Article

Global abundance and size distribution of streams and rivers

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Abstract

To better integrate lotic ecosystems into global cycles and budgets, we provide approximations of the size-distribution and areal extent of streams and rivers. One approach we used was to employ stream network theory combined with data on stream width. We also used detailed stream networks on 2 continents to estimate the fraction of continental area occupied by streams worldwide and corrected remote sensing stream inventories for unresolved small streams. Our estimates of global fluvial area are 485 000 to 662 000 km^2 and are +30–300% of published appraisals. Moderately sized rivers (orders 5–9) seem to comprise the greatest global area, with less area covered by low and high order streams, while global stream length, and therefore the riparian interface, is dominated by 1st order streams. Rivers and streams are likely to cover 0.30–0.56% of the land surface and make contributions to global processes and greenhouse gas emissions that may be +20–200% greater than those implied by previous estimates.

Key words: streams, rivers, global, size distributions, area, carbon cycling, stream order

Introduction

Freshwater ecosystems comprise a small but pivotal fraction of the Earth's surface, with lakes considered to cover <3% of the continents (Downing et al. 2006) and rivers considered to cover around 10% that of lakes (Cole et al. 2007). Because many processes relevant at the global scale, such as carbon burial and CO_2 exchange to the atmosphere, are scaled to lake area (Cole et al. 2007), significant efforts to ascertain the area covered by lakes have been made (Downing et al. 2006). Because of the key role inland waters seem to play in global budgets, preliminary estimates of global lake area (e.g., Downing et al. 2006) are being actively refined through theoretical (e.g., Seekell and Pace 2011) and empirical (e.g., McDonald et al. 2012) means.

With some important exceptions (Jones et al. 2003), river extents have mostly been studied because of flooding risks or their role in geochemical transport. The emphasis has been on elucidating global water discharge, so comparatively little information is available on the surface area covered by the global river network. The incomplete inventory of world rivers and streams has been a major

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impediment to several authors who have attempted to integrate rivers and streams into a view of the role of inland waters in the carbon cycle and other processes (McDowell and Asbury 1994, Duarte and Agusti 1998, Raymond and Cole 2001, Richey et al. 2002). Recent regional analyses of the role of stream in carbon exchange have attempted to overcome this lacuna by coupling intensive GIS surveys with extrapolations based on a smaller number (~100) of low order streams (e.g., Humborg et al. 2010) or using GIS with assumptions about relationships between slope, velocity, discharge, and width (e.g., Butman and Raymond 2011) to estimate the area and size distribution of streams.

Although the role of downstream transport by rivers is evident and widely quantified in global inventories, processes occurring across stream and river surfaces are globally relevant but less obvious. The river–atmosphere interface is an active site of gas fluxes, supporting significant exchanges of CO_2 (Cole and Caraco 2001), CH_4 (Bastviken et al. 2011), and N_2O (Beaulieu et al. 2011), and the river bed interface is an important site for transformations of materials (e.g., denitrification; Seitzinger et al. 2006).

Estimates of global river area have been made, but none covers rivers of all sizes or provides an estimate of their size distribution. The earliest (Lehner and Döll 2004) is restricted to the surface area covered by rivers of 6th order and larger, which were estimated to cover 360 000 km^2 (0.24% of the continental land surface area). Some more recent estimates deliver a global extent of 206 000 km^2 (Downing 2009, Aufdenkampe et al. 2011) from regional samples of rivers and empirical adjustments for under-sampling. Streams smaller than 6th order may have material exchanges of comparable or higher intensity than larger streams (Kling et al. 1991, Mulholland et al. 2008, Rantakari et al. 2010). Small aquatic ecosystems such as ponds and small lakes are of global importance because of the intensity of carbon fluxes (Downing et al. 2008) across their cumulative surface area (Downing et al. 2006), which may be true for small rivers and streams as well. Many fluxes across the water–air interface may be greater in intensity for small versus large streams because the gas exchange coefficient is driven by hydrodynamic turbulence, which varies with discharge and velocity. Hence, a global account of fluxes of materials across the river–air interface requires both knowledge of the global surface area of flowing waters and its distribution across rivers of different sizes (Downing 2009).

