River fragmentation and flow alteration metrics: a review of methods and directions for future research

Suman Jumani, Matthew J Deitch, David Kaplan, Elizabeth P Anderson, Jagdish Krishnaswamy, Vincent Lecours and Matt R Whiles

1 Soil and Water Sciences Department, University of Florida, Gainesville, FL 32611, United States of America
2 Soil and Water Sciences Department, University of Florida, IFAS West Florida Research and Education Center, Milton, United States of America
3 Engineering School of Sustainable Infrastructure & Environment, University of Florida, Gainesville, FL, United States of America
4 Department of Earth and Environment and Institute of Environment, Florida International University, Miami, FL, United States of America
5 Suri Sehgal Centre for Biodiversity and Conservation, Ashoka Trust for Research in Ecology and the Environment (ATREE), Bengaluru, India
6 School of Forest Resources & Conservation, University of Florida, Gainesville, FL, United States of America

E-mail: sumanjumani@ufl.edu and sumanjumani@gmail.com

Keywords: river connectivity, hydrologic connectivity, river fragmentation, flow regulation, dams, watersheds, conservation and management

Abstract

Rivers continue to be harnessed to meet humanity's growing demands for electricity, water, and flood control. While the socioecological impacts of river infrastructure projects (RIPs) have been well-documented, methodological approaches to quantify river fragmentation and flow alteration vary widely in spatiotemporal scope, required data, and interpretation. In this review, we first present a framework to visualise the effects of different kinds of RIPs on river fragmentation and flow alteration. We then review available methods to quantify connectivity and flow alteration, along with their data requirements, scale of application, advantages, and disadvantages. Finally, we present decision-making trees to help stakeholders select among these methods based on their objectives, resource availability, and the characteristics of the project(s) being evaluated. Thematic searches of peer-reviewed literature using topic-relevant keywords were conducted on Google Scholar. The bibliography of selected papers was also reviewed, resulting in the selection of 79 publications. Papers that did not define or apply a specific metric were excluded. With respect to fragmentation, we selected papers focused on instream connectivity and excluded those dealing with overland hydrologic connections. For flow alteration, we selected papers that quantified the extent of alteration and excluded those aimed at prescribing environmental flows. The expected hydrological consequences of various RIP types were 'mapped' on a conceptual fragmentation-flow alteration plot. We compiled 29 metrics of river fragmentation and 13 metrics to flow alteration, and used these to develop decision-making trees to facilitate method selection. Despite recent advances in metric development, further work is needed to better understand the relationships between and among metrics, assess their ecological significance and spatiotemporal scale of application, and develop more informative methods that can be effectively applied in data-scarce regions. These objectives are especially critical given the growing use of such metrics in basin-wide conservation and development planning.

1. Introduction

Spurred by growing human populations, rapid urbanisation, and expanding industrial and commercial activities, rivers continue to be harnessed and regulated to meet humanity’s growing demands for electricity, irrigation, water supply, and flood control (Nilsson 2005, Lehner et al 2011). With more than 58 400 large dams (ICOLD 2019) and 82 891 small hydropower dams (Couto and Olden 2018) worldwide, it is estimated that humans have appropriated more than half the global accessible freshwater
runoff, creating a cumulative reservoir storage capacity of about 6197 km² (Lehner et al. 2011). These dams have fragmented and affected most rivers globally, leaving only an estimated 23% of the world’s large rivers (>1000 km in length) flowing uninterrupted into the ocean (Grill et al. 2019). While these dams and reservoirs have significantly contributed to human development (WCD 2000), they have fundamentally altered riparian ecosystems that depend on the dynamics of streamflow and the movement of water and the materials longitudinally and laterally through the drainage network from headwaters to estuaries and deltas (Poff et al. 1997).

Despite these adverse impacts, hydropower continues to be the world’s largest source of renewable electricity, with a 50% expected increase in production by 2030 (IRENA 2016). Ongoing and future hydropower developments are largely concentrated in developing countries and emerging economies of Asia, South America, Africa and the Balkan region of Europe (Zarfl et al. 2015, Tockner et al. 2016, Winemiller et al. 2016). Within these regions, subsistence communities may be especially dependent on the provisional services that aquatic ecosystems provide (Beck et al. 2012). Moreover, hotspots of existing and proposed dam development often overlap with areas of high freshwater biodiversity and endemism. Examples include the Amazon, Mekong, Congo, Zambezi, Yangtze, Himalayan, and Western Ghats river basins (Tockner et al. 2016, Winemiller et al. 2016, Jumani et al. 2018). In 2018 alone, an additional 21.8 GW of hydropower capacity was installed worldwide (Hydropower Status Report 2019). Conservative estimates suggest over 3700 hydropower dams (>1 MW) are under construction or proposed for further development across the globe (Zarfl et al. 2015). This is in addition to the proliferation of other river infrastructure projects (RIPs) such as small dams, water abstraction schemes, inter-basin transfers or river interlinking projects, flood control structures, and navigation schemes that could cause major alterations in flow and sediment regimes (Grant et al. 2012, Bagla 2014, Dey et al. 2019). Furthermore, even within affected basins, previously untapped headwater streams, characterised by low discharge and high gradient, are increasingly being dammed by the proliferation of small dams and diversion schemes (Couto and Olden 2018).

The hydrological consequences of RIPs on riverine ecosystems are frequently framed in terms of primary effects: reduced river network connectivity (or increased river fragmentation) and flow alteration (Nilsson 2005). Physical structures such as dams, weirs, barrages, and levees fragment the river network, impeding the free movement of water, sediment, organic matter, nutrients, energy, and organisms across space and time (Pringle 2003). The disruption of these water-mediated connections further influences crucial ecosystem processes and functions within river networks (Vannote et al. 1980, Wisen 2002, Hermoso et al. 2011). The loss of this connectivity can be considered along a temporal dimension (seasonality of flows over time) and three spatial dimensions—longitudinal (connectivity along the length of a river channel from the source to the mouth), lateral (connectivity between the floodplain, riparian areas, and the river channel), and vertical (connectivity of stream water column with groundwater) (Ward 1989). Physical structures may also store, divert, and abstract water from the river channel, and hence alter one or more characteristics of the natural flow regime (Richter et al. 2003). Flow regulation describes alteration of the natural flow regime, characterised by variability of flow magnitudes, frequencies, durations, timing, and rates of change within the year and over multi-annual periods. Streamflow directly influences stream water quality and physical habitat characteristics of the river channel and floodplain, thereby maintaining the habitat diversity required to support native biotic communities and ecosystem functions (Richter et al. 1996, Poff et al. 1997). Flow regulation may be caused by the active or passive management of water in rivers; some infrastructure can reduce or augment downstream discharge through specific dam operations or abstraction points, while other forms passively hold water or reduce flows based on the size of the infrastructure and the dynamics of discharge.

Whereas methods to assess connectivity in terrestrial landscapes have long been developed and applied (Tischendorf and Fahrig 2000, Calabrese and Fagan 2004, Kindlmann and Burel 2008), assessments of connectivity in riverine systems is a relatively recent topic of study (Fagan et al. 2002, Wisen 2002, Cote et al. 2009, Wohl 2017). Unlike terrestrial systems, where landscape connectivity is two-dimensional with numerous connectivity pathways, connectivity in river networks is water-mediated and largely driven by river flows (Pringle 2001). On the basis of their hierarchical branched structure, fragmentation in river networks can yield more variable fragment sizes compared to two-dimensional systems (Fagan 2002). Consequently, river fragmentation more severely impacts connectivity due to the existence of fewer possible pathways for water-mediated dispersal and recolonization (Fagan 2002). Furthermore, similar habitat patches that may be geographically proximate to each other in a river network, may be separated by longer stream lengths. This can significantly reduce the potential for recolonization and decrease metapopulation persistence (Fagan 2002, Fullerton et al. 2010). These unique characteristics of aquatic dendritic networks and their inherent spatiotemporal complexities pose a challenge to applying measures of landscape connectivity to river networks (Fagan et al. 2002, Wisen 2002, Cote et al. 2009). However, being able to effectively assess and predict the impacts of RIPs is crucial to inform
Understanding the suite of tools available to characterize river connectivity and flow regulation is important because these metrics can be used in a descriptive manner to quantify impacts of RIPs on both connectivity and streamflow dynamics. These tools can also be used in a prescriptive manner to develop and assess scenarios and environmental flow methodologies to aid in basin-wide conservation and development planning. In places where RIP development trajectories are tending towards proliferation of smaller projects along upstream drainage networks (Zarfl et al 2015, Couto and Olden 2018), there is a growing need to adequately assess reach- and catchment-scale fragmentation and flow regulation to account for these impacts (Athayde et al 2019). Further, recognising that countries with the most aggressive RIP development plans are often data-limited (Auerbach et al 2016), there is a need to compile relevant methods that can be applied in such data-limited environments so that stakeholders in these regions can assess the effects that RIPs might have on aquatic ecosystems and the services they provide.

Within this context, the goals of this paper are to (1) present a conceptual framework for characterizing the effects of RIPs on river fragmentation and flow alteration; (2) review published methods to assess river fragmentation and flow regulation, including metric descriptions, data requirements, output, scale of application, advantages and disadvantages; and (3) present a decision-making tree to help managers and stakeholders select the most appropriate methods based on resource availability and objectives. We conclude by identifying existing data and methodological gaps and discussing important directions for future research, in the context of current global trends of RIP development.

2. Understanding river fragmentation and flow alteration

On the basis of their branching structure, stream networks comprise functional habitats that are hierarchically nested across spatial scales (Rodriguez-Iturbe and Rinaldo 1997, Fullerton et al 2010). Consequently, the relative importance of various connectivity dimensions and drivers of ecological processes varies across spatiotemporal scales (Vannote et al 1980, Ward 1989). The effects of RIPs on connectivity and flow alteration are thus not only influenced by the extent of impact, but also on its location (i.e. headwaters versus tributaries versus the mainstem) and timing (i.e. coincident with high versus low flows) (Fagan 2002, Diebel et al 2015). RIPs can influence stream hydrology, biophysical characteristics, and ecological and functional integrity at many scales (figure 1). Together, these changes impact stream biophysical and chemical characteristics, which further influence aquatic and riparian habitat availability and quality, freshwater biodiversity, and associated ecosystem processes and functions such as nutrient cycling regimes, sediment redistribution, and ecosystem productivity (Dudgeon 2000, Rosenberg et al 2000, Vorosmarty et al 2000, Poff and Hart 2002, Fringle 2003, Nel et al 2009, Anderson et al 2015). These changes can have serious consequences on the livelihoods, food security, and the physical, cultural, and spiritual well-being of river-dependent communities (Richter et al 2010).

While most RIPs influence both connectivity and flow regimes, they may disproportionately affect one or the other depending on the project type and/or location (Farah-Perez et al 2020). Projects can be classified based on size (large, medium, or small based on installed capacity or dam height, though these classifications vary widely by region; Couto and Olden 2018), purpose (hydropower generation, irrigation, water supply, flood control, navigation), and design (with or without diversion/abstraction, storage capacity, and operating regimes). Nevertheless, each project can be expected to influence connectivity and the natural flow regime differently, and their impact can be visualised on a fragmentation-flow alteration plot (figure 2). Since the basin-level impact of these disturbances can be expected to vary from headwaters to the mainstem, the location of these projects will also influence their relative impact. While the specifics of each RIP dictate its actual position on this conceptual plot, it is instructive to ‘map’ different RIP types according to their likely impacts on these two axes (figure 2).

Medium and large dams that aim to impound water, stabilize low flows and eliminate peak flows, such as those built for flood control, water storage, and hydropower generation, are often characterised by high barriers and substantial reservoir storage capacities. These projects are expected to significantly impact both flow regulation and network fragmentation (Grill et al 2014). When such large RIPs are coupled with water abstraction (e.g. for irrigation and water supply projects), their impact on flow alteration can be expected to increase further (figure 2). Since these projects are larger, in terms of capacity and/or size, they tend to occur on higher-order streams. Barriers located further downstream can isolate greater proportions of available upstream habitat and significantly impact metapopulation dynamics such as dispersal and recolonization abilities (Fagan et al 2002, Nilsson 2005, Fullerton et al 2010). Hence, dams farther downstream in the river network
create larger fragment sizes and greater basin-wide fragmentation.

Small hydropower projects (SHPs), frequently touted as green alternatives to larger projects (Couto and Olden 2018), tend to be built across small and medium sized streams (Kibler and Tullos 2013). Usually defined by their power generation capacity, SHPs vary tremendously in definition across countries (from up to 1 MW to up to 50 MW), in size (i.e. variable dam heights, reservoir areas and storage capabilities), and in mode of operation (with or without storage and diversion) (Couto and Olden 2018). Hence, the impact of a single SHP on fragmentation and flow alteration can vary considerably based on the attributes of individual projects and their location in the river network (figure 2). Additionally, due to fewer regulations, numerous SHPs are often commissioned along a single river, leading to substantial cumulative impacts (Kibler and Tullos 2013). SHPs impede river longitudinal connectivity due to the barrier effect, which is exacerbated by the clustering of numerous SHPs on the same river channel. Although SHPs tend to have smaller storage capacities relative to large dams, their impact on the extent of flow alteration can vary based on their location, design, and operating regimes (Timpe and Kaplan 2017). In terms of design, SHPs that store and divert water from a weir to a downstream powerhouse result in the creation of dewatered river stretches, which reduce longitudinal, lateral, and vertical connectivity (Anderson et al 2006, Jumani et al 2018). Comparatively, SHPs that do not store and divert water may have a smaller impact on flow alteration. In terms of operations, continued storage and release operations (commonly employed by SHPs with storage) result in rapidly fluctuating/flashy flows downstream.

