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Does the topology of the river network influence the delivery of riverine ecosystem services?

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Abstract

Riverine ecosystems provide important ecosystem services reflecting their unique forms and functions. While the effects of stressors such as land cover change, climate change and growing economies on Riverine Ecosystem Services (RES) have been well researched, the effect of the structure of the river network itself is less understood. This paper compares the capacity of different river network topologies in the delivery of selected RES. For three contrasting synthetic river network topologies (Long Trellis Narrow; Coastal Dendritic; Inland Dendritic), we applied simple functional equations to model six RES: water supply, hydropower generation, sediment retention, nutrient uptake, flood attenuation and aquatic habitat provision. Results showed that the synthetic topologies deliver different levels of RES, driven by their difference in physical structure. For example, the Inland Dendritic network removed more nitrate and better attenuated flooding due to its relatively longer lower reaches but offered poorer prospects for water supply because the longer reaches were more susceptible to transmission losses (e.g. due to bed seepage). This study provides a valuable first step in understanding the effect of river network topology on RES delivery, and the relative strengths among network types. Understanding these effects can aid decision makers in the conservation and restoration of degraded river basins to preserve RES for future generations.

Key words: Landscape ecology, physical processes, river network topology, riverine ecosystem services, river basin

1. Introduction

Flowing through steep mountains to flat plains, rivers possess unique forms and functions (McCluney et al., 2014; Poole, 2010; Thorp, Thoms, & Delong, 2006) and provide important riverine ecosystem services (RES) (Millennium Ecosystem Assessment, 2005). Ecosystem services are the “benefits” that humans receive from the riverine environment (Costanza et al., 1997). Riverine processes underpin these benefits and include ecosystem function, primary production, nutrient recycling and water transport (Gilvear, Spray, & Casas-Mulet, 2013). Globally, billions of people benefit from RES directly and indirectly (Dufour & Piégay, 2009; Green et al., 2015; Kummu, de Moel, Ward, & Varis, 2011; Millennium Ecosystem Assessment, 2005; Naidoo et al., 2008). Water is key to rural and industrial economic development, contributing to food security, livelihoods, and water security; and generating revenue through hydropower development and energy trading (Dell’Angelo, Rulli, & D’Odorico, 2018; Rosegrant, Ringler, & Zhu, 2009; Timilsina, 2018). In addition, rivers serve as important ecological corridors for species and are home to globally threatened species (Dudgeon et al., 2006; Eros, Schmera, & Schick, 2011; Rodriguez-Iturbe, Muneepeerakul, Bertuzzo, Levin, & Rinaldo, 2009).

Riverine ecosystem services are affected by many anthropogenic activities, particularly land and water management and climate change. Most obviously, riverine flow regimes and connectivity have been fundamentally altered through river regulation and dam building (Bogardi et al., 2012; Davis et al., 2015; Wisser, Fekete, Vörösmarty, & Schumann, 2010). Humans alter land cover to fulfil immediate needs such as shelter and fuel (Foley, DeFries, Asner, Barford, & Gordon, 1879), plus socio-economic and environmental objectives (Vörösmarty & Sahagian, 2000). Land use change has altered catchment water balances and river runoff (DeFries, Asner, & Houghton, 2004; Piao et al., 2007), posing a threat to water supply for human and environmental needs (Karki et al., 2018; Petts, 2009; Walsh et al., 2005). Similarly, climate change has and will influence the spatial and temporal distribution of RES (Davis et al., 2015; Sabater, 2008; Thoms, 2006). As a consequence, freshwater availability, sediment transport, flood regimes, the contraction and expansion of drainage networks, and functioning of biotic communities, are all affected (Bussi, Dadson, Prudhomme, & Whitehead, 2016; Chettri, Uddin, Chaudhary, & Sharma, 2013; Death, Fuller, & Macklin, 2015; Isaak et al., 2010; Lutz, Immerzeel, Shrestha, & Bierkens, 2014).

In addition to the anthropogenic drivers above, a basin’s physical structure (such as basin size, basin shape, basin slope, network topology, drainage density) are important factors in the generation, mediation and spatial distribution of RES (Benda, Poff, Miller, et al., 2004; Flotemersch, Thorp, & Williams, 2010; May & Gresswell, 2003; Mazvimavi, 2003; Vigerstol & Aukema, 2011). A river network structure is not only the physical means for transporting RES downstream, but it equally drives the generation and delivery of multiple ecosystem services (Gilvear et al., 2013). While environmental and ecological processes operating on hillslopes are the primary source of many ecosystem services, network structure affects the way in which diffuse inputs from hillslopes are cumulatively integrated and conveyed in-channel, with reach-scale enhancement or reduction en-route downstream. The arrangement of river links (the individual reaches) within a network affect the length of flow paths connecting hillslopes with the river mouth, and also drive variations in hydraulic characteristics such as gradient and flow velocity along these flow paths. Investigations of the effects of river network topology (RNT) on RES delivery have the potential to improve understanding and management of spatially arranged river network structures. For instance, if degraded river systems have limited water flow, and suffer from eutrophication and water quality issues (Gilvear et al., 2013; Posthumus, Rouquette, Morris, Gowing, & Hess, 2010), then research on the effect of network topology on ecosystem service delivery could help to identify the different capacities of river systems in RES delivery, allowing river managers to prioritise river management activities.