A direct inventory of the surface area covered by all flowing waters and the size distribution of streams and rivers is currently impossible because global-scale remote sensing can only resolve relatively large rivers at the global scale (i.e., >90 m; Lehner 2008). Although remote sensing technology is advancing rapidly, other approaches are needed because an exhaustive, direct inventory is currently impossible. River networks are characterized, as are other branching networks (Borchert and Slade 1981, Yekutielit and Mandelbrott 1994), by well-defined scaling laws describing their branching patterns and, hence, the frequency of branches of different order and size (Horton 1945, Leopold and Maddock 1953, Leopold 1962, Leopold et al. 1964, Schumm 1977). These general laws and the underlying branching theory are applicable across diverse geological and geographical regions and so may be useful in the derivation of global estimates of river size and length.

Number and length of streams of different sizes

Many landscape and hydrodynamic drivers alter stream scales and functions (Benda et al. 2004, Lowe et al. 2006). Because data on global hydrology and discharge across all stream scales are not yet available, we chose to use stream order to create a provisional estimate of global stream area. Both the number of streams and the average length of streams are related to the Strahler (1957) stream order (Leopold et al. 1964, Dodds and Rothman 2000). We acknowledge the many problems associated with the determination of stream order (Minshall 1988), but this approach offers a rich foundation of data and theory on which calculations can be based. In fact, the theory and coefficients are so consistent, or even tautologous, that they have been called "statistically inevitable" (Kirchner 1993). We are certain, however, that better estimates of stream number, length, and area will eventually emerge as detailed global data and models become increasingly accurate (Fekete et al. 2004, Lehner et al. 2011).

The number of streams of each stream order (n_ω) in a given geographical region varies with stream order (ω) as:

$$n_\omega = a \cdot b^\omega, \tag{1}$$

where a and b are fitted constants. The average length of streams of each order ($\bar{l}_\omega$) can be approximated as:

$$\bar{l}_\omega = c \cdot d^\omega \tag{2}$$

where c and d are fitted constants. Substantial amounts of empirical (Rodríguez-Iturbe and Rinaldo 1997) and theoretical (Reis 2006) work has shown that the following ratios of number of streams and length of streams (R_n, and R_l, respectively) tend toward constants (Horton 1945, Schumm 1977, Dodds and Rothman 2000):

$$R_n = \frac{n_\omega}{n_{\omega+1}}, \text{ and} \tag{3}$$

$$R_l = \frac{\bar{l}_{\omega+1}}{\bar{l}_\omega}. \tag{4}$$

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R_n is known as the bifurcation ratio. These ratios have been estimated for many regions around the world. The variables b and d in equations 1 and 2 can be estimated as $R_n = b^{-1}$ and $R_l = d$. Thus, if global or regional values of R_n and R_l are known, the only information missing for the calculation of stream size and stream length distributions are a and c (equations 1 and 2). If one knows the actual or canonical number of streams or total length of streams of any given order in a watershed of interest, a and c can be calculated by rearranging equations 1 and 2:

$$a = \frac{n_\omega}{R_n^{-\omega}}\text{ , and} \tag{5}$$

$$c = \frac{\bar{l}_\omega}{R_l^\omega}\,. \tag{6}$$

The parameters a and c in equations 1 and 2 are estimates of the number and average length of streams of order zero because b^ω and d^ω equal 1 when stream order is zero. Although an untested extrapolation, the consistency of regional hypsometry implies that these values could approximate the number and length of zero order streams (sensu Scheidegger 1965), which approximate ephemeral streams (Gomi et al. 2002, Sheridan and Olson 2003).