Low-head dams and other small RIPs built to facilitate infiltration or water diversion usually cluster closer to the headwater tributaries and result in smaller fragment sizes. While the impact of individual projects might be low, the cumulative fragmentation effects of numerous small RIPs can be significant (Januchowski-Hartley et al 2013). Often designed with very little active storage, these structures often allow for some movement of water and sediment and are expected to have lower individual impacts on flow alteration. Furthermore, their impact on flow regulation can be expected to vary based on the presence or absence of water abstraction (figure 2).
Figure 2 illustrates the major axes of hydrologic fragmentation and alteration, allowing us to coarsely map the expected impacts of different RIPs. However, moving from this conceptual model to a quantitative understanding of connectivity and flow regime alteration requires an understanding of the types of tools and methods available to do so, as well as their specific outputs and data requirements. In the following section, we review the metrics and tools available for quantifying river fragmentation and flow alteration, and in section 4 we provide guidance for selecting the most appropriate tool as a function of the study objective and data availability.

3. Methods to assess river fragmentation and flow alteration

We compiled key readings on the theory, concepts, and methods associated with river network connectivity and the natural flow regime. Thematic searches of published, peer-reviewed literature using topic-relevant keywords were conducted on Google Scholar. Key words used included ‘river connectivity’, ‘river fragmentation’, ‘dendritic connectivity’, ‘hydrologic connectivity’, ‘dam fragmentation’, ‘metrics of flow alteration’, ‘flow regulation’, and ‘hydrologic alteration’. Additionally, personal reference libraries and the bibliography of selected papers were also reviewed to find related and relevant publications. This resulted in the final selection of 79 publications. Papers that did not define or apply a specific metric were excluded from the review. With respect to river fragmentation, we only selected papers focused on instream riverine connectivity and excluded those dealing with overland hydrologic connections (Pringle 2001). Similarly, for flow alteration, we selected papers that quantified the extent of alteration (descriptive metrics) and excluded those aimed at prescribing environmental flows (prescriptive methods).

3.1. Metrics of river fragmentation

Our review resulted in a compilation of 29 metrics or methods to quantify river network connectivity or fragmentation (table 1). Following the classification by Calabrese and Fagan (2004), we grouped these metrics into three categories based on whether they estimate structural, potential, or actual connectivity. Structural connectivity metrics are calculated based on the physical attributes and spatial configuration of the riverscape; potential connectivity metrics combine information describing an ecosystem process...
or organism dispersal abilities along with information on the structural or physical attributes of the riverscape; actual connectivity metrics are based on a measured ecosystem process or the observed movement of individuals along the spatial configuration of the river (Kindlmann and Burel 2008). Hence, potential and actual connectivity metrics will vary based on the target taxa or phenomenon being considered and the spatiotemporal scales at which they occur (Fullerton et al 2010). Table 1 summarises the description, data requirements, output, spatial scale of application, and advantages and disadvantages of each method.

3.2. Metrics of flow alteration
Methods to assess flow alteration can be descriptive or prescriptive in their application. Descriptive metrics are those that quantify or measure flow alteration (i.e. how have riverine flows been altered compared to baseline undisturbed conditions?); prescriptive methods are those aimed at determining environmental flow requirements (i.e. how much water can be extracted or used while still maintaining ecosystem processes and functions?) and usually incorporate one or more descriptive metrics. While the former is often quantified based on scientific data input, the latter is management-oriented and influenced by socio-cultural, economic, and political drivers. This review focuses only on descriptive metrics, as numerous reviews of the application of prescriptive environmental flow methodologies already exist (Jowett 1997, King et al 1999, Tharme 2003, Acreman and Dunbar 2004, Hirji and Davis 2009, Horne 2017). Table 2 summarises the description, data requirements, output, spatial scale of application, and advantages and disadvantages of the 12 main descriptive flow alteration metrics.

4. Decision support
4.1. River connectivity metrics
Although connectivity in river networks has been less studied compared to their terrestrial counterparts, we documented 29 different methods to quantify river connectivity or fragmentation from the scientific literature (table 1). These methods vary considerably in their data requirements, spatial scale of application, and output, each having their own assumptions, advantages, and disadvantages.

Figure 3 presents a decision-making tree to help identify connectivity metrics that can be used based on the study objective, data availability, and distribution of infrastructure projects in the river basin of interest. This decision tree, when used with the information in table 1, allows users to make informed decisions when selecting among the connectivity measures available and to design impact studies with an eye toward quantifying specific outcomes. For example, when assessing the impact of fragmentation on biotic communities, in a case where little or no empirical data are available on the species/taxa of interest, the decision tree presents 16 available structural and potential connectivity metrics to choose from. Similarly, when assessing the impact of fragmentation on basin-wide processes, users can select among 11 different structural, potential, and actual measures (figure 3).

When reviewing these methods holistically, a clear trade-off emerges between data availability and the type of connectivity that can be assessed. While actual connectivity metrics yield the most direct and reliable measure of connectivity, their application across spatial scales is often limited by the availability of field data. Nevertheless, these methods can be effectively applied at finer spatial scales to address specific objectives. For example, actual connectivity metrics are ideal to assess the efficacy of fish passes (Oldani and Baïgûn 2002, Knaepkens et al 2006, Naughton et al 2007), species responses to dam removals (Liermann et al 2017), or the restoration of specific migration pathways (Beasley and Hightower 2000). Among the actual connectivity metrics, only genetic or molecular techniques provide information across extended temporal scales, whereas other methods usually quantify short-term dispersal during the period of data availability.

In contrast, structural connectivity indices are not data-intensive and can be calculated with relative ease across broader spatial scales. However, they provide only a crude estimate of connectivity, which may or may not reflect actual conditions at the scale of their application (Mahlum et al 2014). Given these drawbacks, potential connectivity metrics present a more suitable choice in the absence of empirical data. These metrics can be informed by secondary information on ecological or biotic requirements (such as dispersal probabilities or habitat requirements) and can be used to calculate potential connectivity across broad spatial scales with relative ease. Often, structural connectivity metrics have been modified or adapted to suit research needs and data availability. For example, the Dendritic Connectivity Index (Cote et al 2009) has been used as the basis for other derivative connectivity metrics, such as the River Connectivity Index (Grill et al 2014) and the Fragmentation Index (Díaz et al 2019). Similarly, several structural connectivity metrics can be modified to incorporate additional information to become more ecologically meaningful. For example, river lengths can be weighted based on habitat quality or habitat preference of target taxa (Grill et al 2014, Buddendorf et al 2017). Likewise, for structural metrics that treat all river reaches as equal, increasing weights can be assigned to higher stream orders or increasing river widths based on ecological considerations and scale of analysis (Díaz et al 2019).

When assessing connectivity with respect to a target species or guild, their behaviour, life history,
Table 1. List of river connectivity or fragmentation metrics with their description, data requirements, outputs, spatial scale of application, and advantages and disadvantages.

| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|--------------------------|---------|-------------------------------|------------|---------------|--------------|
| **Structural connectivity metrics** | **Between Centrality** (Freeman 1977) | Reflects the importance of each stream reach in maintaining connections between all other pairs of stream reaches in a riverscape. | River network lengths, Dam locations | Reaches ranked by their importance in maintaining basin-wide connectivity | Stream reach | No primary data needed | Does not assess connectivity across spatial scales |
|  |  |  |  |  | Various development scenarios can be assessed | Does not explicitly analyse the effects of dams |
|  |  |  |  |  | Helps identify important reaches that maintain basin-level connectivity | Values may not change even with the addition/removal of dams |
|  |  |  |  |  | Can be assessed using integral index of connectivity (IIC) or probability of connectivity (PC) metrics (see below) | Treats stream reaches across a longitudinal gradient as ecologically equivalent |
|  |  |  |  |  | Can incorporate natural barriers (waterfalls) | Connectivity treated as a binary value |
|  |  |  |  |  | Can be assessed using integral index of connectivity (IIC) or probability of connectivity (PC) metrics (see below) | Does not incorporate any other ecological characteristics |
|  | **Lateral connectivity classes** (Amoros et al 1987) | Descriptive classes of lateral connectivity (0–5) between the main channel and side channels | Modalities of connection between waterbodies/side channels and the main channel (i.e. extent of connection during high and low flow events) | Five lateral connectivity classes (5–0 indicating completely connected to isolated) | Waterbodies/side channels | One of the few measures of lateral connectivity | Descriptive classes; does not monitor the duration and intensity of the actual hydrological connection |
|  |  |  |  |  | Easy to compute | Assessing modalities of connectivity for each side channel and waterbody can be challenging |
|  |  |  |  |  | Modalities of connection can be assessed based on field observations or satellite imagery | Side channels of different sizes and attributes (and hence having different levels of resilience) may be classified under the same category |
|  |  |  |  |  | Minimal data requirements |  |
|  |  |  |  |  | Seasonal and historical changes over times can be assessed |  |
|  |  |  |  |  | Can be quickly assessed across spatial scales |  |