Research on RES has only been conducted in the last two decades, as has research on the ecological implications of network topology (Fagan, 2002). Combining insights regarding RES and network topology thus involves bringing two young fields together, and there is little scientific literature that addresses the effects of RNT on RES. Rivers are process-response systems (Thorp et al., 2006), comprising networks of dynamically connected (fluvial, hillslope, subsurface) pathways (Czuba & Foufoula-Georgiou, 2014). Individual RES respond to changes in any of the processes of : riverscape connectivity (fluvial, hillslopes, subsurface) (Mitchell, Bennett, & Gonzalez, 2013), hydrologic travel time (Botter, Bertuzzo, & Rinaldo, 2010), or nutrient retention (Howarth et al., 1996; Mulholland et al., 2000; Peterson et al., 2001). Studies have addressed the effects of hillslope processes upon RES delivery like water yield, sediment retention and carbon sequestration (Ausseil, Dymond, Kirschbaum, Andrew, & Parfitt, 2013; Cominoa, Botterob, Pomaricob, & Rossoa, 2014; Joo, Yu, Fentie, & Caroll, 2005; Liu, Crossman, Nolan, & Ghirmay, 2013), but have generally overlooked their interactions at the network scale.

In terms of studies specific to the effects of network topology on RES, existing studies have considered connectivity-based conceptual models specific to sedimentological response (Czuba & Foufoula-Georgiou, 2014) and proposed virtual imaging platforms to assess RES (Large & Gilvear, 2015). Other studies have assessed gross primary productivity (Koenig et al., 2019), carbon sequestration (Bertuzzo, Helton, Hall, & Battin, 2017), nitrogen retention (Grizzetti, Passy, GIlles, Bouraoui, & Luis, 2015; Helton, Hall, & Bertuzzo, 2018; Lautenbach, Kugel, Lausch, & Seppelt, 2011; Mulholland et al., 2008), sediment transportation (Mishra, Sinha, Jain, Nepal, & Uddin, 2019) and habitat suitability under different network topology metrics (Heasley, Clifford, & Millington, 2018). However, these conceptual or empirical models tend to focus on one or a small number of RES rather than considering a range of services. This limits a broader understanding of the interactions between riverine structure and RES delivery at a network scale. This study uses a network-scale approach to model the potential capacity of river networks in the delivery of multiple (six) ecosystem services, and how this varies among different network topologies.

2. Method

The overall method used in this paper is to (i) choose three contrasting river network topologies (RNTs) that are common in nature; (ii) construct idealised synthetic networks to represent each topology type; (iii) select riverine ecosystem services (RES) to model under three contrasting RNTs; (iv) apply simplified models from the scientific literature to estimate RES supplied by each RNT; and (v) compare results between the river topology types. Since the river networks adopted in this study are hypothetical, we have constructed them in such a way that all non-topological factors (basin size, river length, maximum elevation above outlet) are kept constant, and the only varying factor is the topology itself.

2.1 Selection of river network topologies (RNTs)

RNT refers to the geometric shape of the river network, which includes the length and position of streams links and the manner in which they are joined together into a network (Scheidegger, 1967). Most stream segments can be considered as a ‘link’ between two successive junctions (Czuba & Foufoula-Georgiou, 2014), with the exceptions being headwater links, which run from stream head to the first junction downstream, and the final downstream link, which runs from the final junction to the outlet. We adopted three different RNTs (Figure 1 g-i): Long Trellis Narrow (LTN), Coastal Dendritic (CD) and Inland Dendritic (ID) (Gordon, McMahon, & Finlayson, 1992). CD and ID have similar hierarchical branching structure, but ID exhibits more variability in reach length, with reaches increasing in length from headwaters to downstream. In contrast to these, LTN have a single mainstream, with many short low-order tributaries joining along its length (Figure 1 g-i). Though idealized, these three synthetic river network topologies can be considered as simplified representations of real river networks. For example, the Mekong, Danube, Po, Tigris and Yellow River basins show a Long Trellis pattern; the Amazon, Columbia, and Congo River basins represent the Coastal Dendritic pattern; and the Murray-Darling, Indus and Nile River basins have Inland Dendritic patterns. In addition to large-scale river basins, similar categories also occur on smaller scales Figure 1(a-f).

2.2 Configuration of synthetic river network topologies (RNTs)

Each synthetic network in Figure 1(g-i) was implemented as a series of links, connecting each river junction, starting at the stream headwaters, combining at junctions and ultimately ending to the catchment outlet. For the initial comparison, all three different topologies have identical: total catchment area (1000 km^2), total stream length (100 km) – and therefore drainage density (0.1 km^{-1}) – and maximum elevation (50 m relative to catchment outlet). The local catchment areas for individual links are calculated as link length divided by drainage density. For example, a link of length 0.5 km would be assigned a local catchment area of (0.5 / 0.1 =) 5 km^2; thus, if the total catchment area at the upstream end of the link were α km^2, the total catchment area at the downstream end (i.e. just upstream of the next junction) would be α + 5 km². Stream gradients are assigned via a power law with catchment area; thus, higher order streams are flatter. For our synthetic examples all three networks were assumed to have identical hillslope generation rates of runoff (300 mm) and sediment (200 tonnes/km^2) delivered to the river network, and identical nitrate concentrations (100 mg/m^3) in hillslope runoff. These hillslope inputs supplied to the river network are spatially uniform within each of the three networks. For this basic exploratory analysis, we considered only temporally averaged mean flow values; thus, we ignore flow variability with time and its effects upon sediment and nitrate dynamics. We used the following rules to build the stream networks. The CD network has all reaches being of equal length. In contrast, the length of links in the ID network doubles with each increase in stream order (i.e. order two reaches are twice the length of order one reaches, and so on). In LTN, order two reaches are 1.25 times longer the length of order one reaches, and order three reaches are 4 times longer the length of order two reaches. These values were selected with the intention of producing synthetic river networks that appear broadly similar to shapes seen in nature (Figure 1). Summary statistics illustrating differences in the river network topologies are presented in Table 1. River networks and RES were modelled in the R environment (R version 3.5.0).