Width of the world's streams and rivers

Calculation of the surface area of streams, when stream length has been estimated, requires an estimate of the width of streams of each size. Streams increase in width as they flow downstream, join, and increase their order (Horton 1945, Leopold 1962, Leopold et al. 1964). The exact width of each stream is determined by the discharge, slope of the land, land use composition and modification, and geomorphic history (Leopold and Maddock 1953, Hoffer 1995), but the global relationship between stream order and stream width is unknown.

We estimated the relationship between stream order and river width. Data were collected on more than 400 streams from the published literature and were supplemented with original measurements of width from satellite imagery (see Supplementary Information). Stream width as used here is meant to represent the wetted breadth of each river without considering flood plains or side channels. The relationship between stream order and width is strong (Fig. 1), although it shows considerable variation in width within each stream order. This relationship may approximate the true distribution because we added data until the estimated means and medians for each order changed little with each additional datum. Data could only be entered for regions with sufficient geographical work to determine stream order with enough certainty to be published, however, which introduces a potential for bias toward regions where stream studies are frequent. Further, the widths of highest order rivers are somewhat idiosyncratic, because there are few of them (Table 1). The only 12th order river is, apparently, the Amazon, while the only 11th order stream we found documented was the Nile. The width of the Nile is quite narrow, given the trend shown for other orders, but it has been managed extensively for agriculture and passes through diverse climatic zones. There is evidence (Conway 2005) that the Nile's discharge has also declined substantially, possibly accounting for its small width relative to that expected for an 11th order stream. Adding sufficient data to permit more intensive and detailed analyses would be beneficial.

The median width (w) of a 1st order stream is 1.62 m, increasing exponentially with stream order. The data fit an exponential function:

$$w = 0.542 \cdot e^{0.824\omega} \tag{7}$$

($n = 418$, $r^2 = 0.80$, $p < 0.0001$; Fig. 1), although this equation predicts substantially greater widths for 10th through 12th order streams than was observed (Table 1). The river widths (Table 1) are similar to averages extracted from detailed analyses of individual river networks (Guerrini et al. 1998), suggesting that they may be robust.

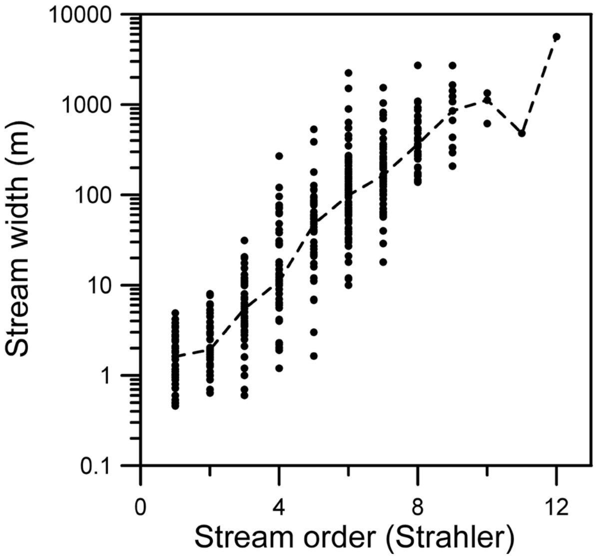

Fig. 1. Relationship between Strahler stream order and the mean width of rivers around the world. Data were extracted from the published literature, and some were supplemented with measurements from satellite imagery (see Supplemental Information). The dashed line connects median stream widths for each stream order.

Table 1. Mean and median of 418 stream width estimates for streams of different order (see Supplementary Information). Stream order is according to Strahler (1957). Data were derived from the published literature and supplemented with stream width measurements made using satellite images (see Supplemental Information). The mean breadth of a channel of order ω was approximated as the average of the median width of streams of order ω and ω-1, assuming a zero order stream would have a width of zero.