(Continued)
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|-----------------------------|------------|---------------|--------------|
| Fragmentation classes (Nilsson et al 2005) | A descriptive measure based on the longest undammed length of the main river channel in relation to the entire channel length. | • River network lengths<br>• Dam locations | Five fragmentation classes (very low to very high) | Sub-basin to basin | • Easy to compute<br>• Minimal data requirements<br>• No primary data needed<br>• Various development scenarios can be assessed<br>• Can assess connectivity across spatial scales | • Subjective classification<br>• Not spatially explicit<br>• Values may not change even with the addition/removal of dams<br>• Cannot incorporate barrier permeabilities<br>• Treats stream reaches across a longitudinal gradient as ecologically equivalent<br>• Does not incorporate any other ecological characteristics | Diaz et al 2019 |
| Barrier density (Park et al 2008) | A descriptive measure calculated as the total number of barriers per total river length | • River network lengths<br>• Number of barriers | Density of barriers per length of river | River reach to basin | • Can incorporate natural barriers<br>• Easy to compute<br>• Minimal data requirements<br>• No primary data needed<br>• Can be calculated across spatial scales<br>• Various development scenarios can be assessed | • Does not explicitly analyse the effects of dams<br>• Not spatially explicit<br>• Treats stream reaches across a longitudinal gradient as ecologically equivalent<br>• Cannot incorporate barrier permeabilities<br>• Headwater RIs that lie beyond the delineated river network are often excluded from analysis<br>• All dams are treated the same despite differences in size and impact<br>• Does not incorporate any other ecological characteristics | Jones et al 2019; Atkinson et al 2020 |
| Connectivity/fragmentation metric | Description                                                                 | Inputs/Data requirements | Outputs                                | Spatial scale of application | Advantages                                                                 | Disadvantages                                                                 | Applications |
|-----------------------------------|------------------------------------------------------------------------------|--------------------------|----------------------------------------|------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------|
| Continuity index (Prato, Comoglio, and Calles 2011) | A descriptive measure calculated as the ratio of total river length to the number of obstacles | - River network lengths  
- Number of barriers | Ratio of total river length to the number of obstacles | River reach to river network | - Easy to compute  
- Minimal data requirements  
- No primary data needed  
- Can be calculated across spatial scales  
- Various development scenarios can be assessed | - Does not explicitly analyse the effects of dams  
- Not spatially explicit  
- Treats stream reaches across a longitudinal gradient as ecologically equivalent  
- Cannot incorporate barrier permeabilities  
- Does not incorporate any other ecological characteristics  
- Headwater RIPS that lie beyond the delineated river network are often excluded from analysis  
- All dams are treated the same despite differences in size and impact | Prato et al 2011 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|----------------------------|------------|--------------|--------------|
| Total remaining core length (Fuller et al 2015) | The length of unaffected core habitat for a specific species or guild, calculated as the difference between the total network length and the length of river affected by fragmentation (sum of upstream and downstream matrix and edge habitats created by each barrier in the network) | • River network lengths • Dam locations • Length of dam-affected matrix and edge habitats • Habitat requirements of target species or guilds | Total remaining core length | Sub-basin to basin | • No primary data needed • Incorporates specific habitat requirement data based on target species or guilds • Can be evaluated for target species, taxa or guilds based on their specific habitat requirements • Accounts for dams of different sizes and ecological impact, i.e. all dams are not treated the same • Can incorporate natural barriers | • Not spatially explicit • Values are centred around a focal taxa or guild, hence not directly comparable • Cannot incorporate barrier permeabilities • Measuring the length of dam-affected matrix and edge habitats can be subjective and challenging • Treats stream reaches across a longitudinal gradient as ecologically equivalent • Results susceptible to change based on the extent of the river network (i.e. sensitive to DEM resolution, flow direction and accumulation algorithms and delineation thresholds used) • Headwater RIPs that lie beyond the delineated river network are often excluded from analysis | Hall et al 2011 |
| Connectivity/fragmentation metric                      | Description                                                                                                                                                                                                 | Inputs/Data requirements                                                                 | Spatial scale of application | Advantages                                                                                                                                                                                                                      | Disadvantages                                                                                                                                                                                                 |
|--------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dam Impact Index (Latrubesse et al. 2017)              | An index calculated from (i) the ratio of river length affected by dams, (ii) ratio of number of major tributaries affected by dams, and (iii) number of dams per basin/sub-basin.                             | • River network length locations; • Dam locations; • Length of dam-upstream impacted reaches | Sub-basin to basin           | • No primary data needed; • Easy to compute; • Incorporates 3 different metrics; • Can assess various developmental scenarios; • Can incorporate natural barriers; • Can account for dams of different sizes and ecological impact. | • Not spatially explicit; • Measuring the length of dam-affected upstream river reaches can be subjective; • Results susceptible to change based on the extent of the river network; • Headwater RIPs that lie beyond the delineated river network are often excluded from analysis. |
| River reach to tributary connectivity index (Li et al. 2018) | Quantifies the unobstructed degree of flow based on the concept of time accessibility. It is calculated as the ratio of the time accessibility of a given volume of streamflow to flow without any barriers from one location to another in the river channel. | • River network length; • Dam locations; • Barrier classification and estimated blocking weights (based on natural flow passability); • Channel cross-section for flow with and without barriers. | River reach to tributary      | • Incorporates aspects of streamflow; • Treats stream reaches across a longitudinal gradient as ecologically equivalent; • Assumes river velocity the same with or without a barrier; • Relies on accurate assessment of cross-sectional area. | • No primary data needed; • Values range between 0 and 1 and are easy to interpret; • Requires expert knowledge on barrier impacts to score barriers; • Cannot incorporate natural barriers. |
| Connectivity/fragmentation metric | Description                                                                 | Inputs/Data requirements                                      | Outputs                                     | Spatial scale of application | Advantages                                                                 | Disadvantages                                                                 | Applications                                                                 |
|-----------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------|--------------------------------------------|------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Integral index of connectivity (IIC) (Pascual-Hortal and Saura 2006) | A habitat reachability index based on habitat availability and binary connectivity values for a target taxa or guild. It assesses the possibility of dispersal between all pairs of stream reaches based on topological distances | - River network lengths or patch area  
- Dam locations  
- Estimate of threshold dispersal distance | Index of connectivity ranging from 0 to 1 | Subbasin to basin | - Easy to compute  
- No primary data needed  
- Various development scenarios can be assessed  
- Can be used to measure maximum dispersal distance  
- Suited to study genetic transmission or connectivity  
- Can assess connectivity across spatial scales  
- Various development scenarios can be assessed | - Barrier permeability treated as a binary value  
- Results susceptible to change based on the extent of the river network  
- Headwater RIs that lie beyond the delineated river network are often excluded from analysis  
- Estimate of threshold dispersal distance can be arbitrary  
- Does not accurately represent the actual number of organisms that move throughout the landscape | Segurado et al 2013; Branco et al 2014; Lehotský et al 2018 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|-------------------------|---------|----------------------------|------------|--------------|--------------|
| Probability of Connectivity (PC) (Saura and Pascual-Hortal 2007) | A habitat reachability index, like the IIC, that assesses the probabilities of dispersal between all pairs of patches or stream reaches. Connectivity is not restricted to binary values. | • River network lengths  
• Dam locations  
• Estimates of dispersal probabilities  
• Directional dam passability values
g | Index of connectivity ranging from 0 to 1 | Subbasin to basin | • No primary data needed  
• Can incorporate continuous barrier permeabilities  
• Can incorporate natural barriers  
• Various development scenarios can be assessed  
• Correctly assumes the probability of passing a barrier is dependent of the probability of passing other barriers  
• Greater importance given to reaches with large flows  
• More accurately represents the number of organisms that move throughout the landscape  
• Distinct upstream and downstream dispersal probabilities can be set  
• Can assess connectivity across spatial scales | • Estimating exact dispersal probabilities can be challenging  
• Results susceptible to change based on the extent of the river network  
• Headwater RIPs that lie beyond the delineated river network are often excluded from analysis | Bodin and Saura 2010; Malvadkar et al 2015 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|-----------------------------|------------|---------------|--------------|
| PCA lateral connectivity metric based on environmental variables (PCA-LC) (Paillex et al 2007) | A surrogate measure of lateral connectivity. Five environmental variables are summarized with a centred principal component analysis to produce a factorial axis that is used as the synthetic variable for the level of connectivity between the main river channel and the cut-off channels. | • Paired sites along the main river and cut-off channels • Measured data on 5 environmental variables (water conductance, aquatic vegetation cover, organic content of the upper sediment layer, diversity of sediment grain size, NH$_3$-N concentration) | Site scores along the primary PCA factorial axis, with increasing values corresponding to increasing connectivity | Sites from which data have been gathered | • One of the few metrics measuring lateral hydrological connectivity • Suitable to river–floodplain systems • The 5 environmental variables are known to integrate the level of connectivity of the floodplain sites with the main river channel • Values of the factorial axis indicate between-sites variability in measured variables • PCA site scores can be rescaled between 0 (lowest connectivity) and 1 (highest connectivity) | • Only a surrogate measure; does not monitor the duration and intensity of the actual hydrological connection • Reliability of this metric depends on the statistical strength of the factorial axis being used • Between-site variability in environmental variables is assumed to be explained only by the extent of lateral connectivity. However, it may also be influenced by other variables, such as season, decomposition, nutrient consumption by plants etc. • Does not account for other connectivity dimensions | Besacier-Monbertrand et al 2014 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|-------------------------|---------|-----------------------------|------------|---------------|--------------|
| Dendritic Connectivity Index—potadromous (Cote et al 2009) | An index of connectivity calculated from stream length, which assesses the potential of a potadromous fish to travel between two chosen points in a river network. Based on coincidence probability (Jager 2000) | • River network lengths<br>• Dam locations<br>• Directional dam passability values<sup>a</sup><br>• Waterfall locations<sup>a</sup> | An index of connectivity ranging from 0 to 100 | River reach to basin | • Can incorporate natural barriers<br>• Easy to compute<br>• Minimal data requirements<br>• No primary data needed<br>• Values range between 0 and 100 and are easy to interpret<br>• Barrier permeabilities can be incorporated<br>• Various development scenarios can be assessed<br>• Can assess connectivity across spatial scales<br>• Distinct upstream and downstream dispersal probabilities for target species/taxa can be set<br>• If species/taxa specific data unavailable, index can be applied with binary passability values (in which case it is a structural metric) | • Results susceptible to change based on the extent of the river network<br>• Treats stream reaches across a longitudinal gradient as ecologically equivalent. Hence, dams placed upstream or downstream can produce same DCI values despite having different ecological impacts<br>• Headwater RIPs that lie beyond the delineated river network are often excluded from analysis<br>• Assumes the probability of passing one barrier is independent of the probability of passing another barrier | Perkin and Gido 2012; Anderson et al 2018 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|----------------------------|------------|---------------|--------------|
| Dendritic Connectivity Index—diadromous (Cote et al 2009) | An index of connectivity calculated from stream length, which assesses the proportion of river length accessible to a diadromous fish from the mouth of a river | River network lengths, Dam locations, Upstream and downstream dam passability values, Waterfall locations | An index of connectivity ranging from 0 to 100 | River reach to basin | Can incorporate natural barriers, Easy to compute, Minimal data requirements, No primary data needed, Values range between 0 and 100 and are easy to interpret, Barrier permeabilities can be incorporated, Various development scenarios can be assessed, Can assess connectivity across spatial scales, Distinct upstream and downstream dispersal probabilities for target species/taxa can be set, If species/taxa specific data unavailable, index can be applied with binary passability values (in which case it is a structural metric) | Results susceptible to change based on the extent of the river network, Values may not change even with the addition/removal of dams upstream of the first dam on the mainstem, Treats stream reaches across a longitudinal gradient as ecologically equivalent, Headwater RIPs that lie beyond the delineated river network are often excluded from analysis, Assumes the probability of passing one barrier is independent of the probability of passing another barrier | Buddendorf et al 2017; Choy et al 2018 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|--------------------------|---------|-----------------------------|------------|---------------|--------------|
| Index of longitudinal riverine connectivity (ILRC) (Crook et al 2009) | evaluate both upstream and downstream effects of dams and water withdrawals on longitudinal connectivity in tropical streams evaluate both upstream and downstream effects of dams and water withdrawals on longitudinal connectivity in tropical streams evaluate both upstream and downstream effects of dams and water withdrawals on longitudinal connectivity in tropical streams Estimates probability that an individual shrimp larva can migrate downstream to the estuary (based on proportion of median flow left in the stream after withdrawal) and return to the reach where it was released as a larva (based on proportion of days with flow over the impoundment) | estimate the probability that an individual 'average' shrimp will be able to migrate downstream to the estuary and return to the reach where it was released as a larva estimate the probability that an individual 'average' shrimp will be able to migrate downstream to the estuary and return to the reach where it was released as a larva estimate the probability that an individual 'average' shrimp will be able to migrate downstream to the estuary and return to the reach where it was released as a larva. • Locations of dams and water-intake structures • Long-term daily streamflow data • Estimated or actual water withdrawal volume data | Index ranging between 0 and 1, split into three classes (high, moderate and low for ILRC scores of 0–0.33, 0.34–0.66, and 0.67–1 respectively) Each water intake structure | The effect of water withdrawal on juvenile shrimps is influenced by individual intakes in addition to all downstream intakes Where there are intakes in linear succession, juvenile shrimps may have to climb past all intakes in order to reach their ultimate habitat. In order to account for the lower probability that an individual juvenile shrimp will successfully scale multiple intakes, the proportion of days with flow for any downstream intake is multiplied by the proportion of days with flow for any upstream intake • Incorporates the effect of flow alteration and dams on longitudinal connectivity • Accounts for upstream and downstream cumulative passage probabilities • Represents longitudinal connectivity of streams from headwaters to estuaries. • Related to a biotic response; ecologically meaningful • Can be evaluated in relation to months of seasonally low discharge and drought | • Data intensive; requires long-term daily streamflow data and water withdrawal volumes • Suited to assess connectivity with respect to shrimp • Connectivity classes are arbitrarily described based on the index value • Assumes larvae are uniformly mixed in the water column although larval density varies with flow volume • Assumes that dam reservoirs do not impede connectivity | Crook et al 2009 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|--------------------------|---------|------------------------------|------------|---------------|--------------|
| Between Centrality—k (Bodin and Saura 2010) | A modified BC metric that weighs each stream reach by its patch area and maximum dispersal probabilities or topological distances (based on whether PC or IIC metric is used). | • River network lengths  
• Habitat area or volume  
• Dam locations  
• Estimates of dispersal probabilities<sup>a</sup> | Reaches ranked by their importance in maintaining basin-wide connectivity | River reach | • No primary data needed  
• Various development scenarios can be assessed  
• Stream reaches carrying larger flows that connect bigger patches are assigned higher weights; more ecologically meaningful  
• Incorporates dispersal probabilities | • Does not assess connectivity across spatial scales  
• Does not explicitly analyse the effects of dams  
• Values may not change even with the addition/removal of dams  
• Headwater/fringe reaches will always be ranked lower | Segurado et al 2013 |

<sup>a</sup> Watanabe et al 2012.
Table 1. (Continued).

| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|--------------------------|---------|-----------------------------|------------|---------------|--------------|
| DEN connectivity model (Padgham and Webb 2010) | Represents the ability of a fish to access different parts of a river network. Model based on habitat length, quality, and directional transition probabilities. | - Habitat quality (0–1)  
- Reach length  
- Dam locations  
- Upstream and downstream connectivity values (0–1)  
- Habitat volume | Matrix of transition probabilities between every pair of reaches in a network + reach scores that indicate equilibrium proportions of a population expected within each reach | River reach to network | - Spatially explicit  
- Can assess connectivity necessary to maintain metapopulations  
- Incorporates upstream and downstream connectivity probabilities  
- Incorporates habitat quality as a variable influencing connectivity  
- It can be applied for one or more target species based on their life history strategies and specific habitat requirements  
- Various development scenarios can be assessed  
- More complex parameters can be applied to the model  
- Weighted by habitat volume; more ecologically meaningful | - Assumes an unlimited range, which is biologically unrealistic. But incorporating restricted species ranges increases uncertainty of estimates  
- Quantifying directional transition probabilities can be challenging; results may vary based on the method used and assumptions made  
- More data intensive  
- Quantifying habitat quality is challenging  
- Computationally more challenging  
- Results susceptible to change based on the extent of the river network  
- Theoretical models with little empirical support | Webb and Padgham 2013 |
Table 1. (Continued).

| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|----------------------------|------------|---------------|--------------|
| Barrier score (Nunn and Cowx 2012) | Each barrier is scored based on a prioritization matrix of fish stock status, passage efficiency, likelihood of access, habitat quantity and habitat quality | Scores (1–5) for:  
- Fish stock status of the target species  
- Passage efficiency of target species  
- Likelihood of access based on upstream passage  
- Habitat quantity  
- Habitat quality | Barrier scores ranging from 1 to 3125 | Each barrier | Easy to compute  
- Suitable to rapidly assess and prioritize migration barriers for passage improvements  
- Can be applied for more than one target species or river basin  
- In cases of lacking empirical data, expert judgement can be used  
- Various development scenarios can be assessed  
- Spatially explicit  
- Incorporates 5 variables: more ecologically meaningful  
- Can incorporate cumulative passage probabilities | Does not quantify connectivity of fragmentation of river reach, network or basin. Instead ranks each barrier based on potential for passage improvements  
- Not applicable across spatial scales  
- Barriers ranked as highest priority need not be the ones that affect connectivity the most  
- Scoring of the five variables for each fragment relies on subjective data or expert judgement | Nunn and Cowx 2012 |
| Connectivity/fragmentation metric                        | Description                                                                                                                                                                                                 | Inputs/Data requirements                                                                 | Outputs                                                                                       | Spatial scale of application | Advantages                                                                                                                                                                                                 | Disadvantages                                                                                                                                                                                                 | Applications |
|---------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| Habitat Connectivity Index of Upstream passage (HCIUP) (Mckay et al 2013) | Assesses upstream fish passage connectivity as a habitat-weighted, cumulative passage rate. By summing across all reaches, the HCIUP is computed as the ratio of accessible to total habitat in the river network | • Metric of habitat availability (river network length, area, volume etc)  
• Upstream connectivity values (0–1)  
• Dam locations  
• Waterfall locations<sup>a</sup> | Ratio of accessible habitat ranging from 0 to 1 | Sub-basin to basin | • Can assess connectivity for target species, taxa or guilds  
• The measure of habitat availability could factor in habitat quality, discharge or other variables of interest (river length, area, volume, length-weighted discharge etc)  
• Can be modified to assess the impacts of fragmentation on other processes such as movement of woody debris or sediment.  
• Incorporates quantum of habitat accessible and the cumulative passage rate to that point  
• Can assess connectivity across spatial scales  
• Can incorporate natural barriers | • Focuses on upstream connectivity only—downstream passage is neglected (suited for diadromous species)  
• Computationally more challenging, especially as network topology becomes more complex  
• Assumes the probability of passing one barrier is independent of the probability of passing another barrier  
• Quantifying transition or connectivity probabilities can be challenging; results may vary based on the method used and assumptions made  
• Values may not change even with the addition/removal of dams | Rodeles et al 2019 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|-------------------------|---------|----------------------------|------------|---------------|--------------|
| River Connectivity Index (RCI) (Grill et al 2014) | An index of connectivity calculated from river flow volume; like DCI, it assesses the potential of a fish to travel between two chosen points in a river network. | • River network lengths  
• Reach wetted widths and heights  
• Dam locations  
• Dam passability values  
• Waterfall locations | An index of connectivity ranging from 0 to 100 | River reach to basin | • Values sensitive to the location of the barrier on the river network (impact of dams further downstream is weighted to be higher by volume)  
• Can incorporate natural barriers  
• No primary data needed  
• Values range between 0 and 100 and are easy to interpret  
• Barrier permeabilities can be incorporated in the analysis  
• Various development scenarios can be assessed  
• Can assess connectivity across spatial scales | • Challenging to derive Grill et al 2015 reach-level habitat volume (computed as reach length x wetted width x water stage/height); often volume estimates are prone to high error in small reaches and regions of poor data-availability  
• Results susceptible to change based on the extent of the river network  
• Headwater RIPS that lie beyond the delineated river network are often excluded from analysis  
• Assumes the probability of passing one barrier is independent of the probability of passing another barrier |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|--------------------------|---------|-----------------------------|------------|---------------|--------------|
| Weighted River Connectivity Index (Grill et al 2014) | An index of connectivity calculated from river flow volume and weighted by ecologically meaningful variables such as river class/e-coregion (RCl\text{class}) or species-specific migration ranges (RCl\text{range}). | • River network lengths  
• Reach wetted widths and heights  
• Dam locations  
• Information on key variables to be used in the weighting  
• Dam passability values\(^a\)  
• Waterfall locations\(^a\) | An index of connectivity ranging from 0 to 100 | River reach to basin | • Values sensitive to the location of the barrier on the river network (impact of dams downstream weighted to be higher by volume)  
• Can incorporate natural barriers  
• Can incorporate other variables of importance such as connectivity between different river classes or migration ranges  
• Values range between 0 and 100 and are easy to interpret  
• Barrier permeabilities can be incorporated in the analysis  
• Various development scenarios can be assessed  
• Can assess connectivity across spatial scales | • Challenging to derive Grill et al 2014 reach-level habitat volume (same as RCI)  
• Results susceptible to change based on the extent of the river network  
• Headwater RPs that lie beyond the delineated river network are often excluded from analysis  
• Assumes the probability of passing one barrier is independent of the probability of passing another barrier |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|-----------------------------|------------|---------------|--------------|
| C metric (Diebel et al 2015)      | Defines the connectivity of a stream reach as a function of the degree of access to and from the range of seasonal habitat types that fish use. The 'C' values for all the segments in a watershed can be aggregated to describe connectivity at the watershed scale. | • River network length  
• Habitat types  
• Barrier passability values  
• Habitat quality metrics<sup>a</sup>  
• Dam locations  
• Waterfall locations<sup>a</sup>  
• Distance-weighted dispersal limit | Connectivity status ranging from 0 to 1 | Reach and watershed level | • Quantifies the individual and cumulative effects of barriers  
• Accounts for natural barriers  
• Accounts for habitat quantity, quality, and distance of different habitat types that can be accessed by stream-resident fish in both directions  
• Incorporates distance-based dispersal limitations  
• Can be defined for an individual species or a fish community  
• Barrier permeabilities can be incorporated  
• Various development scenarios can be assessed  
• Can assess connectivity across spatial scales | • Oriented to stream-resident fish; not suited to diadromous species  
• Does not explicitly analyse the effects of individual dams  
• Treats stream reaches across a longitudinal gradient as ecologically equivalent  
• Results susceptible to change based on the extent of the river network  
• Headwater RPs that lie beyond the delineated river network are often excluded from analysis  
• More data-intensive | O'Hanley et al 2013 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|---------|-----------------------------|------------|---------------|--------------|
| Fragmentation index (Díaz et al 2019) | A fragmentation index calculated from stream length and Strahler stream order | • River fragment lengths  
• River fragment stream order  
• Dam locations | Fragmentation index between 0 to 1 | Sub-basin to basin | • No primary data needed  
• Easy to compute  
• Values range between 0 and 1 and are easy to interpret  
• Values sensitive to the location of the barrier on the river network  
• Can incorporate natural barriers  
• Various development scenarios can be assessed  
• Can assess connectivity across spatial scales  
• Allows assessment of cumulative effects of barriers | • Barrier permeability treated as a binary value  
• Cannot incorporate ecological information  
• Stream orders are dependent on data resolution and threshold of delineation  
• Results susceptible to change based on the extent of the river network  
• All dams are treated the same despite differences in size and impact  
• Headwater RIPs that lie beyond the delineated river network are often excluded from analysis | Díaz et al 2019 |
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|-------------------------|---------|-----------------------------|------------|---------------|--------------|
| Metapopulation models of directed connectivity | A migration model for metapopulation connectivity of salmon (or any other diadromous species) | • River network length  
• Dam locations  
• Locations of population groups and sizes  
• Distance matrix between all populations  
• Distance-based dispersal probability matrix  
• Population source-sink structure as a diagraph | Diagraphs of spatially explicit populations under various scenarios of development (with population size and connectivity strength and direction illustrated) | Basin scale | • Assesses impact of barriers on population or metapopulation of target species in a basin(s).  
Can shed light on source-sink dynamics, colonisation, and network-wide population connectivity  
• Historic and future scenarios of development can be incorporated  
• Incorporates recruitment in its measure of connectivity  
• Spatially explicit  
• Graph theory sheds light on inter-population connectivity and the importance of single populations in a river network  
• Model illustrates system function, and sheds light on restoration strategies | • Data-intensive; requires information on the distribution of Leibowitz and White 2009 distinct populations in a river network, population size and movement dynamics  
• Species-specific and works best for anadromous species  
• Not suited to non-migratory species with small home ranges  
• Defining distinct populations could be subjective  
• Defining strength of inbound and outbound connections could be subjective and error-prone depending on data availability  
• Analysis cannot be carried out across spatial scales |
### Table 1. (Continued).

| Connectivity/fragmentation metric         | Description                                                                 | Inputs/Data requirements                                                                 | Outputs |
|-------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------|---------|
| **Actual connectivity metrics**          |                                                                             |                                                                                         |         |
| Lateral connectivity parameter ($C_d$)   | A connectivity parameter ($C_d$) defined as the average annual duration (days per year) of surface connection of floodplain waterbodies with the main river channel | - Stage-discharge relationship at the upstream end of each side channel  
- Frequency distribution of river discharge  
- Stage at which water flows into the side channel | $C_d$ values for each waterbody  
Waterbodies/side channels |

| Spatial scale of application | Advantages                                                                 | Disadvantages                                                                 | Applications |
|-----------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------|
|                             | Quantifies the duration of actual hydrological connection based on flow data                               | Reliance on multi-year flow data limits its application in data-deficit regions |
|                             | Depends on flow pattern of the river and the position of these waterbodies relative to river height | Cannot assess impacts of proposed scenarios since it relies on flow data       |
|                             | Can be calculated across seasonal and temporal time scales                 | Ability to calculate $C_d$ values for a side channel depends on the availability of a gauging station at its upstream end |
|                             | Waterbodies can be categorised into connectivity classes based on ranges of $C_d$ values                | Change in $C_d$ can be influenced by RIPS or other drivers such as climate change or changes in baseline conditions |
|                             |                                                                           | Does not account for other connectivity dimensions                             |

Reckendorfer et al 2006
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|--------------------------|---------|-----------------------------|------------|---------------|--------------|
| Human observations of movement    | Location of target species/taxa over the study area | Variable, depending on study objectives and design (snorkeling, filming) | Variable | River reach to tributary | Detailed information on actual movement/connectivity and behaviour | Effort intensive | Johnston 2000 |
| Bio-acoustic/hydroacoustic sonar   | Measurement of fish locations, densities, and movement using fixed or mobile acoustic sensors | Primary hydroacoustic sonar data | Variable | River reach to river network | Detailed information on actual movement/connectivity | High data processing | Burwen et al 2005; Dey et al 2019 |

(Continued)
Table 1. (Continued).

| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Outputs | Spatial scale of application | Advantages | Disadvantages | Applications |
|----------------------------------|-------------|--------------------------|---------|----------------------------|------------|---------------|--------------|
| Telemetry                        | Movement information of tagged individuals over space and time | • Telemetry data (usually from PTI, radio or acoustic tags) | Variable | River reach to river network | • Detailed information on actual movement/connectivity and behaviour | • Expensive | Schrank and Rahel 2004; Gosset et al 2006 |
| Direct sampling (electroshocking, seining or trapping) | *In-situ* fish capture | Spatally explicit information on: • Richness • Presence/absence • Abundance • Density • Species composition | Presence-absence data, composition similarity, richness, diversity, abundance and density estimates | River reach to river network | • Detailed information on community composition and changes across spatiotemporal scales | • Limited information on barrier passability | Merritt and Wohl 2006; Alexandre and Almeida 2010; Jumani et al 2018 |

(Continued)
| Connectivity/fragmentation metric | Description | Inputs/Data requirements | Spatial scale of application | Advantages | Disadvantages | Applications |
|-----------------------------------|-------------|-------------------------|----------------------------|------------|---------------|--------------|
| Molecular or genetic markers (such as DNA microsatellites) | Genetic material extracted from tissue samples | Molecular or genetic data on target species, diversity, differentiation or similarity | Subbasin to basin | Quantifies metapopulation connectivity for a given site and species of interest | Requires technical skill to analyse and interpret the data | Wofford et al. 2005; Faulks et al. 2011; Tortonot et al. 2014 |
|                                   |             |                         |                           | Fine spatiotemporal resolution | Connectivity can be assessed at the scale of the populations or individuals | |
|                                   |             |                         |                           | Can shed light on connectivity across temporal scales | Often requires specialised mathematical and computer programming expertise to develop models | |
|                                   |             |                         |                           | Can distinguish between populations and even individuals | Requires collections of specimens or biotic samples | |
|                                   |             |                         |                           |                                  | Significantly more expensive compared to other methods | |

* not essential data requirements
Table 2. List of flow alteration metrics with their description, data requirements, output, spatial scale of application, and advantages and disadvantages.

| Flow alteration metric                  | Description                                                                 | Data requirements                           | Output                                      | Spatial scale of application                                                                 | Advantages                                                                 | Disadvantages                                                                 | Applications |
|-----------------------------------------|------------------------------------------------------------------------------|---------------------------------------------|---------------------------------------------|------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|--------------|
| Annual proportional flow deviation (APFD) (Gehrke et al 1995) | Comparison of post-impact and unimpacted baseline monthly flows, calculated as the sum of the ratios of change in monthly flow (actual—natural) to natural monthly flow | Short-term (1–5 years) monthly flow data across un-impacted and impacted spatial or temporal scales | APFD values ranging from 0 (unregulated river) to 3.46 (where there is a 100% increase or decrease in flow with no seasonal change) | River reach from which hydrological data have been gathered | - Reliance on monthly measured or simulated flow data increases its scope of application even in data-limited environments  
- Simple indicator, can be quickly calculated when flow data are available  
- Indicates how flow volume and seasonal flow patterns are being affected; mitigation measures can be tailored to target restoration  
- Can assess the individual and cumulative impact of reservoirs  
- Sensitivity to changes in flow waveform.  
- Can be calculated at monthly and annual timescales | - Reliance on monthly flow data can limit its application in data-deficit regions  
- Difficult to obtain unimpacted monthly flows  
- Difficult to assess RIs with short post-dam hydrology or no flow gauges  
- Cannot assess impacts of proposed RIs since it relies on post-dam flow data  
- Ability to calculate cumulative impacts depends on the spatial configuration of dams and gauging stations  
- Change in flow parameters between 'before' and 'after' scenarios can be influenced by other drivers such as climate change or changes in baseline conditions (i.e. assumes stationarity)  
- Does not directly relate ecological responses to flow statistics  
- Does not explicitly consider various components of the flow regime  
- Not suitable for ephemeral streams where natural monthly flows can be nil | Ladson et al 1999 |
| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|------------------|--------|-----------------------------|------------|---------------|--------------|
| Indicators of hydrologic alteration (IHA) \( (Richter et al. 1996) \) | Quantifies the eco-hydrological effects of flow regulation by measuring changes in 33 flow statistics, organized within the five primary components of flow regime (flow magnitude, frequency, duration, timing, and rate of change) | Time-series of daily streamflow data | Measures of central tendency and dispersion for 33 hydrologic parameters (i.e. 66 inter-annual statistics) | River reach from which hydrological data have been gathered | • Strong conceptual foundation  
• Quantitatively robust  
• Simple indicators of flow components allow for quick calculation when flow data are available  
• Indicates the degree to which different flow components are being affected; mitigation measures can be tailored to target restoration  
• Analysis supported by an open-access software developed by The Nature Conservancy  
• Can assess the individual and cumulative impact of reservoirs | • Reliance on long-term flow data limits its application in data-deficit regions  
• Difficult to assess dams with short post-dam hydrology or no flow gauges  
• Cannot assess impacts of proposed RIs since it relies on post-dam flow data  
• Extensive data processing to account for data-gaps  
• Ability to calculate cumulative impacts depends on the spatial configuration of dams and gauging stations  
• Assumes stationarity  
• Large number of intercorrelated metrics can be redundant and complicated to apply in flow assessments  
• Does not directly relate ecological responses to flow statistics | Mathews and Richter 2007; Timpe and Kaplan 2017 |
Range of variability approach (RVA) (Richter et al. 1997)

Quantifies the change in the range of variation of 33 IHA parameters from the pre-impact period to the post-impact period. Each parameter is categorised into high, medium or low categories based on user-defined targets, and a hydrologic alteration category is calculated based on relative frequency of the RVA target range not attained.

