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Key Points:
- Lakes/reservoirs connected to rivers decrease in abundance, increase in size, but are uniform in spacing as river size increases
- River network topology with lakes/reservoirs can be classified into four types across the contiguous United States
- Climate is a major control of river network topology with lakes/reservoirs

Supporting Information:
- Supporting Information S1

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The Abundance, Size, and Spacing of Lakes and Reservoirs Connected to River Networks

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Abstract Descriptions of river network topology do not include lakes/reservoirs that are connected to rivers. We describe the properties and scaling patterns of river network topology across the contiguous United States: how lake/reservoir abundance, median lake/reservoir size, and median lake/reservoir spacing change with river size. Typically, lake/reservoir abundance decreases, median lake/reservoir size increases, but median lake/reservoir spacing is uniform across river size. There is a characteristic lake/reservoir size of 0.01–0.05 km^2 and a characteristic lake/reservoir spacing of 1–5 km that shifts to 27–61 km in larger rivers. Climate explains more of the variance in river network topology than both glacial history and constructed reservoirs. Our results provide conceptual models for building river network topologies to assess how lake/reservoir abundance, size, and spacing effect the transport, storage, and cycling of water, materials, and organisms across networks.

Plain Language Summary Rivers and lakes/reservoirs serve different hydrologic, ecologic, and economic roles and are often studied as separate systems. Yet there are many lakes/reservoirs connected to rivers and this connectivity has profound impacts on sediment storage and transport, biogeochemical cycles, and aquatic habitat in both rivers and lakes/reservoirs. Defining the topology of river networks is critical for understanding these processes across entire networks of connected rivers and lakes/reservoirs. We defined river network topology by scaling the abundance, size, and spacing of lakes/reservoirs with river size and identified broadscale controls of network topology.

1. Introduction

River networks and lakes/reservoirs are ubiquitous features of Earth's surface and global water cycle (Oki & Kanae, 2006). River networks form vast branching networks that connect continents to coasts (Allen & Pavelsky, 2018), and many lakes/reservoirs have a direct connection and are therefore part of the river network (Fergus et al., 2017; Hill et al., 2018; Lehner et al., 2011; Schmadel et al., 2018; Wetzel, 2001). However, descriptions of river network topology typically do not include connected lakes/reservoirs (Jones, 2010; Mark, 1983; Mark & Goodchild, 1982). Here we take the view that perennially connected lakes/reservoirs are part of the channel network, and we describe river network topology with lakes/reservoirs.

River network topology is often described using scaling laws fundamental to the fields of geomorphology, hydrology, and stream ecology (Dodds & Rothman, 1999, 2000; Leopold & Maddock, 1953; Maritan et al., 1996; Rinaldo et al., 2006; Vannote et al., 1980). Scaling laws are mathematical relationships that provide simple rules for how properties change across scales or sizes. For example, Horton's laws posit that the number of rivers, mean length of rivers, and watershed areas scale with river size, represented by stream order (Hack, 1957; Horton, 1945; Rodríguez-Iturbe & Rinaldo, 2001; Shreve, 1966; Strahler, 1957; Tarboton et al., 1988). Differences in hydrologic scaling laws across river basins has suggested different underlying geologies or topographies (Cox, 1989; Dunne, 1980), though scaling may be an inevitable property of any network (Kirchner, 1993).

Like river networks, lakes/reservoirs also have characteristic scaling laws (Cael & Seekell, 2016; Cael et al., 2017; Downing et al., 2006; McDonald et al., 2012). The global lake/reservoir size distribution has often been modeled as a Pareto distribution, meaning there are few large lakes/reservoirs and many small lakes/reservoirs, though the exact distribution has been debated (Cael & Seekell, 2016). River network and lake/reservoir scaling laws have been useful for understanding river network evolution and global hydrologic and biogeochemical cycles (Butman et al., 2016; Raymond et al., 2012; Tarboton et al., 1988), but they have described either lakes/reservoirs or rivers but not together.

We take an approach of blending scaling laws, hereafter referred to as *scaling patterns*, for rivers and lakes/reservoirs to describe river network topology. Despite the different mechanisms of formation —erosional mechanics due to geology, slope, climate, biology, and time in rivers (Dunne, 1980; Perron et al., 2012; Rinaldo et al., 1995; Schumm, 1956) versus glacial, tectonic, fluvial, volcanic, coastal, and/or anthropogenic processes that form lakes/reservoirs (Cohen, 2003; Meybeck, 1995)—deriving scaling patterns for river networks with lakes/reservoirs has broad implications. Scaling patterns provide simple rules for generating network topologies to model the effect of lakes/reservoirs on riverine, and vice versa, sediment transport (Arp et al., 2007; Czuba & Foufoula-Georgiou, 2015; Czuba et al., 2017), biogeochemical (Schmadel et al., 2018), and habitat fragmentation processes across networks (Fuller et al., 2015).

It is important to understand how lakes/reservoirs fit into river networks because lakes/reservoirs and rivers differ in their hydrologic, ecologic, and economic roles (Fergus et al., 2017; Jones, 2010; Sayer, 2014; Sedell et al., 1990). In the few cases where lakes/reservoirs have been explicitly included in studies of river networks, the implications have been profound. The world's largest reservoirs alone have increased the water residence time in rivers globally by 300% (Vorosmarty, 1997; Vörösmarty et al., 2000), trapped 20% of the global sediment flux to oceans (Syvitski et al., 2005) and accounted for 40% of global carbon burial within lakes and reservoirs combined (Mendonça et al., 2017). Further, lake/reservoir position, size, and shape affect nitrogen removal, and river networks with lakes/reservoirs generally remove more nitrogen than river networks without lakes/reservoirs (Schmadel et al., 2018). The topology of river networks with lakes/reservoirs —how the abundance, size, and spacing of lakes/reservoirs varies across river size—may therefore influence the aggregate processes that govern the geomorphic evolution of river channels, lakes/reservoirs, as well as how the role of rivers and lakes/reservoirs are interpreted in global hydrologic and biogeochemical cycles.