Order (ω)	*n*	Mean	SD	Predicted mean (eq. 7)	Median	Trapezoidal mean (m)
1	46	1.9	1.1	1.2	1.6	0.8
2	48	2.6	1.8	2.8	1.9	1.8
3	50	7.5	6.3	6.4	5.5	3.7
4	59	27.5	42.0	14.6	11.0	8.3
5	41	72.7	98.1	33.3	47.5	29.3
6	68	194.2	338.7	76.0	99.0	73.3
7	58	245.0	263.4	173.4	164.0	131.5
8	32	511.6	483.3	395.2	365.0	264.5
9	11	988.5	746.9	901.0	852.0	608.5
10	3	1028.0	371.1	2053.9	1125.0	988.5
11	1	481.0	—	4682.1	481.0	803.0
12	1	5676.0	—	10673.4	5676.0	3079.0

Examples of large-scale stream area distributions

Leopold (1962) provided a detailed analysis of the number and length of streams in the conterminous United States (Table 2 in the Supplementary Information) that allows a conservative estimate of the surface area of streams. This can be estimated as the product of the summed length of streams of each order and the average of the median width of each order stream and the width of the next smaller order (assuming stream width declines linearly from lower to upper reaches of a stream segment). The area of rivers and streams seems dominated by 5th through 9th order streams, with low order streams occupying less area. About 35% of the stream area is composed of streams of order <6, which are those not inventoried by global-scale remote sensing and mapping. Summing the area of streams of all orders reveals that about 43 300 km^2 of the United States' land surface is occupied by streams and rivers. This represents approximately 0.56% of the land area of this region. For comparison, this is similar to the total area of the world's 3 largest reservoirs and the global area of the world's agricultural ponds (Downing et al. 2006).

The rivers and streams of the continent of Africa have been studied extensively by Welcomme (1976) to estimate fisheries yields (Welcomme 1976, 1979) using a similar but not identical approach to that of Leopold (1962; Table 3 in the Supplementary Information). Welcomme (1976) created this parallel estimate of continental river abundance, size, and length using an empirical estimate of the relationship between drainage area and stream length, and an empirical estimate of the relationship between stream order and number created from higher order streams. A conservative estimate of the surface area of streams in Africa calculated from the product of the summed length of streams of each order and their average median widths indicates the area of rivers and streams is dominated by 5th through 9th order streams, with low order streams occupying less area. About 37% of the stream area is composed of streams of order <6. Summing the area of streams of all orders reveals that about 90 410 km^2 of Africa's land surface is occupied by streams and rivers. For comparison, this is nearly 50% of the total area covered by world reservoirs (Downing et al. 2006). Although this is twice the area covered by rivers in the United States, Africa is 4 times larger than the United States and has a large area occupied by deserts. Streams and rivers, therefore, cover only about 0.30% of the African continent.

Global extent and size distribution of streams and rivers

The calculations above suggest that the size distribution of streams and rivers is similar among regions with different climates and geography, and that the fluviosity of divergent regions varies only between about 0.30 and 0.56% of land area. Combining the approaches outlined in equation 1–6 with the width distribution of streams and rivers, we can estimate the global extent and size distribution of the world's water courses. We used 2 pathways to do this.

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Table 2. Stream order, number (n_ω), and mean length ($\bar{l}_\omega$) of rivers and streams of the world calculated from known bifurcation ratios (Leopold 1962, Welcomme 1976). These calculations combined with the trapezoidal mean of median stream widths (see text) from Fig. 1 and Table 1 were used to calculate the total area and size distribution of streams in the world. Values of $\bar{l}_\omega$ were derived using the algorithm of Leopold (1962) because length–order algorithms do not differ greatly among regions (Leopold 1962, Welcomme 1976). We used averaged values of *b* and *d* (equations 1 and 2) from two dissimilar regions (Africa and the USA) because estimates of *b* only ranged from 0.2077 to 0.217 (mean 0.21) and *d* only ranged from 2.300 to 2.301 (mean 2.301). Coefficient *a* was approximated from equation 5 for $\omega = 12$, while coefficient *c* (equation 2) was approximated as the average *c* for Africa and the US derived by substituting *d* for R_l in equation 6 (0.695). The length of the Amazon River was taken from Welcomme (1985). Significant digits for n_ω, total length, and area were rounded arbitrarily to about 0.1% of the calculated value.