Time-series of daily streamflow data

Hydrologic alteration category for each of the 33 parameters based on the percentage of years the RVA target range is not attained, expressed as high, medium and low (with hydrologic alteration values of 68%–100%, 34%–67%, and 0%–33% respectively).

River reach from which hydrologic data have been gathered

- Relies on IHA parameters; has a strong conceptual foundation based on natural variability of ecosystems
- Simple to measure when flow data are available
- Indicates the extent of deviation of the range of natural variation for 33 IHA parameters; flow management measures can be tailored accordingly
- Analysis supported by an open-access software developed by The Nature Conservancy
- Can assess the individual and cumulative impact of reservoirs
- Useful for setting flow targets for regulated streams
- Can be adapted based on ecological information and monitoring data
- Uses the pre-development range of natural variation of IHA parameters as a reference to determine the extent to which flow regimes have been altered

Disadvantages

- Reliance on long-term flow data limits its application in data-deficit regions
- Challenging to characterize natural range of variation when streamflow records pre-dating human perturbation are not available
- Applying 33 eflow targets can be complicated
- Difficult to assess dams with short post-dam hydrology or no flow gauges
- Cannot assess impacts of proposed RIPs since it relies on post-dam flow data
- Extensive data processing to account for data-gaps
- Ability to calculate cumulative impacts depends on the spatial configuration of dams and gauging stations
- Assumes stationarity
- Deciding on the measure of dispersion and RVA targets is subjective and based on specific goals
- Does not consider the periodicity or temporal order of IHAs (only considers the frequency of each IHA)

Applications

Richter et al. 1998; Mittal et al. 2014
| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|-------------------|--------|----------------------------|------------|---------------|--------------|
| Degree of regulation (DOR) (Lehner et al 2011) | Calculates the proportion of a river's annual flow that can be withheld by a reservoir or a cluster of reservoirs for a river reach | Reservoir storage capacities and annual discharge | A continuous index of proportions | River reach to river network | • Does not require flow data or information on dam operations; hence can be applied in the most data-deficit regions  
• Input data of reservoir storage capacities and discharge can be estimated even when not available  
• Can be calculated easily across spatiotemporal scales, making it suitable for iterative scenario analysis  
• Can assess the individual and cumulative impact of reservoirs  
• Various development scenarios can be assessed | • Does not explicitly consider the flow regime  
• While high values correspond to higher inter- and intra-annual flow alteration, low values do not always correspond to lower impacts. Low values may be associated with severe impacts on some aspect of the flow regime  
• Impacts may manifest differently in differently sized streams  
• Does not represent impact on biological patterns and processes.  
• Does not consider flow alteration due to water abstraction or river dewatering  
• Cannot be applied in eflow assessments | Grill et al 2019 |
| Flow alteration metric                          | Description                                                                                       | Data requirements                                                                 | Output                                                                 | Spatial scale of application                                                                 | Advantages                                                                                                                                                                                                                     | Disadvantages                                                                                                                                                                                                 | Applications |
|-----------------------------------------------|--------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| Dundee Hydrological Regime Alteration Method (DHRAM) (Black et al. 2005) | Applies the IHA approach to classify the risk of damage to instream ecology from streamflow alterations using a five-class scheme compatible with the requirements of the EC Water Framework Directive | Time-series of daily mean flow in un-impacted and impacted sites in relation to any type of anthropogenic hydrological impact | DHRAM scores (0–30) and DHRAM classes between 1 (Un-impacted condition) and 5 (Severely impacted condition) | River reach from which hydrological data have been gathered | • Indicates the degree to which different flow components are being affected; mitigation measures can be tailored to target restoration  
• Where suitable hydrological data are unavailable or incomplete, synthetic flow data can be generated using approaches outlined in the DHRAM manual  
• Scoring of reaches permits identification of sites requiring further assessments and conservation efforts  
• Analysis supported by a Windows program, WiDHRAM  
• Can assess the individual and cumulative impact of reservoirs | • Reliance on long-term flow data limits its application in data-deficit regions. Use of synthetic data increases the risk of errors, distorting DHRAM results  
• Difficult to assess dams with short post-dam hydrology or no flow gauges  
• Cannot assess impacts of proposed RIs since it relies on post-dam flow data  
• Extensive data processing to account for data-gaps  
• Does not relate ecological response to the flow statistics  
• For widespread status assessments, repeated DHRAM applications on river reaches downstream of alterations will be required  
• Ability to calculate cumulative impacts depends on the spatial configuration of dams and gauging stations  
• Assumes stationarity | Gao et al. 2009 |
| Flow alteration metric           | Description                                                                 | Data requirements | Output                                                                 | Spatial scale of application | Advantages                                                                 | Disadvantages                                                                 | Applications                |
|--------------------------------|-----------------------------------------------------------------------------|-------------------|------------------------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------|
| Hydroecological Integrity Asses... | Uses a Hydrologic Index Tool to calculate 171 streamflow statistics and a Hydrologic Assessment Tool to determine the degree of departure from baseline conditions | Time-series of daily mean flow and peak flow data | 171 biologically relevant streamflow statistics for baseline and altered condition | River reach from which hydrologic data have been gathered | - Indicates the degree to which different flow components are being affected; mitigation measures can be tailored to target restoration. | - Reliance on long-term flow data limits its application in data-deficit regions. | Kennen et al 2009 |

(Continued)
### Table 2. (Continued).

| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|-------------------|--------|-------------------------------|------------|---------------|--------------|
| Environmental flow components (EFC) (Mathews and Richter 2007) | Quantifies changes in 34 flow statistics organized within five major ecologically important flow components: low flows, extreme low flows, high flow pulses, small floods, and large floods. | Time-series of daily streamflow data | Measures of central tendency and dispersion for 34 environmental flow component parameters | River reach from which hydrological data have been gathered | • Complements the original 33 IHA parameters  
• Based on ecologically important flow parameters  
• When pre-impact flow data is available, can be used in RVA analysis  
• Strong conceptual foundation  
• Quantitatively robust  
• Simple indicators of flow components allow for quick calculation when flow data are available  
• Indicates the degree to which different flow components are being affected; mitigation measures can be tailored to target restoration  
• Analysis supported by an open-access desktop software developed by The Nature Conservancy  
• Can assess the individual and cumulative impact of reservoirs | • Reliance on long-term flow data limits its application in data-deficit regions  
• Difficult to assess dams with short post-dam hydrology or no flow gauges  
• Cannot assess impacts of proposed RIPS since it relies on post-dam flow data  
• Extensive data processing to account for data-gaps  
• Ability to calculate cumulative impacts depends on the spatial configuration of dams and gauging stations  
• Assumes stationarity  
• Large number of intercorrelated metrics can be redundant and complicated to apply in environmental flow assessments | Morid et al. 2019 |
| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|-------------------|--------|-----------------------------|------------|--------------|--------------|
| Overall degree of hydrologic alteration (Shiau and Wu 2007) | An index of overall flow regulation based on the integration of individual degree of hydrologic alteration for each of the 33 hydrologic parameters of the IHA | Time-series of daily stream-flow data | Percentage indicating overall flow regulation | River reach from which hydrological data have been gathered | • Based on IHA indicators  
• Collapses the many inter-correlated metrics of IHA into a single value that is easy to interpret and analyse  
• Easy to compute based on the individual degree of hydrologic alteration for each of the 33 hydrologic parameters of the IHA  
• Can assess the individual and cumulative impact of reservoirs | • Reliance on long-term flow data limits its application in data-deficit regions  
• Difficult to assess dams with short post-dam hydrology or no flow gauges  
• Cannot assess impacts of proposed RIFs since it relies on post-dam flow data  
• Does not indicate the degree to which different flow components are being affected  
• Extensive data processing to account for data-gaps  
• Assumes stationarity  
• Does not relate ecological response to the flow statistics | Shiau and Wu 2007 |
| Flow alteration metric                      | Description                                                                 | Data requirements                                                                 | Output                                                                 | Spatial scale of application | Advantages                                                                                                           | Disadvantages                                                                                                                                                                                                                           | Applications                        |
|--------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------|-----------------------------|----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| Ecodeficit/ecosurplus concept (Vogel et al 2007) | Nondimensional metric, based on a flow duration curve (FDC), which represents the deficit or surplus streamflow resulting from flow alteration, as a fraction of the mean streamflow in a typical or median year | Unimpacted and impacted FDCs (or water resource index duration curves) for a period of record or a median annual year | Quantification of difference in the net volume of water available to meet instream flow requirements | River reach from which hydrological data have been gathered | • Less data intensive to compute FDCs • Can be computed over any time period of interest (month, season, or year) and reflect the overall loss or gain in streamflow due to flow regulation during that period • Use of seasonal FDCs can capture seasonal variations • Graphical representation of these metrics provides an easily understood visualization of changes to flow conditions • Water resource index duration curves can also be used (Vogel and Fennessey 1995) | • Although FDCs represent the historical frequency of streamflow conditions, they do not account for the timing or duration of flow events • May not be able to capture the life history requirements of target species • Careful interpretation of results required when period of record FDCs are used • Does not relate ecological response to the flow statistics • Generally, small values of ecodeficit/ecosurplus correspond to low values of hydrologic alteration. • Cannot assess the impact of individual reservoirs on river regulation | Gao et al 2009                      |
| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|-------------------|--------|-----------------------------|------------|---------------|--------------|
| Flow-ecology response curves (part of numerous eflow assessments such as ELOHA, DRIFT) (Poff et al 2010) | Combines hydrology, channel hydraulics, ecology and social processes to build mechanistic links between hydrology and ecology through flow-ecology response curves based on river type. | Time-series of flow data to build the ‘hydrologic foundation’ of baseline and present-day hydrographs; ecological data and expert opinion to create flow-ecology response curves | Flow-ecology response curves for classified rivers across a broad area | River reach from which hydrological data have been gathered | • Accounts for ecological response to flow alteration  
• Factors in a social process where e-flow goals can be societally set  
• Applicable across broader scales  
• Accounts for cumulative effects of all water uses in the catchment  
• Can be continually improved through monitoring, validation, and stakeholder feedback  
• Suited for real-world implications, as it allows policy- and decision-makers and stakeholders to influence the outcome while still being scientifically rigorous  
• Clear applications  
• Relies on existing data and can combine existing literature, expert knowledge, and empirical data | • Relies on extensive and synchronised hydrologic and biological databases  
• Accuracy of outputs depend on accuracy of curves correlating ecological and flow conditions.  
• Links between biotic and abiotic factors are complex and data is mostly imperfect, causing uncertainty  
• Does not account for loss of longitudinal or lateral connectivity due to barriers  
• Science-derived but still subjective given that human stakeholders and decision-makers ultimately decide on targets and which curve to use | Mcclain et al 2014; Cartwright et al 2017; Rosenfeld 2017 |
Table 2. (Continued).

| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|------------------|--------|-----------------------------|-----------|--------------|--------------|
| River Regulation Index (RRI) (Grill et al 2014) | Quantifies how strongly a river may be affected by flow alterations from upstream dams | Reservoir storage capacities and annual discharge (measured or estimated) | Continuous index of proportions | River basin | • Does not require flow data or information regarding dam operations; hence can be applied in most data-deficit regions  
• Input data of reservoir storage capacities and discharge can be estimated even when not available  
• Easily calculated across scales, making it suitable for iterative scenario analysis (including new dams and future scenarios)  
• Various development scenarios can be assessed | • Does not explicitly consider the flow regime  
• While high values correspond to higher inter- and intra-annual flow alteration, low values do not always correspond to lower impacts. Low values may be associated with severe impacts on some aspect of the flow regime  
• Impacts may manifest differently in differently sized streams  
• Does not represent impact on biological patterns and processes  
• Does not consider effects of water abstraction or river dewatering  
• Cannot be applied in eflow assessments | Grill et al 2015 |
Table 2. (Continued).

| Flow alteration metric | Description                                                                 | Data requirements                                                                 | Output                                                                 | Spatial scale of application | Advantages                                                                 | Disadvantages                                                                                   | Applications |
|------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------|
| Effective Degree of Regulation (EDOR) | Ratio of volume of water that is displaced (stored or released) by the operation of a dam or a cluster of dams, to the river’s naturalized flow without dams | Reservoir storage capacities and annual discharge (measured or estimated) Reservoir operation (volume of water released and stored) | Continuous index of proportions | River reach to river network | · Sensitive to changes in reservoir operation  
· Can be calculated at monthly and annual time scales  
· Can assess the effect of climate change on the operation of dams  
· Does not require flow data  
· Easily calculated across scales, making it suitable for iterative scenario analysis | · Reliance on reservoir operation information limits its application  
· Does not encapsulate variability in flow components  
· While high values correspond to higher inter- and intra-annual flow alteration, low values may not correspond to lower impacts. Low values may be associated with severe impacts on some aspect of the flow regime  
· Impacts may manifest differently in differently sized streams  
· Does not represent impact on biological patterns and processes | Ehsani et al 2017 |

