain 10,000 to 250,000 measurements (class B), and basins that contain ≤10,000 measurements (class C) (Fig. 3B). In class A basins (n = 20), we estimated the total RSSA by extending a fitted Pareto frequency distribution down to the median first-order wetted stream width of 32 ± 8 cm (*23*) (Fig. 3C). Both theoretical (*24*, *25*) and empirical (*2*, *25*, *26*) evidence indicates that RSSA is fractal down to first-order streams, although this assumption should be tested. In class B basins (n = 273), which have insufficient GRWL data to exhibit a well-developed fractal RSSA distribution, we used the average Pareto shape parameter established in class A basins (fig. S2) to extend the RSSA distribution to first-order streams (Fig. 3D). Class C basins have very little GRWL data, so we developed an empirical power-law relationship between climate aridity (*27*), basin area (*22*), and percent basin occupied by RSSA (coefficient of determination R^2 = 0.68; Fig. 3E). This relationship is noteworthy because it indicates a link between variations in climate and the extent of rivers and streams at a global scale (*1*). Adding together the RSSA contained in all basins, the global surface area of rivers and streams at mean annual discharge is 773,000 ± 79,000 km^2, or 0.58 ± 0.06% of Earth's nonglaciated land surface (Fig. 4A). We used a Monte-Carlo simulation to calculate the uncertainty of our RSSA estimates in each global

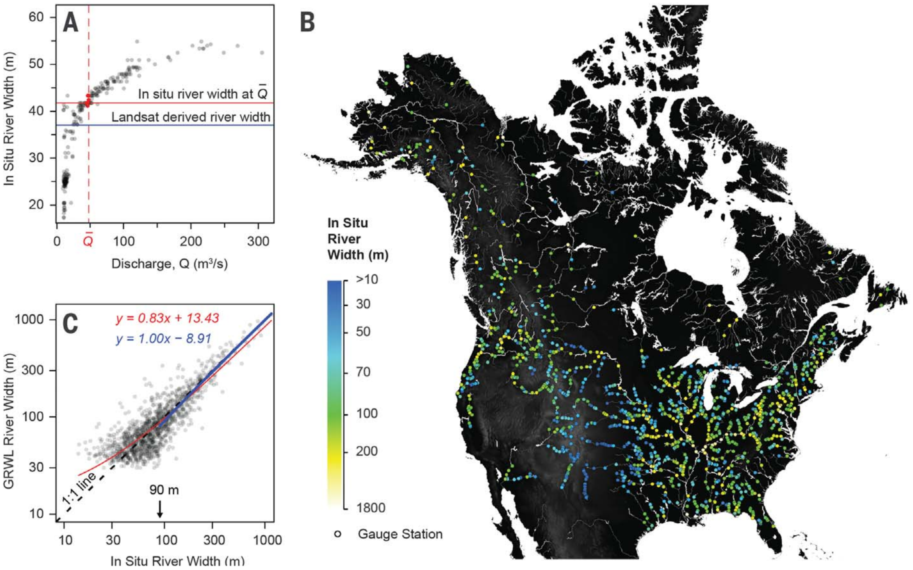

Fig. 2. Validating remote sensing measurements. (**A**) Example of an in situ river discharge-width rating curve used to validate Landsat measurements. (**B**) Gauge stations used in validation, colored by in situ width at mean annual discharge ($\bar{Q}$). (**C**) In situ river widths compared with corresponding Landsat-derived GRWL river widths. Red line, fit to all data; blue line, fit to in situ widths wider than 90 m.