2.3 Selection of riverine ecosystem services (RES)

The Millennium Ecosystem Assessment has classified ecosystem services into provisioning, regulating, cultural and supporting ecosystem services (Millennium Ecosystem Assessment, 2005). The Common International Classification of Ecosystem Services (CICES) has reclassified these services into three “sections”, by combining the supporting and regulatory services under a single ‘regulation and maintenance’ section (Haines-Young & Potschin, 2012). Each section then is categorised into a hierarchy of divisions, groups and classes at increasingly lower levels of the hierarchy (Haines-Young & Potschin, 2018). As described below, we chose six RES, including transmission loss and hydropower generation from the Provisioning section and sediment transportation, flood attenuation, nitrate removal and aquatic habitat provision from the Regulating and Maintenances sections of CICES version 5.1 (Haines-Young & Potschin, 2018) (Table 2).
The six RES (water supply, hydropower generation capacity, sediment retention, flood attenuation, nitrate uptake and physical habitat variability) were chosen because they are tangible and present material benefits to humans and society (Millennium Ecosystem Assessment, 2005), and are easily quantifiable (Large & Gilvear, 2015). Also, the selected six RES are major economic indicators influencing livelihoods and socio-ecological development. Cultural riverine ecosystems, while very important, are intangible with non-materials benefits such as spirituality, recreation, and aesthetic value (Millennium Ecosystem Assessment, 2005), and are thus difficult to quantify.

2.4 Modelling riverine ecosystem services under river network topologies (RNTs)

This section provides a brief discussion of the methods used to quantify each RES (Table 3), with reference to existing scientific literature as appropriate. These equations calculate maximum theoretical RES supplied by river basins at the outlet. The model evaluated RES based on calculations at the link scale, and then accumulated through the river network. For these calculations, flow, sediment and nitrogen balances were maintained in each link allowing for hillslope inputs and losses, which were calculated by the relevant models for the RES (Table 3).

2.4.1 Water supply

The total volume of water available for human use is primarily dependent on hillslope water yields, which we do not consider as a riverine ecosystem service. Rather it is a service provided by hillslopes. We consider how this yield is subjected to transmission losses as it is conveyed downstream through the river network as an RES. Transmission losses, which are expected to vary between topology types, reduce the capacity for human and agricultural water supply, including through permanent water retention in natural storages and evapotranspiration within the upstream river network (Costa, Bronstert, & de Araújo, 2012; Costa, Foerster, de Araújo, & Bronstert, 2013). Transmission losses are primarily due to seepage through the bed and banks of the river into the surrounding soil and aquifer, where it may then be lost to evaporation or transpiration (Costa et al., 2013). Direct evaporation of river water may also be a factor. Thus, transmission loss is usually high in dryland regions (Renard, Nichols, Woolhiser, & Osborn, 2008); for example transmission losses of around 0.8 have been estimated for low gradient reaches in arid zone rivers of central Australia (Costelloe, Grayson, & McMahon, 2006; Knighton & Nanson, 1994). In temperate climates, transmission losses are likely to be lower. The retention of water within the river network is likely to be relatively minor at the river network scale so we ignore water retention and detention in our analysis. We model transmission loss in the river network as a rate per unit length (km) of channel modelled as a power law of stream gradient (Equation 1, Table 3, (Wolman, 1955). Thus, in downstream reaches, which have lower stream gradient (see above) are subject to higher transmission loss. To quantify this RES, we report total river flow (after transmission loss) by each river network at the outlet. Since each RNT has identical area and thus identical hillslope flow generation, any variation is due to the differences in the (synthetically generated) arrangement of links and junctions. See Supplementary material equations S1-S9 for further detail.

2.4.2 Hydropower generation

Hydropower generation potential is in part determined by the interaction of downstream accumulation of discharge and changes in stream gradient. This interaction establishes the potential energy dissipated within the river network, which is the theoretical upper limit on the hydraulic potential for hydropower generation (Resch et al., 2008). Equation 2 (Table 3) calculates the absolute upper limit on potential production and assumes a) there are suitable sites for hydropower production dams, and b) there is complete efficiency of production (i.e. there are no losses in the conversion of hydraulic potential energy to electrical energy apart from the implied loss of energy when water is lost from the river network via transmission losses). Whilst the assumptions will not hold in a real situation, applying this idealised model consistently across all three networks provides a good basis for comparison. We evaluate the hydropower generation capacity (H) by integrating the stream power over all links in the river network (Equation 2, Table 3 and Supplementary material equation S10-S11) and then expressing the result per unit catchment area (Supplementary material equation S12). Although the three RNTs have the same elevation range, they vary in terms of the distribution of reach length, discharge and slope, which leads to expected variation in hydropower generation capacity.