We describe river network topology with lakes/reservoirs by merging the National Hydrography Dataset (NHD) for lakes/reservoirs and the NHDplus for rivers within the contiguous United States. We identified lakes/reservoirs with a direct surface connection to river networks and quantified how lake/reservoir abundance, median lake/reservoir size (i.e., surface area), and median lake/reservoir spacing (i.e., distance along the river network to the closest downstream lake/reservoir) scale with river size, expressed as stream order, for perennial lakes/reservoirs connected to perennial river networks for all watersheds (~25,000 km^2) in the contiguous United States. We present the first measurements of lake/reservoir spacing across the United States, which is critical for understanding where lakes/reservoirs are located across river networks and measures how far water, materials, and organisms travel downstream until they encounter a lake. Together, lake/reservoir abundance, size, and spacing versus stream order describe the basic topology of lakes/reservoirs connected to river networks. We then relate the variability in these scaling patterns across different watersheds to hypothesized controls: climate, glacial history, and human modification via the construction of dams/reservoirs.

2. Materials and Methods

2.1. Data Overview

River networks were represented by the NHD-Plus (NHDPlus V2) for the contiguous United States (McKay et al., 2012) because it includes value-added attributes such as stream order, watershed area, and mean annual discharge (Moore & Dewald, 2016). We merged the NHDplus rivers with the high-resolution NHD lakes/reservoir data to integrate the most updated lake/reservoir data set while maintaining necessary value added attributed for rivers. Note that NHD generally does not distinguish lakes and reservoirs, and many reservoirs are labeled as lakes. Lakes/reservoirs were defined here as anything labeled lake or reservoir within NHD that has a surface area greater than 0.005 km^2. We chose the threshold of 0.005 km^2 because this is in-between minimum thresholds set by previous studies (0.001 km^2 [McDonald et al., 2012] and 0.04 km^2 [Fergus et al., 2017]), lakes/reservoirs smaller than 0.04 km^2 have higher digitization error rates (Soranno et al., 2015), and we focused on perennial lakes/reservoirs only. We excluded any feature identified as a wetland, estuary, or ephemeral/intermittent to isolate only perennial lakes/reservoirs connected to perennial river network. Connected lakes/reservoirs were then identified as the remaining lakes/reservoirs that spatially intersect the perennial river network and have surface water connectivity (an inlet and/or outlet) because a connected lake/reservoir of any size may influence geomorphic, ecological, and hydrologic processes of the connected river and vice versa. We recognize NHD data may not be accurate for the smallest rivers and lakes/reservoirs (Allen et al., 2018; Benstead & Leigh, 2012), but our results should not be impacted given our focus on perennial rivers/lakes/reservoirs at the spatial scale of Hydrologic Unit Code 6 (HUC6) watershed boundaries (~25,000 km^2) and the contiguous United States. A higher resolution river network data set would add mostly temporary streams, perhaps increasing the abundance of connected lakes/reservoirs in small streams, but without impacting downstream results.

Additional geospatial data included water availability, glacial extent, and location of dams across the contiguous United States. For water availability, we extracted the long-term (1981–2010) mean annual precipitation minus potential evapotranspiration over a 4-km grid using Google Climate Engine, which uses the PRISM and NLDAS-2 data products (Huntington et al., 2017). The boundary of maximum glacial extent over the contiguous United States was estimated according to Soller et al. (2011). Connected lakes/reservoirs that are constructed reservoirs (Figure S1 in the supporting information) were identified using a U.S. Geological Survey (2018) data product that located dams within the NHD lake/reservoir polygons based on the National Inventory of Dams (NID). Note NID contains primarily large dams, ~60,000 in the contiguous United States. All data are publicly available (see Acknowledgements), and see supporting information (Krogman & Miranda, 2015) for additional geospatial methods and figures.

2.2. Analysis

We extracted scaling patterns for lake/reservoir abundance, median lake/reservoir size, median lake/reservoir spacing, total lake/reservoir surface area, and lake/reservoir density (number of lakes per length of river, Figure S2) versus stream order similar to Horton's laws for the number of streams, mean length of streams, and mean watershed area versus stream order (Horton, 1945):

$$\log 10(X_\omega) = b\omega + a, \tag{1}$$

where ω represents the stream order; X is either the number of lakes/reservoirs (abundance), the median lake/reservoir surface area (size, km^2), the median lake/reservoir spacing (km), the total lake/reservoir surface area within each stream order (km^2), or lake/reservoir density (#lakes per kilometer); and a and b are fitted scaling parameters. Median values were used, instead of the mean as in Horton's laws, due to nonnormal distributions. The slope, b, indicates the direction and rate of change. The scaling parameters (a and b) were calculated for all watersheds that had sufficient data: at least three different stream orders, each with at least three connected lakes/reservoirs. Three hundred three of 313 HUC6 watersheds with NHD river and lake data in the contiguous United States met these criteria.

Networks show scaling behavior if there is an increasing or decreasing trend with size. We classified scaling patterns as increasing, decreasing, no pattern, or uniform. If the slope (e.g., scaling parameter, b) was within $\pm$10% of zero and the variance across stream orders was high (greater than the 50th percentile), there was no pattern. If the slope was within $\pm$10% of zero and the variance across stream orders was low (less than the 50th percentile), there was a uniform pattern. If there was positive slope beyond the 10% threshold, the pattern was increasing. If there was a negative slope beyond the 10% threshold, the pattern was decreasing (Figure S3).

We examined the spatial variability in river network topology with lakes/reservoirs by grouping watersheds with a similar combination of scaling parameters using k-means and hierarchical clustering. An optimal number of four clusters was first identified using the k-means algorithm and the "elbow" method, indicating the threshold where adding more clusters does not significantly explain more variance (Dugan et al., 2017). Watersheds were then clustered into four distinct river network topology types using a hierarchical algorithm in the cluster package in R (Maechler et al., 2012).