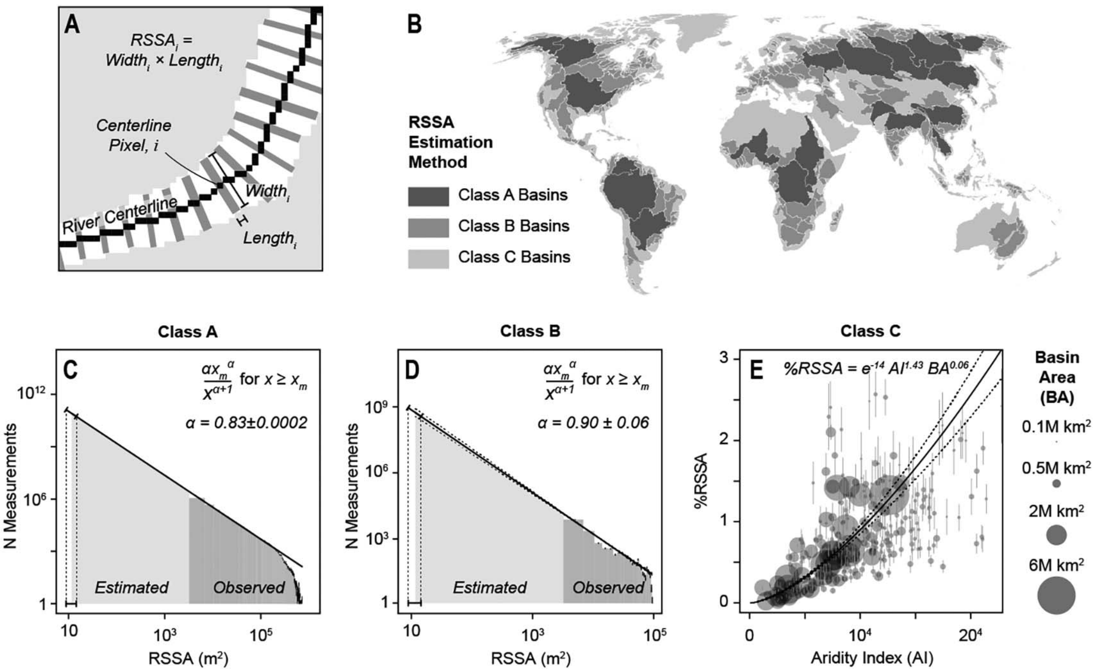

Fig. 3. Estimating the global surface area of rivers and streams. (**A**) Schematic of discretized river and stream surface area measurements (RSSA$_i$, gray bars), with only every fourth measurement shown for clarity. At a given river centerline pixel i, RSSA$_i$ is the product of the river width and the downstream pixel length. (**B**) Map of basins by class; a different RSSA estimation method was used for each class. (**C**) RSSA in class A basins, estimated using a Pareto distribution fit on observed wide rivers and extrapolated to narrower streams unobservable from Landsat (the Amazon basin is shown as an example; see section 2 of the supplementary materials). Throughout the figure, vertical black lines on observed RSSA bins show 1σ uncertainty of GRWL width measurements, and dotted lines are 1σ uncertainty bounds. (**D**) RSSA in class B basins, estimated using a Pareto distribution with a fixed shape parameter, α, fit on observed wide rivers and extrapolated to narrower streams (the Delaware basin is shown as an example). (**E**) RSSA in class C basins, estimated using weighted multiple linear regression of log-transformed percent RSSA (%RSSA) against aridity index and basin area in class A and B basins. Vertical gray lines show 1σ uncertainty bounds.

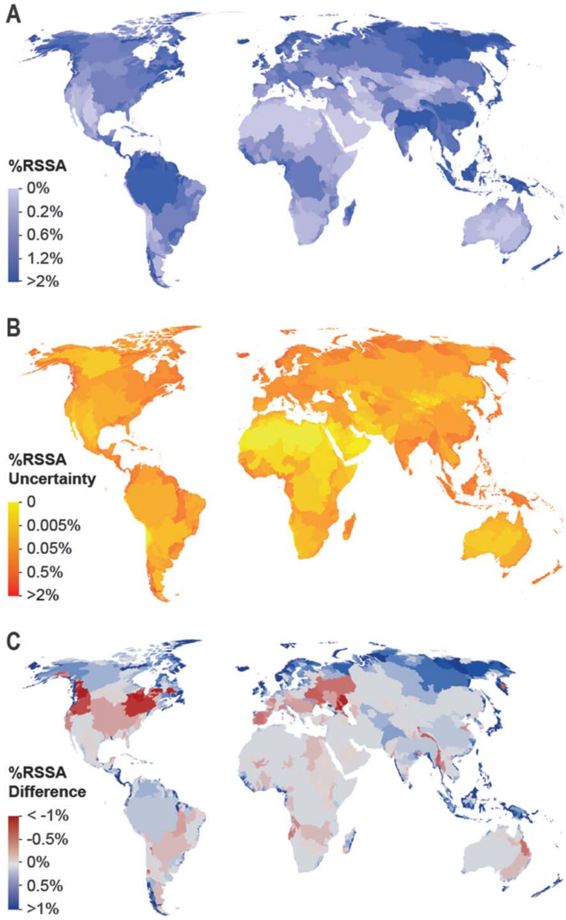

Fig. 4. Global patterns of stream and river coverage. (**A**) Percent of basin covered by river and stream surface area (%RSSA). (**B**) %RSSA uncertainty by basin. (**C**) %RSSA difference between this study and Raymond *et al*. (*1*).

basin, and we found that small, humid basins tend to exhibit the greatest uncertainty (n = 500; Fig. 4B) (*13*).

Our analysis shows that rivers and streams cover a larger portion of Earth's surface than previously estimated (*1*, *2*). We found a RSSA 44 ± 15% greater than that found by Raymond *et al*. (*1*), which is the only other geographically varying global estimate of RSSA (Fig. 4C). Our estimate is also 15 ± 12% greater than the maximum and 59 ± 16% greater than the minimum RSSA estimate from Downing *et al*. (*2*). In the Amazon basin, where a variety of methods have been used to estimate RSSA, we found that rivers and streams occupy 1.33 ± 0.02% of the basin at mean annual discharge, an area 6 to 67% greater than previous estimates (*1*, *28*, *29*). Compared with the current best region-by-region global estimate (*1*), we found more river and stream coverage in the Arctic and less in Europe, the conterminous United States, and some other economically developed regions (Fig. 4C). Previous estimates of global RSSA do not consider extra-climatic influences on RSSA, such as variations in fluvial geomorphology and human modifications to river channels, potentially resulting in an overestimate in some developed regions. For example, RSSA in many developed regions may be less than previously predicted owing to the influence of leveeing and water withdrawal in these areas.

