An expanded role for river networks

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Estimates of stream and river area have relied on observations at coarse resolution. Consideration of the smallest and most dynamic streams could reveal a greater role for river networks in global biogeochemical cycling than previously thought.

Inland waters have long been assumed to be of limited importance in global elemental cycles. Rivers and streams, for instance, were thought to simply shuttle material from the land to the ocean. Evidence is accruing, however, to suggest that lakes and river networks process and store significant amounts of terrestrial material, and are thereby an essential component of global biogeochemical cycles[1–6]. For instance, half of the carbon that enters inland waters could be either buried in sediments or returned to the atmosphere[1]. Such estimates of the contribution of inland waters to global elemental cycling are predicted to climb as more data emerge[7].

Large-scale assessments of biogeochemical cycling in freshwater systems rely on estimates of the areal extent and distribution of freshwater systems, together with scaling relationships for specific biogeochemical processes, such as the evasion of carbon dioxide or methane. These scaling relationships allow rates of specific processes to be scaled with gradients in ecosystem size.

However, recent attempts to use scaling relationships to elucidate the role of rivers and streams in global biochemical cycles are constrained by an incomplete understanding of the distribution and areal extent of river networks across the globe. We suggest that consideration of the smallest and most dynamic streams and rivers will expand the role of river networks in global elemental cycles.

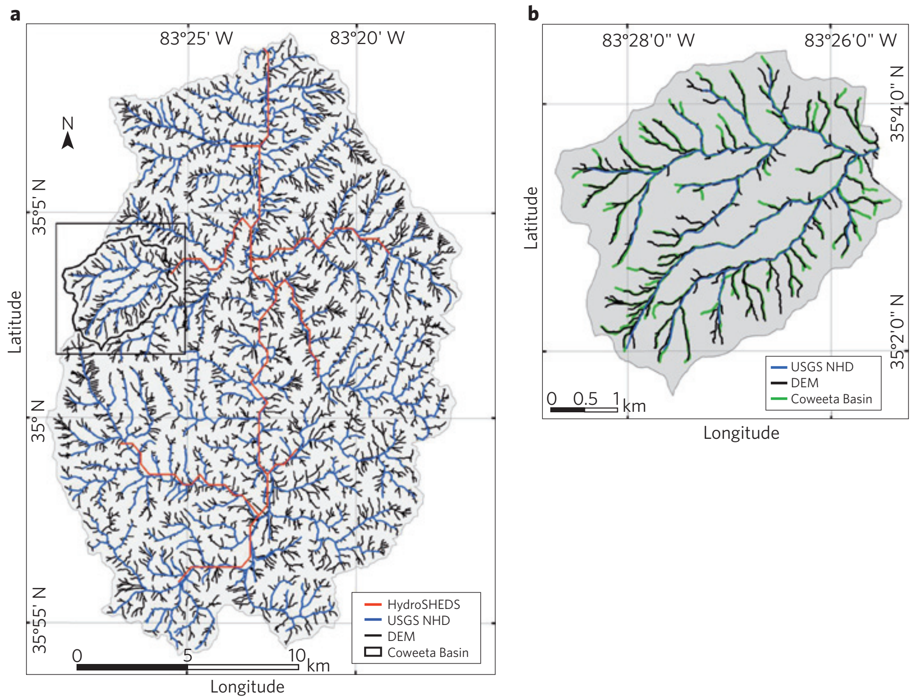

Figure 1 | Drainage networks derived from different data sources. **a**, Drainage networks of the Upper Little Tennessee River catchment based on one of the best global elevation data sets so far, the World Wildlife Fund's HydroSHEDS map derived from space shuttle elevation data (red lines; available at http://hydrosheds.cr.usgs.gov/index.php), and the US Geological Survey's National Hydrography Dataset (NHD; blue lines), fail to capture small streams picked up by a high-resolution digital elevation model (DEM; black lines; based on the US Geological Survey's National Elevation Data). As a result, the drainage density derived from the digital elevation model (3.88 km km^{-2}) is significantly higher than that derived from the NHD (1.23 km km^{-2}). **b**, Comparison of the digital elevation model output (black lines) with observations at Coweeta Creek (green lines; Forest Service data[9]), a sub-basin of the Upper Little Tennessee River catchment, suggests that the digital elevation model provides a reasonably accurate picture of stream and river area. Indeed, drainage densities derived from the model and observations amount to 3.94 and 3.41 km km^{-2}, respectively. The drainage network derived from the US Geological Survey's National Hydrography Dataset is shown for reference.

Under the radar

Despite ongoing technological advances, our understanding of the global role of biogeochemical cycling in freshwater systems is far from complete. The problem stems in part from difficulties in estimating the drainage density of river networks — that is, the total length of stream and river channel per unit catchment area — as well as their total areal extent. Streams and small rivers have often been overlooked by traditional mapping techniques, which typically rely on aerial photographs and satellite imagery, neither of which has sufficient resolution to detect small streams beneath vegetation cover. This shortcoming has led to an underestimation of global stream and river area in studies assessing the role of inland waters in biogeochemical cycles[4,5,7,8].