2.4.3 Sediment retention

Worldwide, around 5 to 10% of eroded sediments reach the oceans and the rest is stored within the catchment and along the river network (Dearing, 2003; Walling, 1999). This regulatory ecosystem service has important benefits for the water quality of receiving water bodies, since contaminants such as pathogens, nutrients and micropollutants can be attached to fine sediments. We modelled sediment retention using a steady-state sediment budget model for the river network. Sediment transport capacity for each link (G_i) (Equation 3, Table 3) is calculated using a generalised sediment transport equation (Prosser & Rustomji, 2000). Sediment is accumulated at each link in the network by varying sediment transport capacities of the upstream and downstream reaches of each link (Walley, Tunnicliffe, & Brierley, 2018). If the supply capacity of a link is higher than downstream transportation capacity of that link, sediment is retained by that link (Sinha, 2005). Sediment retention in our model is represented by subtracting this deposited sediment from sediment flux accumulated to the downstream node. Then, total sediment retention is summed at the catchment outlet across all links in the network (Supplementary material equations S13-S19).

2.4.4 Flood attenuation

River flooding is one of the costliest and most frequent natural hazards faced by human society (Stürck, Poortinga, & Verburg, 2014). Relative travel time distribution is an important determinant of flood peak magnitudes (Troutman & Karlinger, 1985). If travel times from hillslope sources to the catchment outlet are similar between tributaries of a catchment, flood peaks will be superimposed and produce larger downstream flood peaks. In contrast, if tributaries exhibit different travel time, the tendency for their flood pulses to arrive simultaneously is diminished and downstream flood peaks will be smaller. Thus, in our analysis, flood attenuation is characterised as the variance in the distribution of flow path length from hillslope to catchment outlet (weighted by runoff volume and ignoring transmission losses) (Equation 4, Table 3; for detailed calculation see Supplementary material equations S20-S25). Although wave speeds may differ across a real river network, in this analysis we ignore this effect for the purposes of inter-comparison between river network topologies.

2.4.5 Nitrate uptake

Globally, rivers regulate around 30% of the total nitrogen load (Seitzinger et al., 2006; Trimmer et al., 2012; Wollheim et al., 2008) through microbially-mediated denitrification processes in the channel bed and sediments (Arthington, Naiman, McClain, & Nilsson, 2010; Gomez-Velez, Harvey, Cardenas, & Kiel, 2015). The amount of nitrate uptake in a stream reaches relies on the structure, size, and transient storage zones of the network (Helton et al., 2018; Rodriguez-Iturbe et al., 2009; Ye et al., 2012). The mass of nitrate removal within a river network is modelled as the product of the uptake velocity (Equation 5, Table 3) and the plan area (2D horizontal area) of the wetted river channel within the link given as the product of river length and width (where width itself is assumed to be a function of flow; See Supplementary material equations S26-S32). If nitrate supply (i.e. the total mass rate of nitrate supplied by upstream links and the local catchment) is higher than removal rate, the residual nitrate (i.e. after additions and removals) is transported downstream. Having applied these principles in each link of the network individually, the key reported variable is the nitrate load at the outlet. Reach length, flow accumulation and stream gradient all vary between the RNTs, leading to expected variation in nitrate uptake.

2.4.6 Aquatic habitat provision

Rivers and particularly the junction of tributaries provide a favourable environment for aquatic species to grow, interact and disperse (Benda, Andras, Miller, & Bigelow, 2004; Thomson, Taylor, Fryirs, & Brierley, 2001). The amount and diversity of aquatic habitat are determined by geomorphic diversity of river structure (Brierley, Fryirs, Outhet, & Massey, 2002). Therefore, the diversity of a river's physical habitat and network connectivity is a necessary requirement for high biotic production and high species diversity. Here, we consider single channel streams (i.e. excluding multi-channel and braided stream types) and evaluate habitat diversity as the variance in unit stream power Var(p) weighted by link length (Equation 6, Table 3) (Supplementary material equations S33-S38 for detail calculation). We consider unit stream power as a surrogate for channel type (i.e. meandering, step-pool, etc.) and assume that different channel types provide a different composition of physical habitats (Milner, Willby, Gilvear, & Perfect, 2015). Hence, if the unit stream power within the river network exhibits high variance, this network topology is assumed to provide a wider variety of reach-scale habitat and will score high for this RES.

2.5 Sensitivity of ecosystem services delivery to changes in the basin characteristics

One significant limitation of the standardized approach we have used is that the results might be specific to the basin characteristics assumed for the synthetic networks (basin area, river length and elevation). To test whether these basin characteristics influence the changes to services delivery, we evaluated the sensitivity of results to the values of three input variables: basin area, drainage density and basin slope. We applied a one-at-a-time sensitivity analysis method (Crick, Hill, & Charles, 1987; Yu, Cheng, & Zielen, 1991), repeatedly varying one input parameter at a time holding other two parameters constant. We quantified the changes in output by increasing each parameter (basin area, river length or elevation) by 10%, 25%, 50%, 75% and 100%.

3. Results

3.1 Riverine ecosystem services delivery by three topologies

Our results show that the three synthetic topologies have different capacities to deliver the selected six riverine ecosystem services (Figure 2). For example, although the water delivered to the stream network from the hillslopes was assumed constant (300 mm/year), the water supply delivery of ID is lower than for CD and LTN (Figure 2a). Similarly, hydropower generation capacity varied across the networks with higher hydropower potential in CD compared to LTN and ID (Figure 2b). Sediment retention, for a yearly load of 200 tonnes of sediment, is 192, 190, and 197 tonnes per year in LTN, CD and ID, respectively (Figure 2c). This shows that the amount exported out from the catchment varies considerably (i.e. from 3 to 10 tonnes). The variance of flow path lengths for ID is more than four times higher than the other two RNT types, so its ability to attenuate floods (according to the adopted definition) is much higher (Figure 2d). Similarly, with a constant input of nitrate, ID retains the highest amount of nitrate among the three topologies (Figure 2e). Lastly, ID has the highest physical habitat variability for aquatic species (Figure 2f).