We tested if the differences in river network topology was related to broadscale controls such as water availability, glacial history, and the fraction of lakes/reservoirs that are constructed reservoirs within a watershed. Nondimensional scaling analysis (NMDS, vegan package, R) was used because it collapses the variance across many variables, here four different scaling parameters (abundance, size, spacing, and total surface area), in a two-dimensional space where the Euclidean distance between points (individual watersheds) is proportional to the differences in scaling parameters (e.g., longer distances equals greater

Table 1
Total River Length, Abundance of Connected Lakes/Reservoirs, the Fraction of Those Lakes/Reservoirs That Are Constructed Reservoirs, the Modal Lake/Reservoir Size, and the Modal Lake/Reservoir Spacing Within All Stream Orders in the Contiguous United States

Stream order	Total river length (km)	# Lakes/ reservoirs	Fraction constructed reservoirs	Modal lake/reservoir size (km^2)	Modal lake/reservoir spacing (km)
1	3,083,733	98,959	0.17	0.02	1.3 (64)
2	977,043	25,472	0.25	0.01	1.8 (49)
3	526,619	11,012	0.26	0.01	0.9
4	281,447	5,110	0.20	0.01	0.8 (25)
5	148,735	1,987	0.25	0.01 (5.3)	0.8 (14)
6	76,669	901	0.26	0.01 (8.1)	4.6 (26)
7	34,778	330	0.25	0.02 (38)	36
8	13,927	87	0.30	0.02 (59)	27
9	5,246	47	0.34	0.04 (102)	61

Note. Numbers in parentheses indicate the secondary mode.

differences in scaling parameters and thus different river network topologies). Correlating the NMDS ordination of the scaling parameters with potential controls tests if water availability, binary history of glaciation, and fraction of constructed reservoirs can explain the variation in river network topology across all watersheds within the United States.

3. Results and Discussion

Within the contiguous United States, there are 143,909 lakes/reservoirs directly connected to river networks and 908,695 lakes/reservoirs without a direct surface connection, 14% of all lakes/reservoirs are connected. This value differs from a previous estimate of 33% (Hill et al., 2018) because we used a higher resolution lakes/reservoirs database and excluded ephemeral/intermittent waters, but the true fraction of connected lakes/reservoirs is likely higher. Of the 143,909 connected lakes/reservoirs, 27,536 (19%) are constructed reservoirs (i.e., large reservoirs with an NID dam). Constructed reservoirs are in all stream orders (first to ninth) in the contiguous United States except the lower Mississippi River (10th order). The highest fraction of constructed reservoirs occurs in eighth- to ninth-order rivers (30–34% of lakes/reservoirs) and the lowest in first-order rivers (17% of lakes/reservoirs; Table 1).

3.1. Describing River Network Topology With Lakes/Reservoirs

Lakes/reservoirs that are connected to river networks across the contiguous United States have a characteristic size and spacing. The modal lake/reservoir size is 0.01–0.05 km^2 across all stream orders, but in rivers fifth order and larger, there is a second mode between 5 and 102 km^2 (Figure 1, Table 1, and Figure S4). The lake/reservoir size distribution within each stream order becomes less of a power law as stream order increases (Figures S5 and S6). The modal lake/reservoir spacing is 1–5 km but shifts to 27–61 km in rivers greater than sixth order. Rivers smaller than sixth order typically have a secondary lake/reservoir spacing mode of 14–64 km (Figure 1, Table 1, and Figure S4). Aggregating the data within the contiguous United States, lake/reservoir abundance decreases, median lake/reservoir size increases, and median lake/reservoir spacing increases with stream order (Figure 2).

Breaking the contiguous United States into its watersheds (e.g., HUC6 watershed boundaries), there are dominant scaling patterns in lakes/reservoirs connected to river networks. Lake/reservoir abundance decreases with stream order in 93% of watersheds (Figure 2). Median lake/reservoir size increases with stream order in 55% of watersheds, while 28% are uniform, 11% have no pattern, and 6% decrease. Median lake/reservoir spacing is uniform with stream order in 34% of watersheds, while 30% have no pattern, 20% increase, and 16% decrease. Clustering the scaling parameters that describe river network topology across all watersheds reveals four general types of networks that differ from each other primarily in how lake/reservoir size and spacing vary across stream order (Figures 3, S7, and S8).

Constructed reservoirs bend the fractal rules of lake/reservoir size distributions (Steele & Heffernan, 2017) causing shifts in the bimodality and the characteristic lake/reservoir size across stream orders (Figure S5).

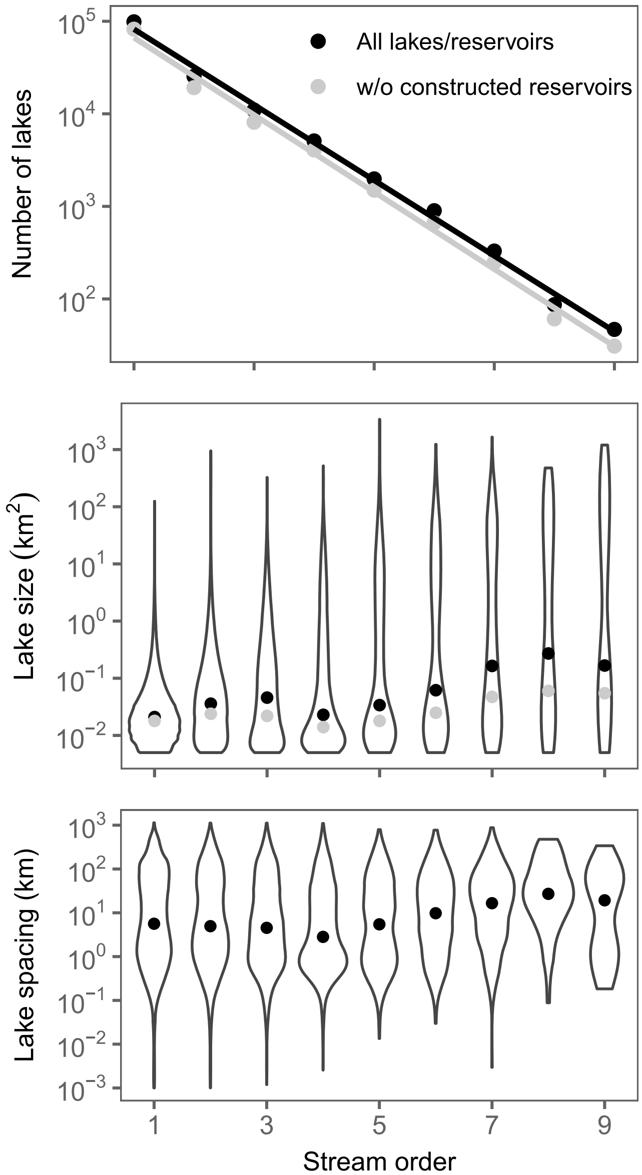

Figure 1. Lake/reservoir abundance, size distribution (km^2), and spacing distribution (km) within each stream order. The violin shapes show the full distribution of lake/reservoirs size and spacing (Figure S4) and the points represent the median. Black colors show all lakes/reservoirs and gray colors show data after removing constructed reservoirs. There is a significantly decreasing trend in lake/reservoirs abundance ($p < 0.00001$), increasing trend in median lake/reservoir size ($p = 0.002$), and increasing trend in median lake/reservoir spacing ($p = 0.007$). Axes labeled lakes (instead of lakes/reservoirs) for visual clarity.