(Continued)
| Flow alteration metric | Description | Data requirements | Output | Spatial scale of application | Advantages | Disadvantages | Applications |
|------------------------|-------------|-------------------|--------|----------------------------|------------|---------------|--------------|
| Statistical models of the counterfactual (Valle and Kaplan 2019) | Model-based evaluation of how post-dam hydrology differs from ‘what would have happened’ in the absence of the impact | Time-series of hourly, daily, or monthly flow or water level data and other relevant hydroclimate data (water levels, flows, precipitation, etc) | Magnitude and statistical likelihood of difference between each post-impact observation and the expected pre-impact value | River reach from which hydrological data have been gathered | • Avoids assumptions of stationarity inherent to ‘before-after’ analyses  
• Captures uncertainty associated with data gaps  
• Can identify statistically significant alteration without a prescribed period of post-impact data  
• Explicitly identifies post-impact observations that deviate from expected behaviour; not restricted to pre-conceived flow metrics or statistics | • Requires hydroclimate data to build models of response variables (water level or flow) in the pre-impact period, which may not be available  
• Assume climate variables are not impacted by dams or their reservoirs  
• Does not explicitly account for land use/land cover change  
• Difficult to summarize as a simple index | Valle and Kaplan 2019 |

Table 2. (Continued).
Figure 3. Decision-making tree for selection of river connectivity metrics based on objective, data availability, and distribution of infrastructure projects in the basin. Superscripts indicate barrier passability values to be binary (b) or continuous (c); The symbol ♦ indicates method designed to assess connectivity for fish communities. Colours blue, black, and orange indicate structural, potential, and actual connectivity metrics, respectively.

and resource requirements (especially directionality of movement, dispersal distances, and migration) should influence metric selection. For example, when assessing connectivity for diadromous species, the DCI-d, Weighted RCI, ILRC, DEN connectivity model, HCIUP, or the Metapopulation model of directed connectivity could be applied. Metric selection should also be informed by the distribution of RIPs in the study area. Some metrics, such as Fragmentation classes, DCI-d, BC-k, and HCIUP, may not reflect any change with the addition or removal of dams because of the way they are defined. For example, when using Fragmentation classes (Nilsson et al. 2005), dammed large tributaries are assigned a fragmentation score of 2. This score remains the same irrespective of the number of dams present. Similarly, when applying the DCI-d (Cote et al. 2009) at the scale of the river network with binary dam passabilities, the addition or removal of dams above the first barrier will not alter the index value. Hence, these metrics should only be used in specific instances where applicable. Another consideration for river length-dependent metrics is the presence of RIPs on seasonal headwater streams. Often such dams lie beyond the delineated stream network and are consequently excluded from the analysis (as done in Hoenke et al. 2014, Anderson et al. 2018). Hence, when numerous RIPs are situated in headwater streams or when connectivity in headwater reaches needs to be specifically assessed, these metrics should be used with caution.

An important application of fragmentation metrics is the optimization of barrier removal or placement to maximise connectivity for a target species or taxa (Mckay et al. 2017). The reliability and ecological significance of the connectivity metric used in these applications are crucial, and hence the use of structural metrics should be avoided in these cases. When more reliable metrics are unavailable due to data limitations, all attempts should be made to validate structural metrics with empirical field data and determine their spatial scale of influence. Another point of consideration is that structural and potential
metrics that rely on river network lengths are prone to non-uniform change based on the extent of the river network delineated, which itself is dependent on the resolution of the base data, delineation techniques and thresholds used (Zhou and Liu 2002, Murphy et al 2008, Ariza-Villaverde, Jiménez-Hornero, and Gutiérrez de Ravé 2015, Kumar et al 2017). It is important to note that these changes are an artefact of changing river network lengths and do not signify a change in actual connectivity.

4.2. Flow alteration metrics

A vast majority of research related to flow alteration caused by RIPs is prescriptive and mostly aimed at recommending environmental flows in regulated streams (Hirji and Davis 2009, Poff et al 2010, Horne 2017). These approaches have been well studied and reviewed in the scientific literature, but comparatively far fewer descriptive measures of flow alteration exist. Descriptive measures allow users to assess the extent of alteration of a river’s natural flow regime in response to various anthropogenic influences relative to undisturbed baseline conditions. Since streamflow is a master variable influencing water quality, physical habitat characteristics, ecosystem functions and processes, and native biotic communities (Poff et al 1997), quantifying the extent of flow alteration has important implications for basin-wide conservation and development planning, and for setting suitable environmental flow recommendations.

Our review documented 13 descriptive measures of flow alteration. These methods vary in their data requirements, spatial scale of application, and output, each having their own assumptions, advantages and disadvantages (table 2). Figure 4 presents a decision-making tree to help users select a suitable method to assess flow alteration given the availability of streamflow, reservoir storage and discharge data, and specific objective. This decision tree, when used with the information in table 2, can allow users to make informed decisions about the types of flow alteration measures that can be quantified in different contexts. For example, when long-term observed or simulated streamflow data are available, we identified 10 available methods to assess flow alteration. Of these, the IHA, RVA, DHRAM, EFC, and HIAP quantify the degree to which different flow components (i.e. flow magnitude, frequency, duration, timing, and rate of change) are affected. This contrasts with the APFD, Overall Degree of Hydrologic Alteration and Ecodeficit/Ecosurplus methods which quantify the extent of flow alteration over a given time scale. Flow-ecology response curves and statistical models of the counterfactual can be used to assess both the alteration to various flow components and overall flow over a period of time (figure 4).

When long-term streamflow data are unavailable, as is the case in numerous developing countries witnessing a surge in dam development, we identified only three possible methods- DOR, RRI, and EDOR-that require data on reservoir storage capacities and annual discharge. Though these metrics are useful in data-deficit regions and are easy to calculate, they provide no insight on how various components of the flow regime are affected over time. They also do not consider the impacts of water abstraction (except for EDOR), diversion, and dewatering of river channels. This is especially problematic if the study area has numerous small or low-head dams with little or no reservoir storage. Furthermore, the impacts of flow regulation as measured by these methods can manifest differently in differently sized streams, despite having the same numerical values. To this end, reach-scale classification through characteristics such as geomorphic features may be useful to relate ecological relationships in regions with deficient streamflow records (Poff et al 2010). Complex alphanumeric classification methods (e.g. Rosgen 1994) may prove overly cumbersome to relate channel features to ecological systems (Simon et al 2007); simpler geomorphic classifications that describe variations in processes such as sediment mobility and stream power (Montgomery and Buffington 1997, Poff et al 2006) can explain ecological relationships where streamflow alteration cannot be assessed. Such classification methods could be useful for relating effects of river discharge to ungauged streams.

All but one of the above methods utilise streamflow, reservoir storage and/or discharge data to calculate various flow statistics without relating to an ecological response. If users need a metric that links flow alteration to an ecological response, the flow-ecology response curve is a versatile approach that can be used to assess the extent of change to one or more flow components or overall flow in relation to ecological responses of interest (Poff et al 2010).

Overall, the efficacy of all the connectivity and flow alteration metrics listed above will be greatly influenced by spatiotemporal extent and resolution of input data (Murphy et al 2008, Yang et al 2014, Woodrow et al 2016), uncertainties or errors associated with modelled or simulated data (Bond and Kennard 2017), and compatibility of scale of response and scale of analysis (Gaucherel 2007, Mahlum et al 2014). While no single method can be all-encompassing, the selection of appropriate connectivity and flow alteration metrics should be carefully made based on the study objective, data availability, and a thorough knowledge of the assumptions, advantages, and disadvantages of the available methods.

5. Applications and directions for future research

The methodological advancements in characterizing river fragmentation and flow alteration described above provide a wide variety of tools for researchers
and resource managers to understand the effects of RIPs on river ecosystems. A range of these metrics can be effectively applied to guide monitoring and adaptive management programs aimed at maximizing riverine and ecological connectivity and restoring or maintaining the natural flow regime under various scenarios of existing and proposed RIP development. They can also be applied to identify priority reaches for the implementation of mitigation measures, and aid in the creation of basin-wide conservation and development plans not only after but also before projects are implemented. The growth and utility of such tools have coincided with widely available resources to facilitate analysis: increasing access to GIS and computational capabilities (such as FIPEX (Fisheries and Oceans Canada 2011), FIDIMO (Radinger et al 2014), online repositories of dams (such as GRAND (Lehner et al 2011), GOODD (Mulligan, van Soesbergen, and Säenz 2020), FRIReD (Zarlí et al 2015), spatial datasets of hydrologic networks (such as HydroSHEDS (Lehner et al 2008), HydroBASINS (Lehner and Grill 2013) and streamflow data (GSCD (Beck et al 2013); GRDC (http://grdc.bafg.de), FLO1K (Barbarossa et al 2018); RiverATLAS (Linke et al 2019)) has made several fragmentation and flow alteration indices more readily applicable across larger spatial scales. Despite these advances, there remain numerous areas for further research to improve the performances of these metrics, especially given their applications in basin-wide conservation and development planning. These are briefly discussed below.

5.1. Relationships among metrics
Although river connectivity and flow alteration characterize two different types of variables, because flows control hydrologic connectivity, the two variables often interact and influence one another (Grill et al 2014). For example, dam-induced flow alterations can result in reduced wetted channel widths and/or depths, which can affect lateral and vertical connectivity (Junk et al 1989, Wiens 2002). Water abstraction and diversions can create dewatered river stretches which impede water-mediated longitudinal connectivity (Deitch, Kondolf, and Merenlender 2009). Large reservoirs can significantly alter thermal regimes, which can further act as a thermal barrier to various organisms (Caudill et al 2013). While most measures of connectivity focus on the longitudinal dimension, far fewer metrics are aimed at assessing lateral and vertical connectivity. Additionally, since river connectivity is water-mediated, the force and direction of flow exerts a strong influence on ecological connectivity and ecosystem processes such as transport of sediment, nutrients, and organisms with limited or no mobility (Fullerton et al 2010). Hence, connectivity measures that do not account for flow can be misleading in terms of ecological

Figure 4. Decision-making tree for selection of flow alteration metric to be used based on data availability. Temporal scale of streamflow data required: sd = sub-daily, d = daily, m = monthly. # Incorporates ecological data of interest to build flow-ecology curves
connectivity. In order to address these issues, future research should be aimed at developing methods that (a) measure the interactions between connectivity and flow alteration and metrics within each category, (b) measure lateral and vertical connectivity, and (c) incorporate the effects of flow within connectivity metrics. Understanding relationships among connectivity and flow alteration metrics can provide additional insights regarding the effects of RIPs on stream ecosystems over space and time. From a management perspective, connectivity metrics could be combined with flow alteration metrics to inform prescriptive tools for maintaining environmental flows. In regions where time or resources are limited, relationships between metrics that require extensive data collection (such as actual connectivity or flow alteration methods that require streamflow data) and metrics that do not (such as structural connectivity indices and flow alteration methods that do not require streamflow data) may be useful for extrapolating actual connectivity more broadly in a region, or for understanding conditions where metrics diverge.

5.2. Ecological significance
The actual ecological relevance of most flow alteration and connectivity metrics remains largely unknown. This is especially true for structural connectivity indices that are gaining rapid popularity and widespread implementation (Perkin et al 2015, Anderson et al 2018). Despite this knowledge gap, numerous assessments and prescriptive documents use connectivity indices to prioritize barrier removal, under the assumption that an increase in connectivity (as defined by a particular index) will improve biotic communities (Bourne et al 2011, Perkin et al 2015). Similarly, the ecological relevance of most flow alteration indices has not been adequately studied. Since ecological responses are expected to be influenced not only by connectivity and flow alteration metrics, but also by other environmental factors and the behaviour and resource requirements of the target species or taxa, assessing these relationships across river classes (Dallaire et al 2019) become essential. Hence, rigorous field studies that quantify the association between these metrics and biotic communities (such as fish (Perkin and Gido 2012, Mahlum et al 2014), macroinvertebrates (Solans and Jalón 2016), and riparian vegetation (Mcmnamay et al 2013)) and/or ecosystem processes and functions (such as sediment transport and primary productivity (Yarnell et al 2015)) are an important area for further research. Such empirical studies can not only inform the ecological relevance of connectivity and flow alteration measures, but can also shed light on how behavioural components influence ecological connectivity across spatial and temporal scale (Fullerton et al 2010).

5.3. Spatial and temporal scales of application
The ecological utility of a connectivity or flow alteration index will depend its spatiotemporal scale of application and the species, assemblage or ecosystem process being considered (Crooks and Sanjayan 2006, Gauchere 2007, Llausás and Nogué 2012). Since different species perceive habitats at different spatial scales across their life-history stages, their response to fragmentation and flow alteration will likely be scale-dependent, and also influenced by their habitat and resource requirements (Rossi and van Halder 2010, Llausás and Joan 2012). Generally, as spatial scales of analysis increases, other confounding landscape-level variables (such as elevation, land use, discharge) begin to influence response communities (Mahlum et al 2014). The application of spatial graph and network models across hierarchical river networks presents an opportunity to better understand factors influencing ecological connectivity across spatial scales (Erős and Lowe 2019). Similarly, due to temporal shifts in streamflow, ecosystem processes, and species life-history stages, ecological connectivity and flow alteration need to be assessed over adequate temporal (or seasonal) scales based on the ecological response being considered to avoid misrepresentation of results (Fullerton et al 2010). While it may not be feasible to quantify connectivity across all spatiotemporal scales, it is essential that further research be aimed at identifying the range of scales over which connectivity and flow alteration metrics may influence populations or processes of interest (Fullerton et al 2010).