3.2 Sensitivity of service delivery to changes in basin characteristics

The sensitivity test results (Figure 3) show that there are no substantial differences in the relative RES provision among three network topologies when testing different values of the three parameters (basin area, drainage density and basin slope). Although the values themselves increase or decrease in response to the changes, the relative ranking of the three RNTs remains unchanged in all cases. This indicates that, in general, the points made above are robust to the catchment parameter values assumed in the synthetic analysis.

4. Discussion

Based on these results, river network topology has a significant impact on the generation and delivery of ecosystem services as defined by the models presented in this paper. Such a finding is new to river science. Despite each synthetic network having constant basin properties (basin size, river length, maximum elevation, hillslope runoff generation, sediment generation and nutrient load), we observed differences in modelled RES with different topology. The variations in model outputs are solely due to the influence of topology/shape of the river networks. For the range of values considered here, river network topology has a similar or greater effect on RES compared to watershed size, slope, or drainage density for all RES.

4.1 Why do RES provisions vary among river network topologies?

A short and wide catchment produces a flashy runoff regime (Gordon et al., 1992), and water has to travel lower distances. Thus, being less subject to transmission loss, CD and LTN networks deliver more water. However, because of the shorter reach lengths and travel times, streams of CD and LTN have low capacity to regulate floods. As a result, water availability is high, but flood attenuation is low in CD and LTN. The ID networks topology produces greater variation in flow path distances from source areas to the outlet which is expected to produce higher peak flood discharges at the outlet. Mitchell et al., (2013) predicted that reduced river network connectivity will reduce water supply, downstream flooding, water quality, and soil erosion. While connectivity itself is not reduced in our networks, the spatial clustering of junction points higher in the ID catchment could be expected to have similar effects. Water availability in ID is lower in downstream reaches (due to channel losses) and our result show that ID has a higher capacity to retain nitrate and sediment. The shorter a reach, the lower the retention rate (Wollheim, Vörösmarty, Peterson, Seitzinger, & Hopkinson, 2006), leading to a greater load per unit reach length. As a result, excessive nitrate that is not retained by the short upstream reaches is exported to higher-order reaches downstream (Mulholland et al., 2008), similar to ID networks in this study. If the recipient reaches are larger, nitrate uptake velocity decreases (Hall, Baker, Rosi-Marshall, & Tank, 2013) because the longer water residence time makes larger streams more effective at removing nitrogen (Seitzinger et al., 2002; Wollheim et al., 2006). Our model of nitrate removal considered the effect of stream size on uptake velocity (based on the variation in flow velocity through the river networks) and identified that LTN has the lowest capacity for nitrate removal. In contrast, Helton et al., (2018), without considering the effect of stream size on uptake velocity, showed that narrow catchments (like our LTN) remove a lot more nutrient than more rectangular or square like topologies. Such differences in result highlights the importance of model assumptions and the choice of which aspect of system can be usefully simplified for modelling network-scale outcomes.

Network topology exerts a first order control upon sediment flux (Benda, Andras, Miller, et al., 2004; Benda & Dunne, 1997; Benda, Poff, Miller, et al., 2004) and the higher energy of steep channels initiates the entrainment of bed sediments (Heimann et al., 2015). Energy-initiated sediment transport from upstream reaches of transitional zones will differ among network types, and so sediment retention capacity in LTN, CD and ID will also differ. In our networks, 192, 190 and 197 tonnes per year of sediment is retained for LTN, CD and ID networks respectively and these rates of sediment retention are consistent with the literature (Walling, 1999). However, this also implies that the sediment loads exported from LTN and CD catchments are respectively 2.67 and 3.33 times higher than that of ID. This substantial difference between topologies reflects the fact that sediment dynamics across basins is largely influenced by variable river length (Czuba & Foufoula-Georgiou, 2014; Gordon et al., 1992). Interestingly, close to full retention of sediment occurs at a relatively low drainage area in ID networks (Figure 3c). A particularly long low-gradient mainstream is a characteristic of the ID network. Higher rates of sediment retention occur in these low gradient downstream rivers where sediment supply typically exceeds transport capacity leading to sediment deposition along the channel and on the floodplain (Noe & Hupp, 2009). As drainage area increases the length of this low-gradient mainstem river also increases and hence there is increasing retention of sediments (Figure 3c). The dominant effect of a long low gradient mainstem river in ID networks means that saturation of sediment retention occurs at lower basin drainage area than with the other network types.

Similarly, nitrate removal reaches the maximum possible rate at relatively low drainage areas in the ID network (Figure 3e). Nitrate is supplied from hillslopes which mostly drain to the steeper low order river reaches in the ID network. In reality, nitrate is removed through a variety of processes as water flows downstream through the river network (Mulholland et al., 2008; Winemiller & Jepsen, 1998). Real-life catchments with long travel distances (and hence travel time) from hill slope to basin outlet give these processes greater time to act, leading to more nitrate removal.