The size distribution of constructed reservoirs versus all other lakes/reservoirs diverge; constructed reservoirs grow in size as stream order increases, while all other lakes/reservoirs maintain a consistent size distribution (Figure S6). Therefore, constructed reservoirs caused scaling patterns in lake/reservoirs size to emerge, further shown by the shift in lake/reservoirs size scaling patterns from predominantly increasing (with constructed reservoirs) to predominantly no pattern (when constructed reservoirs are removed; Figure 2).

The lake/reservoir spacing distributions and variation scaling patterns is a topic of future research, but we hypothesize that it is related to the uneven peppering of all lakes/reservoirs (connected or unconnected) across the landscape and river network branching patterns. Across the contiguous United States, first-order streams would be expected to have a bimodal lake/reservoir spacing distribution since at least natural lakes tend to be clustered within particular regions of the landscape (Downing et al., 2006; Meybeck, 1995), and lake/reservoir spacing is either short in lake/reservoir dense areas, or long in lake/reservoir scarce areas. Lake/reservoir spacing can vary from 100 m to greater than 1,000 km within any stream order across the United States (Figure 1). Therefore, any pattern in median lake/reservoir spacing with stream order—uniformity, increasing, or decreasing—is perhaps unexpected and will be examined in future work.

3.2. Controls of River Network Topology With Lakes/Reservoirs

Climate is a dominant control, at least from the controls analyzed here, of river network topology with lakes/reservoirs. Correlating the NMDS with potential controls shows the differences between the scaling parameters across all watersheds is significantly correlated ($p = 0.001$) with water availability, glacial history, and the fraction of lakes/reservoirs that are constructed reservoirs (Figure S8). Climate, expressed as water availability, accounts for 24% of the variance in the scaling parameters in NMDS space, glaciation accounts for 7%, and the fraction of constructed reservoirs accounts for 5%. Climate influences both where rivers and lakes/reservoirs occur and how they change over time. For example, climate is a primary control of river network topology (without lakes/reservoirs; Perron et al., 2012; Zanardo et al., 2013), fluvial sediment transport (Basso et al., 2015), and the density of all lakes/reservoirs in different regions of the world (Cohen, 2003; Fergus et al., 2017; McDonald et al., 2012; Meybeck, 1995) and as shown here the topology of river networks with lakes/reservoirs.

Surprisingly, constructed reservoirs and glaciation only explain a small amount of the differences in network topology with lakes/reservoirs across the United States. The low explanatory power, lack of correlation along the x axis of the ordination (Figure S8), and heterogeneous spatial organization of network types across the United States (Figure 3) suggest that additional factors shape river network topology. Geology, land use, river management decisions, and their interaction influence network topology with lakes/reservoirs and warrant further study. For example, urban land use homogenizes lake/reservoir size distributions across diverse climates within the United States (Steele & Heffernan, 2017; Steele et al., 2014), while agriculture land use drains and builds both lakes/reservoirs and streams (Downing et al., 2006; Smith et al., 2002). And dam and reservoir construction is motivated by a variety of political, economic, climatic, geologic, and management factors (Ho et al., 2017; World Commission on Dams, 2000), which have certainly shaped the current network topology.

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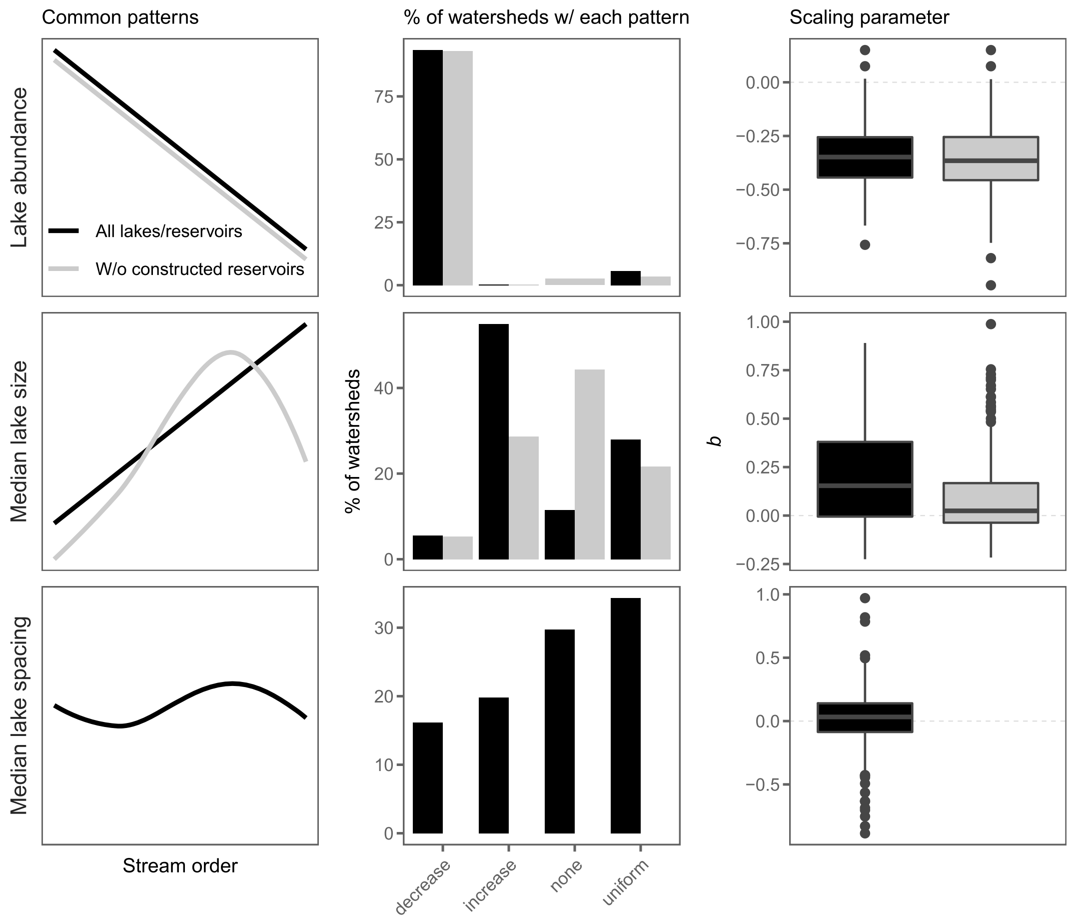