5.4. Applications in data-scarce regions
One of the greatest challenges in understanding the effect of RIPs on connectivity and flow alteration is the effective application of informative indices in data-scarce regions. Most tropical developing countries striving to recognise their hydropower potential are characterised by high levels of freshwater biodiversity and the presence of river-dependent local communities (Auerbach et al 2016). These regions are also often limited in terms of long-term hydrologic and ecological data availability. Hence, despite there being a strong need for science-based management and decision-making, the lack of available resources precludes effective assessments of existing and proposed RIPs across spatiotemporal scales. The development of ecologically meaningful measures of connectivity and flow alteration that can be applied in such data-deficit regions to aid monitoring, restoration, and conservation development efforts remains a vital research frontier. Additionally, concerted efforts to establish partnerships and collaborations between governments, project proponents, scientists, water-managers and NGOs can go a long way in improving hydrologic data availability, which can then aid in informing water management policy and decision-making. Similar collaborations to establish a network
of gaging stations and collect periodic data on river habitat variables and biotic communities can provide the foundation required to apply more sophisticated and informative methods to assess the impacts of RIPS and create basin-wide monitoring and conservation plans (Horne 2017).

Conclusion

Continued demand for non-fossil fuel-based energy and water supply to meet the needs of growing human populations and zero-emission power will likely contribute to increasing reliance on RIPS through the 21st century. While the impacts of these projects on aquatic, riparian, and terrestrial ecosystems may be profound, tools to evaluate or predict the effects of RIPS on river ecosystems can provide critical information for conservation and management to mitigate their impacts in the future. Resource managers across the globe, over a wide range of technical capacities, need to understand the tools that are available for analysing how RIPS alter connectivity and streamflow. To this end, decision support remains one of the most important contributions that hydrologists and ecologists can make to sustain aquatic ecosystems.

Our review highlights the substantial progress toward understanding the hydrological consequences of RIPS, yet significant gaps remain. The recent proliferation of research using remotely sensed metrics to evaluate river network fragmentation and flow alteration highlights the potential for remote sensing to support applications including comparisons across broad regions and predictions of future impacts, but it also underscores their limitations. Without organism-based, field-based data collection, the ecological meaning of such metrics is unsupported. Assessments of actual ecological impacts will require extensive measurement of factors such as presence and absence (and changes over time), movement, and dispersal of organisms under a range of conditions. Such studies may be complex and expensive and require multi-year study relative to remote sensing studies, but they are a necessary step for conservation and sustainability of aquatic ecosystems in the future.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

We gratefully thank Mr Aldo Farah-Pérez and Mr Siddarth Machado for their invaluable suggestions on the manuscript. We express our sincere gratitude to the editor and two anonymous reviewers for their comments and suggestions, which have greatly improved the quality of this manuscript. We also acknowledge the United States Department of Agriculture Hatch Grant No. FLA-WFC-005577 and the University of Florida Soil and Water Sciences Department for their support to enable open-access publication.

ORCID iD

Suman Jumani  https://orcid.org/0000-0002-2292-7996

References

Acreman M C and Dunbar M J 2004 Defining environmental river flow requirements: a review Hydrol. Earth Syst. Sci. Discuss. 8 861–76

Alexandre C M and Almeida P R 2010 The impact of small physical obstacles on the structure of freshwater fish assemblages River Res. Appl. 26 977–94

Amoros C, Roux A L, Reygrobelle J L, Bravard J P and Pautou G 1987 A method for applied ecological studies of fluvial hydrosystems Regulated Rivers: Res. Manage. 1 17–36

Anderson D, Moggridge H, Warren P and Shucksmith J 2015 The impacts of ‘run-of-river’ hydropower on the physical and ecological condition of rivers: physical and ecological impacts of ROR hydropower Water Environ. J. 29 268–76

Anderson E P et al 2018 Fragmentation of Andes-to-Amazon connectivity by hydropower dams Sci. Adv. 4 eaao3642

Anderson E P, Freeman M C and Pringle C M 2006 Ecological consequences of hydropower development in Central America: impacts of small dams and water diversion on neotropical stream fish assemblages River Res. Appl. 22 397–411

Ariza-Villaverde A B, Jiménez-Hornero F J and de Ravé E G 2015 Influence of DEM resolution on drainage network extraction: a multifractal analysis Geomorphology 241 243–54

Athayde S, Duarte C G, Gallardo A L C F, Moretto E M, Sangoi I A, Dibo A P A, Siqueira-Gay J and Sánchez L E 2019 Improving policies and instruments to address cumulative impacts of small hydropower in the Amazon Energy Policy 132 265–71

Atkinson S, Bruen M, O’ Sullivan J J, Turner J N, Ball B, Carlson J, Bullock C, Caserly C M and Kelly-Quan M 2020 An inspection-based assessment of obstacles to salmon, trout, Eel and lamprey migration and river channel connectivity in Ireland Sci. Total Environ. 719 137215

Auerbach D A, Buchanan B P, Alexiades A V, Anderson E P, Encalada A C, Larson E I, Mcmanamay R A, Poe G L, Walter M T and Flesker A S 2016 Towards catchment classification in data-scarce regions Ecolhydrology 9 1235–47

Bagla P 2014 India plans the grandest of canal networks Science 345 128–128

Barbarossa V, Huijbregts M A J, Beusen A H W, Beck H E, King H and Schipper A M 2018 FLO1k, global maps of mean, maximum and minimum annual streamflow at 1 Km resolution from 1960 through 2015 Sci. Data 5 180052

Beasley C A and Hightower J E 2000 Effects of a low-head dam on the distribution and characteristics of spawning habitat used by striped bass and American shad Trans. Am. Fish. Soc. 129 1316–30

Beck H E, van Dijk A J M, Miralles D G, Richard A M, de Jeu R, Bruijnzel S, Mvctir T R and Schelldens J 2013 Global patterns in base flow index and recession based on streamflow observations from 3394 catchments Water Resour. Res. 49 7843–63

Beck M W, Claassen A H and Hundt P J 2012 Environmental and livelihood impacts of dams: common lessons across development gradients that challenge sustainability Int. J. River Basin Manage. 10 73–92

Besacier-Montrbrertrand A-L, Paulex A and Castella E 2014 Short-term impacts of lateral hydrological connectivity...
restoration on aquatic macroinvertebrates River Res. Appl. 30 557–70
Black A R, Rowan J S, Duck R W, Bragg O M and Celand B E 2005 DHRA: a method for classifying river flow regime alterations for the EC water framework directive Aquat. Conserv.: Mar. Freshwater Ecosyst. 15 427–46
Bodin Ö and Saura S 2010 Ranking individual habitat patches as connectivity providers: integrating network analysis and patch removal experiments Ecol. Modell. 221 2393–405
Bond N R and Kennard M J 2017 Prediction of hydrologic characteristics for ungauged catchments to support hydroecological modeling: predicting hydrologic metrics Water Resour. Res. 53 8781–94
Bourne C M, Kehler D G, Wiersma Y F and Cote D 2011 Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity Aquat. Ecol. 45 389–403
Branco P, Segurado P, Santos J M and Ferreira M T 2014 Prioritizing barrier removal to improve functional connectivity of rivers J. Appl. Ecol. 51 1197–206
Buddendorf W B, Malcolm I A, Geris J, Wilkinson M E and Soulsby C 2017 Metrics to assess how longitudinal channel network connectivity and in-stream Atlantic salmon habitats are impacted by hydropower regulation Hydrolog. Process. 31 2132–42
Burwen D, Fleischman S, Maxwell S and Pfisterer C 2005 A retrospective on hydroacoustic assessment of fish passage in Alaskan rivers J. Acoust. Soc. Am. 117 2366–7
Calabrese J M and Fagan W F 2004 A comparison-shopper’s guide to connectivity metrics Frontl. Ecol. Environ. 2 529–36
Cartwright J, Baldwin C, Nebiker S and Knight R 2017 Putting flow-ecology relationships into practice: a decision-support system to assess fish community response to water-management scenarios Water 9 196
Caudill C C, Keever M L, Clabough T S, Naughton G P, Burke B J and Peery C A 2013 Indirect effects of impoundment on migrating fish: temperature gradients in fish ladders slow dam passage by adult chumook salmon and steelhead PloS One 8 e55866
Choy M, Lawrie D and Edge C B 2018 Measuring 30 years of improvements to aquatic connectivity in the greater toronto area Aquat. Ecosyst. Health Manage. 21 342–51
Cote D, Kehler D G, Bourne C and Wiersma Y F 2009 A new measure of longitudinal connectivity for stream networks Landscape Ecol. 24 101–13
Couto T B and Olden J D 2018 Global proliferation of small hydropower plants – science and policy Frontl. Ecol. Environ. 16 161–100
Crook K E, Pringle C M and Freeman M C 2009 A method to assess longitudinal riverine connectivity in tropical streams dominated by migratory biota Aquat. Conserv.: Mar. Freshwater Ecosyst. 19 714–23
Crooks K R and Sanjayan M 2006 Connectivity Conservation vol 14 (Cambridge: Cambridge University Press) (http://hdl.handle.net/10536/DOR/DU-3000894)
Dallaire C O, Lehner B, Sayre R and Thieme M 2019 A multidisciplinary framework to derive global river reach classifications at high spatial resolution Environ. Res. Lett. 14 024003
Deitch M J, Mathias Kondolf G and Merenlender A M 2009 Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California Wine Country River Res. Appl. 25 118–34
Dey M, Kishanawami J, Morisaka T and Kelkar N 2019 Interacting effects of vessel noise and shallow river depth elevate metabolic stress in Ganges river dolphins Sci. Rep. 9 15426
Díaz G, Arriagada P, Górski K, Link O, Karelovic B, Gonzalez J and Habit E 2019 Fragmentation of Chilean Andean rivers: expected effects of hydropower development Rev. Chil. Hist. Nat. 92 1
Diebel M W, Fedor M, Cogswell S and O’Hanley J R 2015 Effects of road crossings on habitat connectivity for stream-resident fish River Res. Appl. 31 1251–61
Dudgeon D 2000 Large-scale hydrological changes in Tropical Asia: prospects for riverine biodiversity BioScience 50 793
Ehsani N, Vörösmarty C J, Fekete B M and Stakhiv E Z 2017 Reservoir operations under climate change: storage capacity options to mitigate risk J. Hydrol. 555 435–46
Enós T and Lowe W H 2019 The landscape ecology of rivers: from patch-based to spatial network analyses Curr. Landscape Ecol. Rep. 4 103–12
Fagan W F 2002 Connectivity, fragmentation, and extinction risk in dendritic metapopulations Ecology 83 3243–9
Fagan W F, Unmack P J, Burgess C and Minckley W L 2002 Rarity, fragmentation, and extinction risk in desert fishes Ecology 83 3250–6
Farah-Perez A, Uña-Villalobos G, Picado-Barboza J and Anderson E P 2020 An analysis of river fragmentation by dams and river dewatering in Costa Rica River Res. Appl. 36 1442–1448
Faullks L K, Gilligan D M and Beheregaray L B 2011 The role of anthropogenic vs. natural in-stream structures in determining connectivity and genetic diversity in an endangered freshwater fish, Macquaria perch (Macquaria australasica) Ecol. Appl. 4 589–601
Fisheries and Oceans Canada 2011 The Fish Passage Extension for ArcGIS (FIPEX) Freeman L C 1977 A set of measures of centrality based on betweenness Sociometry 40 35–41
Fuller M R, Doyle M W and Strayer D L 2015 Causes and consequences of habitat fragmentation in river networks: river fragmentation Ann. N. Y. Acad. Sci. 1355 31–51
Fullerton A H, Burnett K M, Steel E A, Filcroft R L, Pess G R, Feist B E, Torgersen C E, Miller D I and Sanderson B L 2010 Hydrological connectivity for riverine fish: modelization challenges and research opportunities Freshwater Biol. 55 2215–37
Gao Y, Vogel R M, Kroll C N, Poff N L and Olden J D 2009 Development of representative indicators of hydrologic alteration J. Hydrol. 374 136–47
Gauchecel C 2007 Multiscale heterogeneity map and associated scaling profile for landscape analysis Landscape Urban Plan. 82 95–102
Gehrke P C, Brown P, Schiller C B, Moffatt D B and Bruce A M 1995 River regulation and fish communities in the murray-darling river system, Australia Regulated Rivers: Res. Manage. 11 363–75
Gosset C, Rives J and Labonne J 2006 Effect of habitat fragmentation on spawning migration of brown trout (Salmo trutta L.) Ecol. Freshwater Fish 15 247–54
Grant E H C, Lynch H J, Muneepeerakul R, Arunachalam M, Rodríguez-Itrurbe I and Fagan W F 2012 Interbasin water transfer, riverine connectivity, and spatial controls on fish biodiversity PLoS One 7 3
Grill G et al 2019 Mapping the world’s free-flowing rivers Nature 569 215–21
Grill G, Dallaire C O, Chouinard E F, Sindorf N and Lehner B 2018 Development of new indicators to evaluate river fragmentation and flow regulation at large scales: a case study for the Mekong river basin Ecol. Indic. 45 148–59
Grill G, Lehner B, Lunsmoen A E, Macdonald G K, Zarfb C and Liermann C R 2015 An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales Environ. Res. Lett. 10 015001
Hall C, Joshi A, Arora K and Frisk M G 2011 The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity Landscape Ecol. 26 95–107
Henriksen J A, Heasly J, Kernen J G and Nieswand S 2006 Users’ manual for the hydroecological integrity assessment process software(including the New Jersey assessment tools) U. S. Geological Survey
Hermoso V, Linke S, Prenda J and Possingham H P 2011 Addressing longitudinal connectivity in the systematic conservation planning of fresh waters: connectivity in freshwater conservation planning Freshwater Biol. 56 57–70