The variable stream length of ID networks displayed a higher length weighted variance in unit stream power (0.59-49.6) compared to the LTN networks (0.14-21.97) and uniform types of CD networks (1.36-21.17). This indicates that ID river basin offers more diverse network-scale physical habitats and are likely to thus support greater aquatic biodiversity. Benda, Poff, et al., (2004) predicted that species richness is directly dependent on the physical heterogeneity of different parts of the river network. Similarly, Heasley et al., (2018) found that distance network density and habitat diversity show positive correlation resulting to greater species richness. Therefore, the composition and diversity of species are likely to be influenced by network topology (Baguette, Blanchet, Legrand, Stevens, & Turlure, 2013; Holyoak & Lawler, 2005; Leibold et al., 2004; Seymour, Fronhofer, & Altermatt, 2015). For example, we may see greater species diversity across ID networks than corresponding CD or LTN networks.

4.2 Sensitivity to scale

These models can be applied to river basins across the world whether small or large. The adopted synthetic river network topologies in this study are intended to represent some of the different topologies that occur in real river basins (Figure 1). But the synthetic topologies adopted in this study are subject to a number of simplifying assumptions and modelled at the small basin scale of 1000 km^2. The next step in this research is to apply the models to real river systems, both large and small, and to use real world input data to investigate the relationship of topologies and RES.

4.3 Relevance to stream and catchment management

These findings are of significance as they allow a better understanding of the potential for supply of multiple ecosystem services in river networks of different structures. This provides information on riverine ecosystem services at a catchment scale that are amenable to holistic river basin management approaches. Such approaches could include water-related disaster preparedness and mitigation plans, strategies for ecological corridor restoration, and adoption of suitable technology and infrastructures to enhance RES delivery. For example, if a river is of Long Trellis Narrow type, the total potential hydropower generating capacity might be useful in deciding whether that basin can sustain further hydropower plants. At the same time, this study suggests that LTN river basins have a low propensity for provision of diverse aquatic habitats, potentially meaning that resident organisms would be less resistant to disturbances. Therefore, when designing infrastructure (e.g. hydropower development), planners could maintain extra attention to these areas to protect and conserve biodiversity. Finally, river networks that are Long Trellis Narrow or Coastal Dendritic have low capacity to attenuate floods. Therefore, planners in LTN and CD types of river basins may need to carefully design disaster preparedness plans. Moreover, if developers are planning for new settlements, this study gives an option whether to select areas that are influenced by LTN or CD structured rivers.

Given the profound dependence of many human populations on the provision and delivery of multiple RES, it is important that we understand their fundamental driving mechanisms. While the results from this study are highly abstracted, they demonstrate the likely importance of river network topology on the provision and delivery of the riverine ecosystem services upon which so many humans rely.

Data Availability Statement (DAS)

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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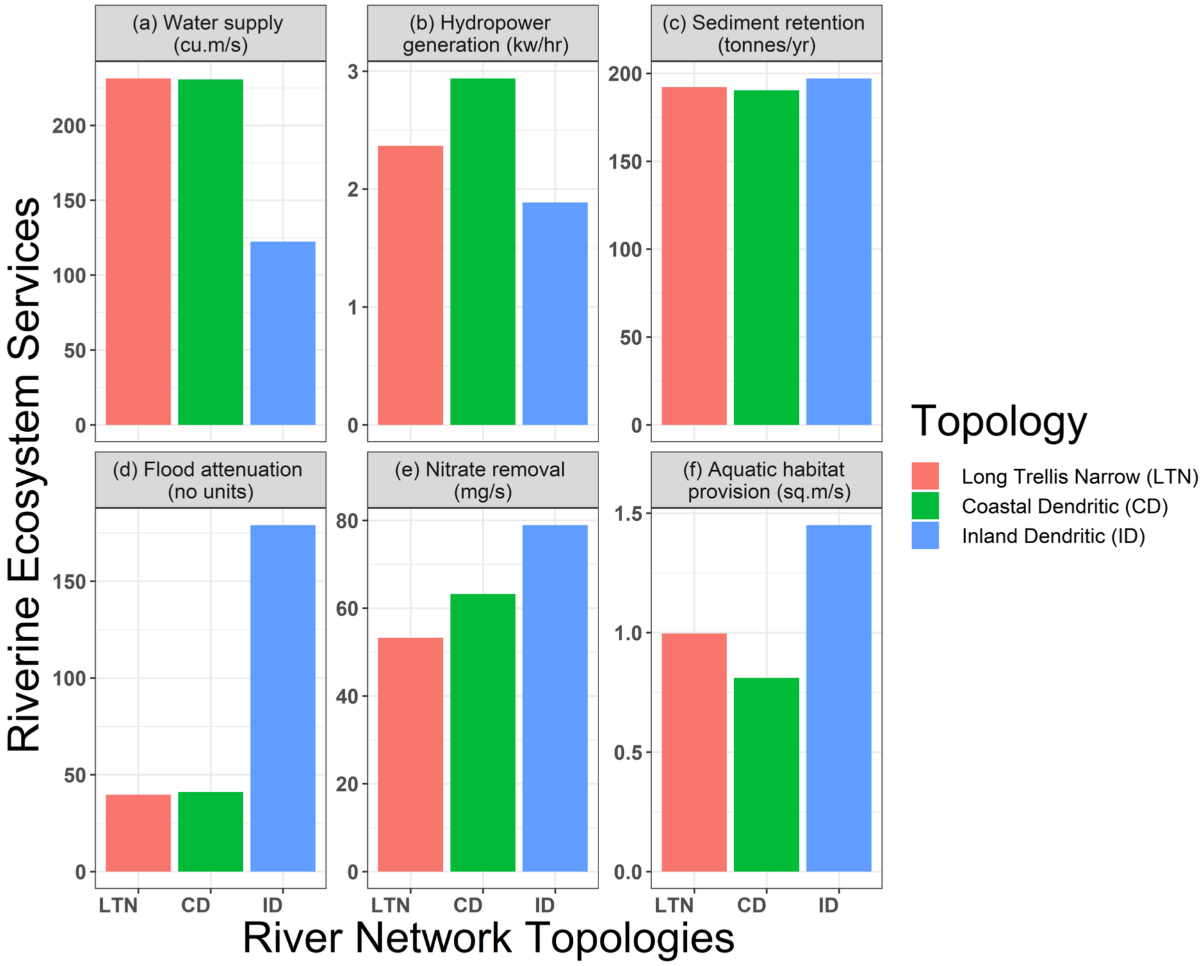