Order (ω)	n_ω	$\bar{l}_\omega$ (km)	Total length (km)	Width (m)	Area (km^2)
1	28 550 000	1.6	45 660 000	0.8	36 500
2	6 000 000	3.7	22 061 000	1.8	39 200
3	1 260 000	8.5	10 660 100	3.7	39 600
4	264 000	19.5	5 151 100	8.3	42 500
5	55 500	44.8	2 489 000	29.3	72 800
6	11 700	103.2	1 202 700	73.3	88 100
7	2450	237.4	581 200	131.5	76 400
8	515	546.2	280 800	264.5	74 300
9	110	1256.7	135 700	608.5	82 600
10	23	2891.7	65 600	988.5	64 900
11	5	6653.8	31 700	803.0	25 400
12	1	6437.0	6440	3079.0	19 800

First, because of broad interregional similarity among river networks around the world and the reliability of physical rules determining the branching of river networks, we treated the world's rivers as a single branching river network. Because there is only one 12th order river in the world (the Amazon), and this river has a stream length ($\bar{l}_\omega$) of 6487 km (Welcomme 1985), the likely number of streams, their length, and their surface area can be approximated (see legend of Table 2 for methods and assumptions). This approach delivers a global river and stream surface area around 662 000 km^2 or 0.45% of the continental land surface. Around 35% of global stream length and number is made up of streams smaller than order 6. For example, there are likely to be about 29 million small, 1st order streams in the world, which comprise 52% of all stream lengths and riparian zones on the planet (Fig. 2). Stream area, in contrast, is concentrated in larger systems. Because of the form of rivers and the shape of bifurcation relationships, a relatively large proportion of stream and river area is composed of rivers of orders 5–9 (Fig. 2), and the main stem of the 12th order stream (Amazon) comprises about 3% of world stream area.

A second, independent estimate of river area can be made by assessing the fraction of diverse, well studied landscapes composed of rivers and extrapolating this fraction to the global land area. The average fraction of continents that rivers and streams comprise in Africa and the United States is about 0.43%. Extrapolating this fraction across the total land area of the world (0.43% of 150 million km^2) yields an estimate of 640 400 km^{2,} which is remarkably close to estimates made from bifurcation analyses (Table 2). Finally, Lehner and Döll (2004) estimated the global, total river, and stream area from aerial and satellite imagery to be 360 000 km^2. This area only includes rivers and streams that are >5th order (Bernhard Lehner, McGill University, pers. comm.), so, according to size-class inventories estimated here (e.g., Table 2), they were able to include only 65% of the stream area of all sizes. Therefore, assuming that 35% of global river area is of 5th order or smaller, the Lehner and Döll estimate from remote sensing implies a global river and stream area of 485 000 km^2, which is somewhat lower than estimates made from bifurcation analyses.

Both of these approaches can yield improved accuracy as more detailed global data become available. Scaling stream orders up from a known number of streams of any intermediate order, rather than from the 12th order Amazon, could yield a more stable estimate but would require reliable global inventory of the numbers of streams of diverse orders. Assuming a set fraction of the continental area occupied by streams based on inventories in 2 countries is also more arbitrary than would be desirable. The stream area will be strongly influenced by the prevalence of very wet or very dry lands in a region's surface. For example, the United States is thought to be