Figure 2. (left) Conceptual figure of the most common patterns in lake/reservoir abundance, median lake/reservoir size, and median lake/reservoir spacing with stream order. Watersheds with no scaling pattern in median lake/reservoir size often had a midorder peak in median lake/reservoir size. (center) The proportion of Hydrologic Unit Code 6 watersheds with lake/reservoir abundance, size, and spacing versus stream order scaling patterns classified as increasing, decreasing, no pattern, or uniform. (right) Boxplots of the scaling parameter (*b*), or slope, of lake/reservoir abundance, median lake/reservoir size, and median lake/reservoir spacing from all watersheds. Black colors show all data, and gray colors show data after removing constructed reservoirs. We did not calculate lake/reservoir spacing without constructed reservoirs since they were present in all stream orders and removing constructed reservoirs would simply increase lake/reservoir spacing. Axes labeled lakes (instead of lakes/reservoirs) for visual clarity.

The impact of constructed reservoirs is noteworthy and likely contributes to the observed spatial patterns in network topology across the United States. Of the watersheds, 94% have at least one constructed reservoir, and constructed reservoirs were found in all stream orders (except 10th order) across the contiguous United States. Entire regions of the United States are known to have few natural lakes (e.g., much of the southeast). Therefore, constructed reservoirs, and other artificial lakes/reservoirs, have transformed river networks into river networks with lakes/reservoirs. For example, while network types tend to fall within certain regions (e.g., type B was largely along the Appalachian Mountains and Piedmont, and type D was largely within the arid West and Great Plains), river network topology can look similar across diverse landscapes from the arid southwest to the glaciated highlands in the Northeast.

4. Implications

The scaling patterns and the lake/reservoir size and spacing distributions describe the topology river networks and have implications for the transport, storage, and cycling of water, materials, and organisms. The observed river network topologies (Figure 3) provide heuristics for building conceptual and theoretical models of the cumulative impacts of lakes/reservoirs on river network processes. For example, for an

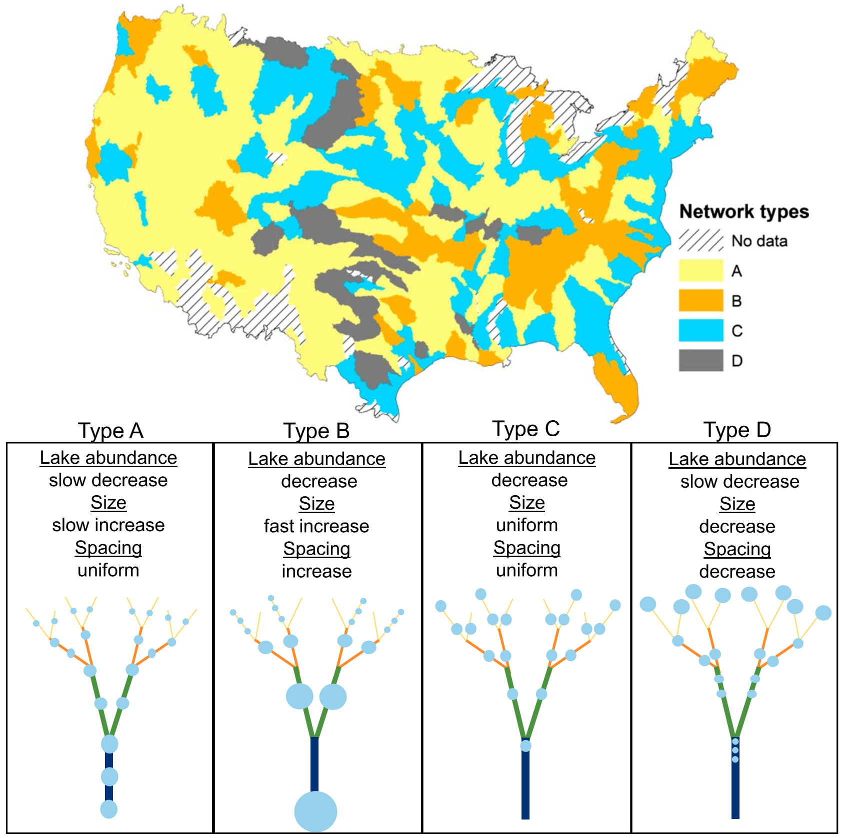

Figure 3. (top) Spatial organization of river network types. Map of Hydrologic Unit Code 6 watersheds in contiguous United States clustered into four river network types. Areas labeled "no data" either had missing National Inventory of Dams lakes/reservoirs data (2 watersheds), are the Great Lakes (5), are watersheds with a large portion of area within bordering countries (10), are entirely coastal or floodplain Hydrologic Unit Codes without significant channel networks (6), or did not have enough connected lakes/reservoirs to extract patterns (10). (bottom) Conceptual diagram that depicts one example of how the four types of river network topology could be represented based on the observed, average patterns in lake/reservoir abundance, median size, and median spacing. The colors of the river lines represent different stream orders. Figure is labeled lakes (instead of lakes/reservoirs) for visual clarity.

individual lake/reservoir to have an effect on storage and/or cycling of materials, the relative size between the lake/reservoir and river is important, with larger lakes/reservoirs relative to the river having a greater effect largely by increasing water residence time (Jones, 2010; Schmadel et al., 2018). Therefore, we would expect lakes/reservoirs to be significant for processes across the entire network when lake/reservoir size increases with stream order. If lake/reservoir size decreases or is uniform with stream order, the influence of lakes/reservoirs on riverine processes may decrease downstream. However, lake/reservoir abundance and spacing must also be considered, particularly for the movement of aquatic species that prefer lake/reservoir habitat and may disperse more easily with short distances between lakes/reservoirs (Jones, 2010; Luecke & MacKinnon, 2008; Randall et al., 1995). If lake/reservoir spacing decreases downstream, the cumulative effect of serial lakes/reservoirs may compensate for a small lake/reservoir size. For example, in river network types A and B (Figure 3), lakes/reservoirs are important for riverine processes in both small and large rivers. However, in network types C and D, only lakes/reservoirs within the headwaters are likely to be important and can thus be targeted for management actions, since lakes/reservoirs in large rivers are either too small or too far apart.