Figure 2 RES delivery of river network topology.png

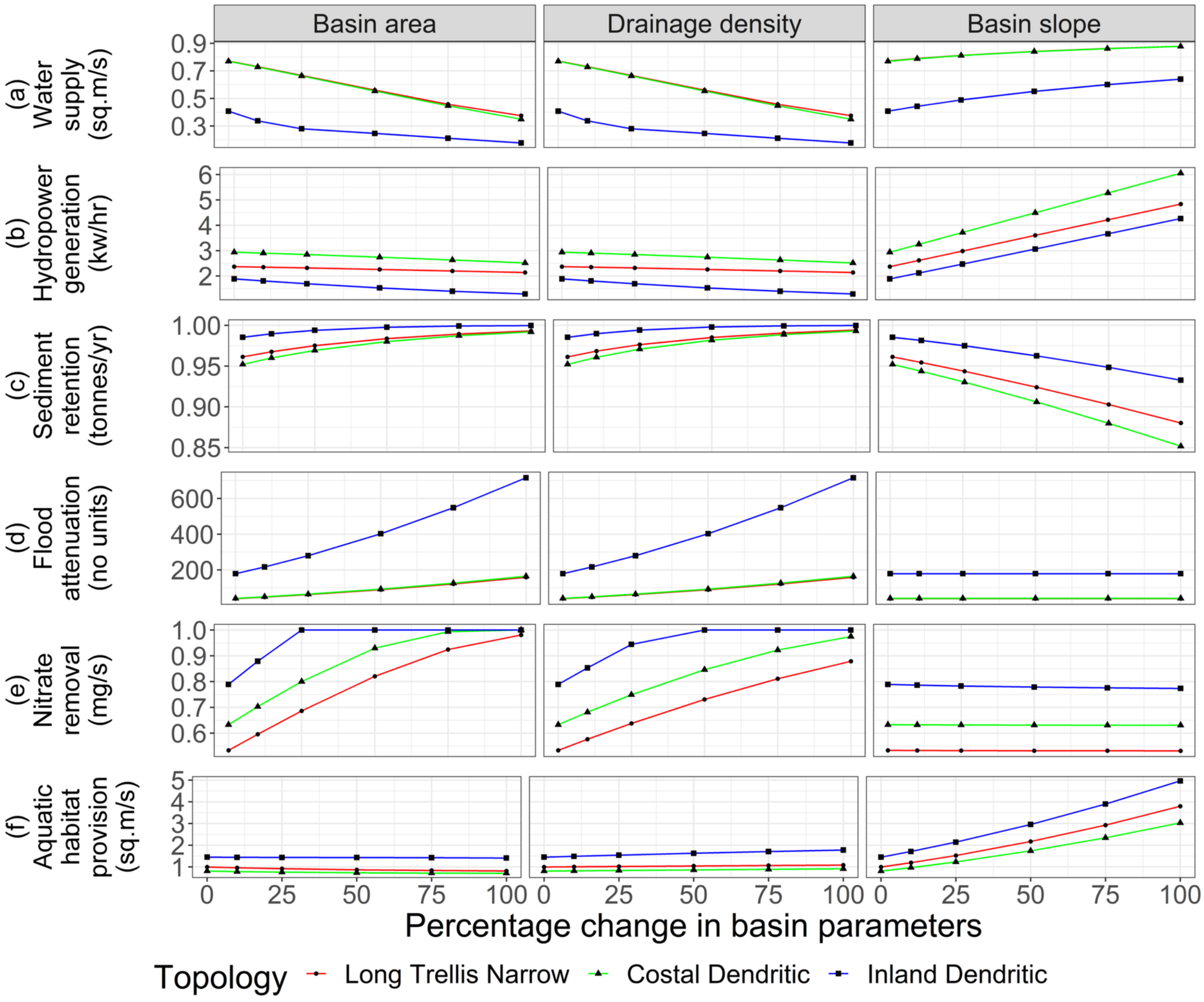

Figure 3 Sensitivity Analysis.png

List of Tables

Table 1. Summary statistics of stream pattern, topographic and stream channel variables of the three synthetic river networks

River Network topologies	No of links (reaches)	Max. stream/reach length (km)	Minimum stream/reach length (km)	Average stream/reach length (km)	Maximum fall in km (distance to outlet from high point)
Long Trellis Narrow	21	19.23	3.85	4.76	21
Coastal Dendritic	15	6.67	6.67	6.67	21
Inland Dendritic	15	25	3.125	6.67	21

Table 2. Riverine ecosystem services modelled in this study. Definitions are adopted (and in some cases modified) from CICES version 5.1 (Haines-Young & Potschin, 2018).