A comparison of map- and model-based estimates of drainage density in an intensively studied catchment illustrates the extent of the uncertainty. The Upper Little Tennessee River flows through the Blue Ridge Mountains of the southeastern United States. According to the US Geological Survey's best maps, drainage density amounts to a conservative 1.23 km km^{-2} in this basin. Digital elevation models can provide a more detailed picture of smaller channels that are often overlooked by traditional mapping techniques, and thus a more accurate representation of drainage density. These models use traditional topographic maps, as well as aerial, satellite, radar and laser imagery data, to provide a three-dimensional gridded map of surface terrain. Computer models of stream networks can be generated from digital elevation models. With some field verification of headwater streams, these computer models can be tuned to achieve a much better map of small streams than traditional techniques. According to a high-resolution digital elevation model, drainage density in the Upper Little Tennessee River basin amounts to 3.88 km km^{-2}, which is triple that derived from the more traditional map-based approach (Fig. 1a). The difference can largely be attributed to the inclusion of small perennial streams in the digital elevation model.

One potential drawback with digital elevation models is their reliance on morphologically defined channels based on remote sensing of elevation, which may or may not be characterized by a perennial flow of water. As such, these models may overestimate drainage density. However, comparison of the model output with a map derived from extensive field observations in the Coweeta Creek watershed, a sub-basin of the Upper Little Tennessee River[9] (Fig. 1b), suggests that the digital elevation model produces a reasonably accurate map of the perennial streams, but includes some additional channels that require further verification in the field. Nevertheless, even when these questionable channels are excluded from the map derived from the digital elevation model, the drainage density is 3.69 km km^{-2}, which is still three times that suggested by the map-based approach.

Small but active

If estimates of stream and river area continue to grow as more accurate measurement techniques emerge, the consequences for our understanding of stream and river biogeochemistry, and its significance, could be important. So far, large-scale assessments of biogeochemical cycling in inland waters have relied on conservative and defensible estimates of stream and river area, which omit the smaller channels[4–6,10,11]. However, small stream and river ecosystems tend to be particularly active, from a biogeochemical perspective, because the water they convey has a great deal of contact with both the benthic substrate and the atmosphere. For example, rates of carbon dioxide out-gassing from small streams are two to three times higher than those observed in larger rivers[4]. Small increases in the estimated area of small streams could therefore have disproportionately large consequences for global estimates of carbon dioxide out-gassing.

Current global estimates of carbon dioxide efflux from streams and rivers would increase from 0.56 Pg C yr^{-1} (ref. 4) to 1.2 Pg C yr^{-1} if the highest published estimate of river and stream area[10] — reliant on mapping and hydrogeomorphic modelling — was assumed. If, instead, a 50% increase in the global area of small rivers (1st to 5th order) is assumed, which could be realistic given our analysis of the Upper Little Tennessee River above, out-gassing would rise to 1.6 Pg C yr^{-1}, equivalent to around half the carbon dioxide currently thought to be released from all inland waters combined, including wetlands[4].

Networks of small, biogeochemically active streams can also be extremely variable in time. Their density can increase eightfold or more during wet periods, as intermittent and ephemeral channels initiate and sustain flow. This temporal pattern of expansion and contraction is an integral feature of river networks, particularly in the arid and semi-arid biomes that dominate Earth's terrestrial surface[12]. The biogeochemical function of intermittent and ephemeral streams, which may flow for only short periods of time, is poorly understood[12]. Yet these transitory streams represent interfaces between the aquatic and terrestrial environment. Such interfaces tend to be associated with intense biogeochemical activity[13]. Thus, the role of non-perennial streams in ecosystem processes may also be more significant than is currently appreciated.

Detailed delineation

Fortunately, continuing developments in the resolution of digital elevation models mean that the accuracy of future stream and river delineations looks set to increase. Models of stream networks and drainage density can be further improved by incorporating laser-derived topographic data, as well as multiple predictive parameters of stream channels, such as annual precipitation, topographic relief, vegetation, soils and geology[14–17], but this is not yet commonly done.

We are not the first to point out that small stream and river systems are systematically underestimated by most hydrographic maps. However, previous studies have largely focused on the consequences of this underestimation for biodiversity[18–20]. We suggest that better data are also needed to elucidate the role of streams and rivers in global biogeochemical cycles.

In sum, it is time to reconsider our view of fluvial systems. Instead of representing them as minor components of total inland water area, as often assumed, we should try thinking of them as dense networks of metabolically active conduits that together form a globally important link between terrestrial ecosystems, the oceans and the atmosphere. ❒

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