By coupling a new understanding of river network topology with geospatial data sets and network modeling, we can examine how different types of river networks with lakes/reservoirs transport sediment, propagate geomorphic adjustment (Benda et al., 2004; Czuba & Foufoula-Georgiou, 2015; Czuba et al., 2017; Gran & Czuba, 2017), process carbon and nutrients (Bertuzzo et al., 2017; Helton et al., 2018; Wollheim et al., 2008), and disperse species (Fuller et al., 2015). Previous descriptions of river networks and their scaling laws have been instrumental for understanding of geomorphic patterns (Dietrich et al., 1992; Tarboton et al., 1989), timing of discharge (Kirkby, 1976; Mantilla et al., 2011), and dispersal and production of aquatic insects (Sabo & Hagen, 2012). Similarly, the scaling patterns of network topology with lakes/reservoirs and the distributions of lake/reservoir size and spacing provide simple rules for generating theoretical river networks with varying numbers, sizes, and spacings of lakes/reservoirs across stream orders. In the simplest case, Hortonian expressions (Table S1) can be used to distribute lakes/reservoirs across a river network that approximate lake/reservoir abundance, median size, and median spacing. In addition, the distributions of lake/reservoir size and spacing from a particular stream order, or the whole network, can be sampled to build a more realistic river network. Lakes/reservoirs are an integral part of river networks across the contiguous United States and in many regions of the world. This work further emphasizes the importance of representing channel networks as a combination of rivers and lakes/reservoirs. Lake/reservoir abundance, ubiquity across stream orders, and the short distances between lakes/reservoirs highlight that the network topologies presented here may profoundly influence the form and function of both rivers and the connected lakes/reservoirs.

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References

Allen, G. H., & Pavelsky, T. M. (2018). Global extent of rivers and streams. *Science*, *361*(6402), 585–588. https://doi.org/10.1126/science.aat0636

Allen, G. H., Pavelsky, T. M., Barefoot, E. A., Lamb, M. P., Butman, D., Tashie, A., & Gleason, C. J. (2018). Similarity of stream width distributions across headwater systems. *Nature Communications*, *9*(1), 610. https://doi.org/10.1038/s41467-018-02991-w

Arp, C., Schmidt, J., Baker, M., & Myers, A. (2007). Stream geomorphology in a mountain lake district: Hydraulic geometry, sediment sources and sinks, and downstream lake effects. *Earth Surface Processes and Landforms*, *32*(4), 525–543. https://doi.org/10.1002/esp.1421

Basso, S., Frascati, A., Marani, M., Schirmer, M., & Botter, G. (2015). Climatic and landscape controls on effective discharge. *Geophysical Research Letters*, *42*, 8441–8447. https://doi.org/10.1002/2015GL066014

Benda, L., Andras, K., Miller, D., & Bigelow, P. (2004). Confluence effects in rivers: Interactions of basin scale, network geometry, and disturbance regimes. *Water Resources Research*, *40*, W05402. https://doi.org/10.1029/2003WR002583

Benstead, J. P., & Leigh, D. S. (2012). An expanded role for river networks. *Nature Geoscience*, *5*(10), 678–679. https://doi.org/10.1038/ngeo1593

Bertuzzo, E., Helton, A. M., Hall, R. O. Jr., & Battin, T. J. (2017). Scaling of dissolved organic carbon removal in river networks. *Advances in Water Resources*, *110*, 136–146. https://doi.org/10.1016/j.advwatres.2017.10.009

Butman, D., Stackpoole, S., Stets, E., McDonald, C. P., Clow, D. W., & Striegl, R. G. (2016). Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting. *Proceedings of the National Academy of Sciences*, *113*(1), 58–63. https://doi.org/10.1073/pnas.1512651112

Cael, B. B., Heathcote, A. J., & Seekell, D. A. (2017). The volume and mean depth of Earth's lakes. *Geophysical Research Letters*, *44*, 209–218. https://doi.org/10.1002/2016GL071378

Cael, B. B., & Seekell, D. A. (2016). The size-distribution of Earth's lakes. *Scientific Reports*, *6*(1), 29633. https://doi.org/10.1038/srep29633

Cohen, A. S. (2003). *Paleolimnology: The history and evolution of lake systems*. New York: Oxford University Press.

Cox, K. (1989). The role of mantle plumes in the development of continental drainage patterns. *Nature*, *342*(6252), 873–877. https://doi.org/10.1038/342873a0

Czuba, J. A., & Foufoula-Georgiou, E. (2015). Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. *Water Resources Research*, *51*, 1401–1421. https://doi.org/10.1002/2014WR016139

Czuba, J. A., Foufoula-Georgiou, E., Gran, K. B., Belmont, P., & Wilcock, P. R. (2017). Interplay between spatially explicit sediment sourcing, hierarchical river-network structure, and in-channel bed material sediment transport and storage dynamics. *Journal of Geophysical Research: Earth Surface*, *122*, 1090–1120. https://doi.org/10.1002/2016JF003965

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., McKean, J., & Bauer, R. (1992). Erosion thresholds and land surface morphology. *Geology*, *20*(8), 675–679. https://doi.org/10.1130/0091-7613(1992)020<0675:ETALSM>2.3.CO;2

Dodds, P. S., & Rothman, D. H. (1999). Unified view of scaling laws for river networks. *Physical Review E*, *59*(5), 4865–4877. https://doi.org/10.1103/PhysRevE.59.4865

Dodds, P. S., & Rothman, D. H. (2000). Scaling, universality, and geomorphology. *Annual Review of Earth and Planetary Sciences*, *28*(1), 571–610. https://doi.org/10.1146/annurev.earth.28.1.571

Downing, J. A., Prairie, Y., Cole, J., Duarte, C., Tranvik, L., Striegl, R. G., et al. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography*, *51*(5), 2388–2397. https://doi.org/10.4319/lo.2006.51.5.2388

Dugan, H. A., Bartlett, S. L., Burke, S. M., Doubek, J. P., Krivak-Tetley, F. E., Skaff, N. K., et al. (2017). Salting our freshwater lakes. *Proceedings of the National Academy of Sciences*, *114*(17), 4453–4458. https://doi.org/10.1073/pnas.1620211114