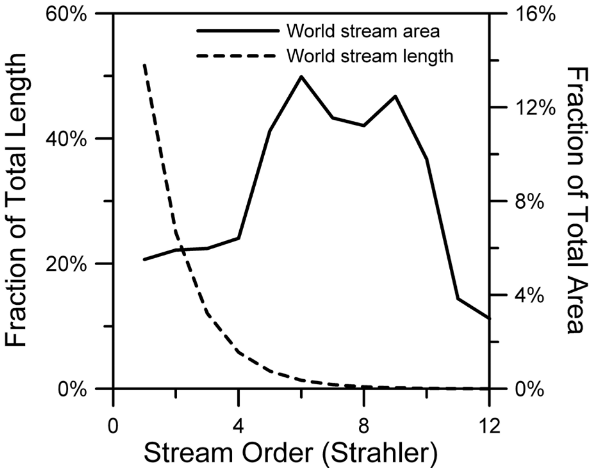

Fig. 2. Fraction of world river and stream area and length related to stream order. Calculations are from Table 2 and are based on a total world stream area of 662 041 km^2 and total world stream length of 88 320 409 km.

about 6% desert while Africa may be as much as 30% desert. The area of hot and cold (e.g., Antarctica) deserts as a fraction of global continent area is intermediate between these (20%). Although the average fraction of stream area of the estimates from Africa and the United States may be closer to the accurate global fraction, there is no doubt that refining global stream data would be beneficial.

Implications of revised global stream-area estimate

The estimates of global river area derived here range between 485 000 and 662 000 km^2. Because our estimates attempt to consider streams of all sizes, they are 33–300% greater than past estimates (Lehner and Döll 2004, Lehner 2008, Downing 2009, Aufdenkampe et al. 2011), but they also encompass an unpublished estimate of 570 000 km^2 cited recently (Battin et al. 2008). We acknowledge room for improvement in these estimates. For example, stream order is a convenient tool for making this initial estimate, but streams of the same order can differ substantially in dimensions and morphology and can be somewhat subjective. Relating stream discharge to stream dimensions could also be a useful approach because discharge could be scaled with geography, weather, and climate change (Coe et al. 2008, Beighley et al. 2009, Butman and Raymond 2011). A further need for improvement is implied by the fact that river networks are temporally dynamic. First order streams are defined as the smallest permanently flowing watercourses, although this is difficult to determine in practice; therefore, this overall approach necessarily ignores ephemeral streams. If we extrapolate the theoretical calculation of ephemeral streams on the planet using equations 1–6 to n_ω= zero order (Benda et al. 2005, Clarke et al. 2008), the calculations suggest about 137 million ephemeral streams with an average length of 0.3 km. Assuming that their average wetted breadth would be around 0.35 m when flowing, ephemeral streams may cover nearly 20 000 km^2, which is more than the main stem of the Amazon.

Also not yet considered in our estimates are expanded areas of rivers during periods of flood. Flooding of large areas of watersheds is well-known in tropical regions (Decharme et al. 2008) and increases the areal extent of tropical rivers 100–1000-fold (Melack and Hess 2009). Even boreal basins like the Ob’ River can increase in area to inundate 10% or more of the entire watershed during spring flooding (Papa et al. 2007). Our estimates attempted to account for the area of streams and rivers when not in flood or drought (see Supplementary Information). Finding ways to account for the temporal dynamics of stream systems, however, as well as adding detail concerning differing fluviosity in divergent climates and topographies, would deliver important improvements.

Here we used several approaches to estimate the global area covered by rivers and streams. These estimates suggest that rivers and streams cover approximately 0.3–0.56% of the land surface when not in flood or drought. Our global estimate of the abundance and area of streams and rivers implies that all lotic processes are substantially more important to global budgets than previous estimates suggested. For example, river–atmosphere efflux of CO_2 may likely be more than double previous estimates (Cole and Caraco 2001, Cole et al. 2007), CH_4 diffusion and ebullition 50% greater than recent assessments (Bastviken et al. 2011), and N_2O emission 20% or more greater than predicted by river-network models (Beaulieu et al. 2011), owing simply to the larger area that rivers and streams cover compared to those assumed by earlier studies. Accurate data on stream and river coverage and size distribution are prerequisite for correct estimates of the role of running waters in large-scale biogeochemical processes.

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