Section	**Division**	**Ecological clause**	**Riverine Ecosystem Services (RES)**	**Goods and benefits to human**
Provisioning (Abiotic)	Water	*Natural, surface water bodies….*	*Surface water that we can use for consumptive (drinking) and non-consumptive use (irrigation)*	*Volume of potable water in public supply system*
		The flow of water on land….	*...that can be converted to electrical or mechanical energy*	*Amount of water for hydropower generation*
Regulation & Maintenance	Transformation of biochemical or physical inputs to ecosystems	*The fixing and storage of an organic or inorganic substance by a species of plant, animal, bacteria, fungi or algae*	*Sediment retention*	*Sediment retention by the rivers to filter waste and provide quality of water for human, biodiversity and maintain health of river*

		Transformation of an organic or inorganic substance by a species of plant, animal, bacteria, fungi or algae…	*Nitrate uptake that mitigates its harmful effect*	*Filtering wastes that mitigates its harmful effects and reduces the costs of disposal by other means*
	Regulation of physical, chemical, biological conditions	*The regulation of water flows by virtue of the chemical and physical properties or characteristics of ecosystems….*	*Flood attenuation*	*Regulating the flows of water in the river system to mitigate the damage as a result of reduced magnitude and frequency of flood/storm events*
		The presence of ecological conditions (usually habitats) necessary for sustaining populations of species….	*Providing habitats for wild plants and animals*	*Sustainable populations of useful or iconic species that contribute to a service in another ecosystem.*

Table 3. Functional equations (1-6) to model RES.

Riverine Ecosystem Services (RES)		Functional equations applied to j links to calculate RES	Notes	References
Provisioning	Transmission loss	$t_i = k_{\text{loss}} S_i^{m_{\text{loss}}}$ **…Equation (1)** t_i= transmission loss in each link k_{loss} (transmission loss coefficient) = 0.00001 m_{loss} (transmission loss exponent) = -1.0 k_{loss} and m_{loss} are model parameters which were adjusted to provide realistic cumulative transmission losses across the network.	Using the stream profile's power function S = tQ^z (Wolman, 1955), stream gradient for the i^{th} link S_i is modelled as a power function of upstream catchment area A_i $S_i = k_1 A_i^{k_2}$ Sub-catchment area for links A_i = link length/drainage density We use k_2 = -0.85 as a typical value and adjusted k_1 so that the maximum elevation within	(Costa et al., 2013)

			the river network is 50 m. This gives average gradient values of 0.118, 0.158 and 0.136 for Inland Dendritic, Coastal Dendritic and Long Trellis Narrow topologies respectively. We calculated the stream gradient of cumulative stream reach (as a power function of upstream contributing area and additional area contributed by individual stream reach) and then transmission loss for stream reaches are calculated.	
	Hydropower generation	$\boldsymbol{H = \sum_j \rho g Q_i \Omega_i L_i}$ **………. Equation (2)** H = Hydropower generation potential	This equation calculates optimum capacity to generate hydropower	(Gogoase et al., 2017)
Regulating/ Maintenance	Sediment transportation capacity	$\boldsymbol{G_i = k_{\mathrm{sed}} W_i^{(1-m_{\mathrm{sed}})} Q_i{}^{m_{\mathrm{sed}}} s_i{}^{p_{\mathrm{sed}}}}$ **…Equation (3)** G_i = Sediment transportation capacity $m_{\mathrm{sed}} = p_{\mathrm{sed}} = 1.4$ (Prosser & Rustomji, 2000) coefficient $k_{\mathrm{sed}} = 3000$ is adjusted value to give typical sediment retention rates across the catchments.	Channel width (W_i) for each river link (i) is modelled using a downstream hydraulic geometry equation, which is generally a power law of discharge (Q_i in m^3/s) $W_i = aQ_i^b$ (Leopold & Maddock, 1953) a = 8 (Park, 1977) b = 0.44 We choose a plausible value of a = 8 which produced realistic mean velocities and	(Prosser et al., 2001)

			width-depth ratios for our three river networks.	
	Flood Attenuation	$\boldsymbol{var(l) = \frac{\sum_n q_i}{(\sum_n q_i)^2-\sum_n q_i^2}\sum_n q_i\left(l_i - \bar{l}\right)^2}$ … ……… **Equation (4)** ***var*** = variance in the distribution of flow path length, **n** = number of links, $\boldsymbol{q}_i$ is the streamflow added to the i^{th} link by the contributing catchment area, (i.e. runoff generated by intermediate area) $\boldsymbol{l}_i$ = distance of upstream node from catchment $\boldsymbol{\bar{l}}$ = average path length.		We proposed this equation based on the conceptual findings by (Troutman & Karlinger, 1985).
	Nitrate removal	$\boldsymbol{\log_{10}(v_f) = -0.462\log_{10}[NO_3^-] - 2.21}$……**Equation (5)** v_f = nitrate uptake velocity in cm/s NO_3^- = Nitrate concentration	(Mulholland et al., 2008) used field observations to show that v_f declines exponentially with $[NO_3^-]$ with the empirical relation.	(Mulholland et al., 2008)
	Aquatic habitat provision	$\boldsymbol{p_i = \frac{\rho g Q_i s_i}{w_i}}$ ……**Equation (6)** p_i = *unit* stream power	This equation, in this study, is used as a surrogate for river network-scale habitat diversity.	
	<u>Common variables used in above equation and their description:</u> Q_i = discharge or cumulative runoff of the i^{th} link in the network S_i= stream gradient for the i^{th} link, modelled as a power function of upstream catchment area A_i			

	Ω_i = Stream power of the i^{th} link L_i= the length of the i^{th} link in the network W_i = Channel width ρ = density of water (1000 kg/m^3) g = gravitational acceleration (9.81 m/s^2)