Dunne, T. (1980). Formation and controls of channel networks. *Progress in Physical Geography*, *4*(2), 211–239. https://doi.org/10.1177/030913338000400204

Fergus, C. E., Lapierre, J. F., Oliver, S. K., Skaff, N. K., Cheruvelil, K. S., Webster, K., et al. (2017). The freshwater landscape: Lake, wetland, and stream abundance and connectivity at macroscales. *Ecosphere*, *8*(8). https://doi.org/10.1002/ecs2.1911

Fuller, M. R., Doyle, M. W., & Strayer, D. L. (2015). Causes and consequences of habitat fragmentation in river networks. *Annals of the New York Academy of Sciences*, *1355*(1), 31–51. https://doi.org/10.1111/nyas.12853

Gran, K. B., & Czuba, J. A. (2017). Sediment pulse evolution and the role of network structure. *Geomorphology*, *277*, 17–30. https://doi.org/10.1016/j.geomorph.2015.12.015

Hack, J. T. (1957). *Studies of longitudinal stream profiles in Virginia and Maryland*. Washington, DC: US Government Printing Office.

Helton, A. M., Hall, R. O. Jr., & Bertuzzo, E. (2018). How network structure can affect nitrogen removal by streams. *Freshwater Biology*, *63*(1), 128–140. https://doi.org/10.1111/fwb.12990

Hill, R. A., Weber, M. H., Debbout, R. M., Leibowitz, S. G., & Olsen, A. R. (2018). The lake-catchment (LakeCat) dataset: Characterizing landscape features for lake basins within the conterminous USA. *Freshwater Science*, *37*(2), 208–221.

Ho, M., Lall, U., Allaire, M., Devineni, N., Kwon, H. H., Pal, I., Raff, D., et al. (2017). The future role of dams in the United States of America. *Water Resources Research*, *53*, 982–998. https://doi.org/10.1002/2016WR019905

Horton, R. E. (1945). Erosional development of streams and their drainage basins, hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin*, *56*(3), 275–370. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

Huntington, J. L., Hegewisch, K. C., Daudert, B., Morton, C. G., Abatzoglou, J. T., McEvoy, D. J., & Erickson, T. (2017). Climate engine: Cloud computing and visualization of climate and remote sensing data for advanced natural resource monitoring and process understanding. *Bulletin of the American Meteorological Society*, *98*(11), 2397–2410. https://doi.org/10.1175/BAMS-D-15-00324.1

Jones, N. E. (2010). Incorporating lakes within the river discontinuum: Longitudinal changes in ecological characteristics in stream–lake networks. *Canadian Journal of Fisheries and Aquatic Sciences*, *67*(8), 1350–1362. https://doi.org/10.1139/F10-069

Kirchner, J. W. (1993). Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks. *Geology*, *21*(7), 591–594. https://doi.org/10.1130/0091-7613(1993)021<0591:SIOHSL>2.3.CO;2

Kirkby, M. (1976). Tests of the random network model, and its application to basin hydrology. *Earth Surface Processes and Landforms*, *1*(3), 197–212. https://doi.org/10.1002/esp.3290010302

Krogman, R. M., & Miranda, L. (2015). A classification system for large reservoirs of the contiguous United States. *Environmental Monitoring and Assessment*, *187*(4), 174. https://doi.org/10.1007/s10661-014-4244-1

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., et al. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502. https://doi.org/10.1890/100125

Leopold, L. B., & Maddock, T. (1953). The hydraulic geometry of stream channels and some phyriographic implications. In *Quantitative measurement of some of the hydraulic factors that help to determine the shape of natural stream channels: Depth, width, velocity, and suspended load, and how they vary with discharge as simple power functions; their interrelations are described by the term "hydraulic geometry"* (pp. 1–16). Washington, DC: U.S. Government Printing Office.

Luecke, C., & MacKinnon, P. (2008). Landscape effects on growth of age-0 Arctic grayling in tundra streams. *Transactions of the American Fisheries Society*, *137*(1), 236–243. https://doi.org/10.1577/T05-039.1

Maechler, M., P. Rousseeuw, A. Struyf, M. Hubert, & K. Hornik (2012). Cluster: Cluster analysis basics and extensions, R package version, 1(2), 56.

Mantilla, R., Gupta, V. K., & Troutman, B. M. (2011). Scaling of peak flows with constant flow velocity in random self-similar networks. *Nonlinear Processes in Geophysics*, *18*(4), 489–502. https://doi.org/10.5194/npg-18-489-2011

Maritan, A., Rinaldo, A., Rigon, R., Giacometti, A., & Rodríguez-Iturbe, I. (1996). Scaling laws for river networks. *Physical Review E*, *53*(2), 1510–1515. https://doi.org/10.1103/PhysRevE.53.1510

Mark, D. M. (1983). On the composition of drainage networks containing lakes: Statistical distribution of lake in-degrees. *Geographical Analysis*, *15*(2), 97–106.

Mark, D. M., & Goodchild, M. F. (1982). Topologic model for drainage networks with lakes. *Water Resources Research*, *18*(2), 275–280. https://doi.org/10.1029/WR018i002p00275

McDonald, C. P., Rover, J. A., Stets, E. G., & Striegl, R. G. (2012). The regional abundance and size distribution of lakes and reservoirs in the United States and implications for estimates of global lake extent. *Limnology and Oceanography*, *57*(2), 597–606. https://doi.org/10.4319/lo.2012.57.2.0597

McKay, L., Bondelid, T., Dewald, T., Johnston, J., Moore, R., & Rea, A. (2012). *NHDPlus version 2: User guide*. Washington, DC: National Operational Hydrologic Remote Sensing Center.

Mendonça, R., Müller, R. A., Clow, D., Verpoorter, C., Raymond, P., Tranvik, L. J., & Sobek, S. (2017). Organic carbon burial in global lakes and reservoirs. *Nature Communications*, *8*(1), 1694. https://doi.org/10.1038/s41467-017-01789-6

Meybeck, M. (1995). Global distribution of lakes. In A. Lerman, D. M. Imboden, & J. R. Gat (Eds.), *Physics and chemistry of lakes* (pp. 1–35). Berlin, Heidelberg: Springer.