The upward revision of the total global surface area of the fluvial network implies that interactions between rivers and the atmosphere are likely greater than previously thought. The upward revision is particularly pronounced in the Arctic, where the impacts of climate change on carbon fluxes are of major concern (*30*). Our findings also imply that the atmosphere plays a greater role in controlling the thermal dynamics and aquatic chemistry of river and stream water (*5*, *6*). The downward revision of RSSA in economically developed regions may be related to the large-scale impact of human modification on the fluvial network, although this hypothesis requires further testing. The largest sources of unquantified uncertainty in our RSSA estimate likely originate from the distribution of surface area for intermediate-sized rivers and streams and the seasonal variation of RSSA within river networks. As we develop analyses to address these uncertainties, our conclusions provide a robust first-order RSSA estimate that will be useful for improving the accuracy of large-scale fluvial biogeochemical fluxes.

REFERENCES AND NOTES

1. P. A. Raymond *et al*., *Nature* **503**, 355–359 (2013).
2. J. A. Downing *et al*., *Inland Waters* **2**, 229–236 (2012).
3. D. Bastviken, L. J. Tranvik, J. A. Downing, P. M. Crill, A. Enrich-Prast, *Science* **331**, 50 (2011).
4. E. R. Hotchkiss *et al*., *Nat. Geosci.* **8**, 696–699 (2015).
5. D. Butman *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **113**, 58–63 (2016).
6. D. Caissie, *Freshw. Biol.* **51**, 1389–1406 (2006).
7. G. P. Peters *et al*., *Nat. Clim. Chang.* **3**, 4–6 (2012).
8. A. Dai, in *Terrestrial Water Cycle and Climate Change* (John Wiley & Sons, 2016), pp. 17–37.
9. L. B. Leopold, T. Maddock Jr., "The hydraulic geometry of stream channels and physiographic implications" (USGS Professional Paper 252, U.S. Geological Survey, 1953).
10. Global Runoff Data Centre, Long-term mean monthly discharges and annual characteristics of GRDC stations (2017); available at www.bafg.de/.
11. G. H. Allen, T. M. Pavelsky, *Geophys. Res. Lett.* **42**, 395–402 (2015).
12. T. M. Pavelsky, L. C. Smith, *IEEE Geosci. Remote Sens. Lett.* **5**, 70–73 (2008).
13. Materials and methods are available as supplementary materials.
14. Z. F. Miller, T. M. Pavelsky, G. H. Allen, *Hydrol. Earth Syst. Sci.* **18**, 4883–4895 (2014).
15. M. P. Clark *et al*., *Water Resour. Res.* **51**, 5929–5956 (2015).
16. D. Yamazaki *et al*., *Water Resour. Res.* **50**, 3467–3480 (2014).
17. Y. Yoon, E. Beighley, H. Lee, T. Pavelsky, G. Allen, *J. Hydrol. Eng.* **21**, 05015030 (2016).
18. T. M. Pavelsky *et al*., *J. Hydrol. (Amst.)* **519**, 1516–1525 (2014).
19. S. Biancamaria, D. P. Lettenmaier, T. M. Pavelsky, *Surv. Geophys.* **37**, 307–337 (2016).
20. C. J. Gleason, L. C. Smith, *Proc. Natl. Acad. Sci. U.S.A.* **111**, 4788–4791 (2014).
21. J.-F. Pekel, A. Cottam, N. Gorelick, A. S. Belward, *Nature* **540**, 418–422 (2016).
22. B. Lehner, G. Grill, *Hydrol. Processes* **27**, 2171–2186 (2013).
23. G. H. Allen *et al*., *Nat. Commun.* **9**, 610 (2018).
24. J. W. Kirchner, *Geology* **21**, 591–594 (1993).
25. I. Rodríguez-Iturbe, A. Rinaldo, *Fractal River Basins: Chance and Self-Organization* (Cambridge Univ. Press, 2001).
26. M. E. Morisawa, *Geol. Soc. Am. Bull.* **73**, 1025–1046 (1962).
27. R. J. Zomer, A. Trabucco, D. A. Bossio, L. V. Verchot, *Agric. Ecosyst. Environ.* **126**, 67–80 (2008).
28. R. E. Beighley, V. Gummadi, *Earth Surf. Process. Landf.* **36**, 1059–1071 (2011).
29. L. L. Hess *et al*., *Wetlands* **35**, 745–756 (2015).
30. X. Feng *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **110**, 14168–14173 (2013).
31. G. H. Allen, T. M. Pavelsky, Global River Widths from Landsat (GRWL) Database. Zenodo (2018); https://doi.org/10.5281/zenodo.1297434.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/361/6402/585/suppl/DC1
Materials and Methods
Figs. S1 to S7
References (*32*–*42*)
Data S1

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