Moore, R. B., & Dewald, T. G. (2016). The road to NHDPlus—Advancements in digital stream networks and associated catchments. *JAWRA Journal of the American Water Resources Association*, *52*(4), 890–900. https://doi.org/10.1111/1752-1688.12389

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, *313*(5790), 1068–1072. https://doi.org/10.1126/science.1128845

Perron, J. T., Richardson, P. W., Ferrier, K. L., & Lapotre, M. (2012). The root of branching river networks. *Nature*, *492*(7427), 100–103. https://doi.org/10.1038/nature11672

Randall, R., Minns, C., & Kelso, J. (1995). Fish production in freshwaters: Are rivers more productive than lakes? *Canadian Journal of Fisheries and Aquatic Sciences*, *52*(3), 631–643. https://doi.org/10.1139/f95-063

Raymond, P. A., Zappa, C. J., Butman, D., Bott, T. L., Potter, J., Mulholland, P., et al. (2012). Scaling the gas transfer velocity and hydraulic geometry in streams and small rivers. *Limnology & Oceanography: Fluids & Environments*, *2*(1), 41–53. https://doi.org/10.1215/21573689-1597669

Rinaldo, A., Banavar, J. R., & Maritan, A. (2006). Trees, networks, and hydrology. *Water Resources Research*, *42*, W06D07. https://doi.org/10.1029/2005WR004108

Rinaldo, A., Dietrich, W. E., Rigon, R., Vogel, G. K., & Rodrlguez-Lturbe, I. (1995). Geomorphological signatures of varying climate. *Nature*, *374*(6523), 632–635. https://doi.org/10.1038/374632a0

Rodríguez-Iturbe, I., & Rinaldo, A. (2001). *Fractal river basins: Chance and self-organization*. Cambridge, UK: Cambridge University Press.

Sabo, J. L., & Hagen, E. M. (2012). A network theory for resource exchange between rivers and their watersheds. *Water Resources Research*, *48*, W04515. https://doi.org/10.1029/2011WR010703

Sayer, C. D. (2014). Conservation of aquatic landscapes: Ponds, lakes, and rivers as integrated systems. *Wiley Interdisciplinary Reviews Water*, *1*(6), 573–585. https://doi.org/10.1002/wat2.1045

Schmadel, N. M., Harvey, J. W., Alexander, R. B., Schwarz, G. E., Moore, R. B., Eng, K., et al. (2018). Thresholds of lake and reservoir connectivity in river networks control nitrogen removal. *Nature Communications*, *9*(1), 2779. https://doi.org/10.1038/s41467-018-05156-x

Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin*, *67*(5), 597–646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

Sedell, J. R., Reeves, G. H., Hauer, F. R., Stanford, J. A., & Hawkins, C. P. (1990). Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. *Environmental Management*, *14*(5), 711–724. https://doi.org/10.1007/BF02394720

Shreve, R. L. (1966). Statistical law of stream numbers. *The Journal of Geology*, *74*(1), 17–37. https://doi.org/10.1086/627137
Smith, S., Renwick, W., Bartley, J., & Buddemeier, R. (2002). Distribution and significance of small, artificial water bodies across the United States landscape. *Science of the Total Environment*, *299*(1–3), 21–36. https://doi.org/10.1016/S0048-9697(02)00222-X
Soller, D. R., Packard, P. H., & Garrity, C. (2011). Database for USGS map I-1970—Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains.
Soranno, P. A., Bissell, E. G., Cheruvelil, K. S., Christel, S. T., Collins, S. M., Fergus, C. E., et al. (2015). Building a multi-scaled geospatial temporal ecology database from disparate data sources: Fostering open science and data reuse. *GigaScience*, *4*(1), 28. https://doi.org/10.1186/s13742-015-0067-4
Steele, M. K., & Heffernan, J. B. (2017). Land use and topography bend and break fractal rules of water body size-distributions. *Limnology and Oceanography Letters*, *2*(3), 71–80. https://doi.org/10.1002/lol2.10038
Steele, M. K., Heffernan, J. B., Bettez, N., Cavender-Bares, J., Groffman, P. M., Grove, J. M., et al. (2014). Convergent surface water distributions in U.S. cities. *Ecosystems*, *17*(4), 685–697. https://doi.org/10.1007/s10021-014-9751-y
Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology. *Eos, Transactions of the American Geophysical Union*, *38*(6), 913–920. https://doi.org/10.1029/TR038i006p00913
Syvitski, J. P., Vörösmarty, C. J., Kettner, A. J., & Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, *308*(5720), 376–380. https://doi.org/10.1126/science.1109454
Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1988). The fractal nature of river networks. *Water Resources Research*, *24*(8), 1317–1322. https://doi.org/10.1029/WR024i008p01317
Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1989). Scaling and elevation in river networks. *Water Resources Research*, *25*(9), 2037–2051. https://doi.org/10.1029/WR025i009p02037
U.S. Geological Survey (2018). U.S. National Hydrography in FileGDB 10.1 format, edited, United States Geological Survey. Retrieved from http://prd-tnm.s3-website-us-west-2.amazonaws.com/?prefix=StagedProducts/Hydrography/NHD/National/HighResolution/GDB/
Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*(1), 130–137. https://doi.org/10.1139/f80-017
Vorosmarty, C. (1997). The storage and aging of continental runoff in large reservoir systems of the world. *Ambio*, *26*, 210–219.
Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, *289*(5477), 284–288. https://doi.org/10.1126/science.289.5477.284
Wetzel, R. G. (2001). *Limnology: lake and river ecosystems*. San Diego, CA: Academic Press, Gulf Professional Publishing.
Wollheim, W. M., Vörösmarty, C. J., Bouwman, A., Green, P., Harrison, J., Linder, E., et al. (2008). Global N removal by freshwater aquatic systems using a spatially distributed, within-basin approach. *Global Biogeochemical Cycles*, *22*, GB2026. https://doi.org/10.1029/2007GB002963
World Commission on Dams (2000). *Dams and development: A new framework for decision-making: The report of the world commission on dams*. London: Earthscan.
Zanardo, S., Zaliapin, I., & Foufoula-Georgiou, E. (2013). Are American rivers Tokunaga self-similar? New results on fluvial network topology and its climatic dependence. *Journal of Geophysical Research: Earth Surface*, *118*, 166–183. https://doi.org/10.1029/2012JF002392