Hirji R and Davis R 2009 Environmental Flows in Water Resources Decision Making Environmental Flows in Water Resources Policies, Plans, and Projects: Findings and Recommendations (Washington, D.C: World Bank) 21–40

Hoeksema M, Kumar M and Batt L 2014 A GIS based approach for prioritizing dams for potential removal Ecol. Eng. 64 27–36

Horne A C (ed) 2017 Water for the Environment: From Policy and Science to Implementation and Management (London: Elsevier; Academic Press, an imprint of Elsevier)

Hydropower Status Report 2019 International Hydropower Association 2019 (available at: www.hydropower.org/status2019)

ICOLD 2019 International commission on large dams 2019 (available at: www.icold-cigb.org/article/GR_world_register/general_synthesis/number-of-dams-by-country-members)

IRENA 2016 Renewable energy statistics 2016 (Abu Dhabi: The International Renewable Energy Agency)

Isaak D J, Thurow R F, Rieman B E and Dunham J B 2007 Chinook salmon use of spawning patches: relative roles of habitat quality, size, and connectivity Ecol. Appl. 17 352–64

Jaeger J A G 2000 Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation Landscape Ecol. 15 115–30

Januchowski-Hartley S R, McIntyre P B, Diebel M, Doran P J, Infante D M, Joseph C and David Allan J 2013 Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings Front. Ecol. Environ. 11 211–7

Johnston C E 2000 Movement patterns of imperiled blue shiners (Pisces: Cyprinidae) among habitat patches Ecol. Freshwater Fish 9 170–6

Jones J et al 2019 A comprehensive assessment of stream fragmentation in Great Britain Sci. Total Environ. 673 736–62

Jowett I G 1997 Instream flow methods: a comparison of approaches Regulated Rivers: Res. Manage. 13 115–27

Junami S, Rao S, Kelkar N, Machado S, Krishnaswamy J and Vaidyanathan S 2018 Fish community responses to stream flow alterations and habitat modifications by small hydropower projects in the Western Ghats biodiversity hotspot, India Aquat. Conserv.: Mar. Freshwater Ecosyst. 28 979–93

Junk W J, Bayley P B and Sparks R E 1989 The flood pulse concept in river–floodplain systems Can. Spec. Publ. Fish. Aquat. Sci. 106 110–27

Kennen J G, Henriksen J A, Heasley J, Cadie B S and Terrell J W 2009 Application of the hydroecological integrity assessment process for Missouri streams 1138 U.S. Geological Survey

Kihler K M and Tullos D D 2013 Cumulative biophysical impact of small and large hydropower development in Nu River, China: biophysical impact of small and large hydropower Water Resour. Res. 49 3104–18

Kindlmann P and Burel F 2008 Connectivity measures: a review Landscape Ecol. 23 879–90

King J, Tharme R E and Brown C 1999 Definition and implementation of instream flows World Commission on Dams (Cape Town)

Knaepkens G, Baekelandt K and Eens M 2006 Fish pass effectiveness for hulldot (Cottus gobio), Perch (Perca fluviatilis) and Roach (Rutilus rutilus) in a regulated lowland river Ecol. Freshwater Fish 15 20–29

Kumar B, Patra K C and Lakshmi V 2017 Error in digital network and basin area delineation using D8 method: a case study in a sub-basin of the Ganga J. Geol. Soc. India 89 65–70

Ladson A R, White I L, Doolan J A, Finlayson B L, Hart B T, Lake P S and Tilleard J W 1999 Development and testing of an index of stream condition for waterway management in Australia Freshwater Biol. 41 453–68

Lasne E, Lek S and Lafaille P 2007 Patterns in fish assemblages in the loire floodplain: the role of hydrological connectivity and implications for conservation Biol. Conserv. 139 258–68

Latrubesse E M et al 2017 Daming the rivers of the Amazon basin Nature 546 363–9

Lehner B and Grill G 2013 Global river hydrometry and network routing: baseline data and new approaches to study the world’s large river systems: global river hydrometry and network routing Hydrol. Process. 27 2171–86

Lehner B, Verdin K and Jarvis A 2008 New global hydrometry derived from spaceborne elevation data Eos Trans. Am. Geophys. Union 89 93

Lehotsky M, Rusnak M, Kidova A and Dudažik J 2018 Multitemporal assessment of coarse sediment connectivity along a braided-wandering river Land Degrad. Dev. 29 1249–61

Leibowitz S G and White D E N I S 2009 Modeling the Effect of Stream Network Characteristics and Juvenile Movement on Coho Salmon (Oncorhynchus Kisutch) 203–224

Li H, Zhou D, Su Z, Zhang J, Jiang Y and Zang Y 2018 Barrier-based longitudinal connectivity index for managing urban rivers Water 10 1701

Liermann M, Pess G, McNerney M, McMillan J, Elofson M., Bennett T and Moses R 2017 Relocation and recolonization of coho salmon in two tributaries to the Elwha river: implications for management and monitoring Trans. Am. Fish. Soc. 146 955–66

Linke S et al 2019 Global hydro–environmental sub-basin and river reach characteristics at high spatial resolution Sci. Data 6 283

Llausás A and Joan N 2012 Indicators of landscape fragmentation: the case for combining ecological indices and the perceptive approach Ecol. Indic. 15 85–91

Mahluum S, Kehler D, Cote D, Wiersma Y F and Stanfield L 2014 Assessing the biological relevance of aquatic connectivity to stream fish communities Can. J. Fish. Aquat. Sci. 71 1852–63

Mal vadkar U, Scatena F and Leon M 2015 A comparison of connectivity metrics on watersheds and implications for water management River Res. Appl. 31 256–67

Mathews R and Richter B D 2007 Application of the indicators of hydrologic alteration software in environmental flow settings JAWRA J. Am. Water Resour. Assoc. 43 1400–13

McClain M E, Subaluksky A L, Anderson E P, Dessu S B, Melese A M, Ndomba P M, Mtamba J O D, Tamatamah R A and Mligo C 2014 Comparing flow regime, channel hydraulics, and biological communities to infer flow–ecology relationships in the Mara River of Kenya and Tanzania Hydrolog. Sci. J. 59 801–19

Mckay S K, Cooper A R, Diebel M W, Elkins D, Oldford G, Roghair C and Wieferich D 2017 Informing watershed connectivity barrier prioritization decisions: a synthesis River Res. Appl. 33 847–62

Mckay S K, Schramski J R, Conyngham J N and Fischchen J C 2013 Assessing upstream fish passage connectivity with network analysis Ecol. Appl. 23 1396–409

Mcnamamay R A, Orth D J, Dooloff C A and Mathews D C 2013 Application of the ELOHA framework to regulated rivers in the upper tennessee river basin: a case study Environ. Manag. 51 1210–21

Mertt D M and Wohl E E 2006 Plant dispersal along rivers fragmented by dams River Res. Appl. 22 1–26

Mittal N, Mishra A, Singh R, Bhave A G and Van der valk M 2014 Flow regime alteration due to anthropogenic and climatic changes in the Kangsabati River, India Ecolhydrol. Hydrobiol. 14 182–91
Montgomery D R and Buffington J M 1997 Channel-reach morphology in mountain drainage basins Geol. Soc. Am. Bull. 109 596–611
Morid R, Shimatani Y and Sato T 2019 Impact assessment of climate change on environmental flow component and water temperature—Kikuchi River J. Ecolhydrodynamics 4 488–105
Mulligan M, van Soesbergen A and Leonardo S 2020 GOODD, a global dataset of more than 38,000 georeferenced dams Sci. Data 7 1–8
Murphy P N C, Ogilvie J, Meng F R and Arp P 2008 Stream network modelling using lidar and photogrammetric digital elevation models: a comparison and field verification Hydrol. Process. 22 1747–54
Naughton G P, Caudill C C, Peery C A, Clabough T S, Jepson M A, Bjornn T C and Stuehrenberg L C 2007 Experimental evaluation of fishway modifications on the passage behaviour of adult chinook salmon and steelhead at Lower Granite Dam, Snake River, USA USA River Res. Appl. 23 99–111
Nel J L, Roux D J, Aller B, Ashton P J, Cowling R M, Higgins J V, Thieme M and Viers J H 2009 Progress and challenges in freshwater conservation planning Aquat. Conserv.: Mar. Freshwater Ecosyst. 19 474–83
Nilsson C 2005 Fragmentation and flow regulation of the world’s large river systems Science 308 405–9
Nilsson C, Reidy C A, Dymiusn M and Revenga C 2005 Fragmentation and flow regulation of the world’s large river systems Science 308 405
Nunn A D and Cowx I G 2012 Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys AMBIO 41 402–9
O’Hanley J R, Wright J, Diebel M, Fedora M A and Soucy C L 2013 Restoring stream habitat connectivity: a proposed method for prioritizing the removal of resident fish passage barriers J. Environ. Manage. 125 19–27
Oldani N O and Baigún C R M 2002 Performance of a fishway system in a major South American dam on the Parana River (Argentina–Paraguay) River Res. Appl. 18 171–83
Padgham M and Webb J A 2010 Multiple structural modifications to dendritic ecological networks produce simple responses Ecol. Model. 221 2537–45
Paillex A, Castella E and Carron G 2007 Aquatic macroinvertebrate response along a gradient of lateral connectivity in river floodplain channels J. North Am. Benthological Soc. 26 779–96
Park D, Sullivan M, Bayne E and Scrimgeour G 2008 Landscape-scale stream fragmentation caused by hanging culverts along roads in Alberta’s boreal forest Can. J. For. Res. 38 556–75
Pascual-Hortal J and Saura S 2006 Comparison and development of new graph-based landscape connectivity indices: towards the prioritization of habitat patches and corridors for conservation Landscape Ecol. 21 959–67
Perkin J S and Gido K B 2012 Fragmentation alters stream fish community structure in dendritic ecological networks Ecol. Appl. 22 2176–87
Perkin J S, Gido K B, Cooper A R, Turner T E, Osborne M J, Johnson E R and Mays K B 2013 Fragmentation and dewatering transform great plains stream fish communities Ecol. Monogr. 85 73–92
Pini Prato E, Comoglio C and Calles O 2011 A simple management tool for planning the restoration of river longitudinal connectivity at watershed level: priority indices for fish passes J. Appl. Ichthyol. 27 75–79
Poff N L et al 2010 The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards ecological limits of hydrologic alteration Freshwater Biol. 55 147–70
Poff N L, Allan J D, Bain M B, Karr J R, Prestegaard K L, Richter B D, Sparks R E and Stromberg J C 1997 The natural flow regime BioScience 47 769–84
Poff N L and Hart D D 2002 How dams vary and why it matters for the emerging science of dam removal BioScience 52 659
Poff N L, Olden J D, Pepin D M and Bledsoe B P 2006 Placing global stream flow variability in geographic and geomorphic contexts River Res. Appl. 22 149–66
Pringle C M 2001 Hydrologic connectivity and the management of biological reserves: a global perspective Ecol. Appl. 11 981–98
Pringle C 2003 What is hydrologic connectivity and why is it ecologically important? Hydrol. Process. 17 2685–9
Radinpor J, Kail J and Wolter C 2014 FIDIMO — a free and open source GIS based dispersal model for riverine fish Ecol. Inf. 24 238–47
Reckendorfer W, Baranyi C, Funk A and Schneider F 2006 Floodplain restoration by reinforcing hydrological connectivity: expected effects on aquatic mollusc communities J. Appl. Ecol. 43 474–84
Richter B D, Baumgartner J V, Braun D P and Powell J 1998 A spatial assessment of hydrologic alteration within a river network Regulated Rivers: Res. Manage. 14 329–40
Richter B D, Baumgartner J V, Powell J and Braun D P 1996 A method for assessing hydrologic alteration within ecosystems Conserv. Biol. 10 1163–74
Richter B D, Mathews R, Harrison D L and Wigington R 2003 ecologically sustainable water management: managing river flows for ecological integrity Ecol. Appl. 13 200–24
Richter B D, Pastel S, Revenga C, Scudder T, Lehner B, Churchill A and Chow M 2010 Lost in development’s shadow: the downstream human consequences of dams Water Altern. 3 29
Richter B, Baumgartner J, Wigington R and Braun D 1997 How much water does a river need? Freshwater Biol. 37 231–49
Rodeles A A, Leunda P M, Elso J, Ardaiz J, Galicia D and Miranda R 2019 Consideration of habitat quality in a river connectivity index for anadromous fishes Inland Waters 9 278–88
Rodriguez-Iturbe I and Rinaldo A 1997 Fractal River Basins: Chance and Self-Organization (Cambridge: Cambridge University Press)
Rosenberg D M, Mccully P and Pringle C M 2000 Global-scale environmental effects of hydrological alterations: introduction BioScience 50 746
Rosenfeld J S 2017 Developing flow–ecology relationships: implications of nonlinear biological responses for water management Freshwater Biol. 62 1305–24
Rosgen D L 1994 A classification of natural rivers Regulated Rivers: Res. Manage. 61 152–75
Schick R S and Lindley S T 2007 Directed connectivity among fish populations in a riverine network J. Appl. Ecol. 44 1116–26
Schrank A J and Rahel F J 2004 Movement patterns in inland cutthroat trout (Oncorhynchus clarkii saltus): management and conservation implications Can. J. Fish. Aquat. Sci. 61 1533–43
Segurado P, Branco P and Ferreira M T 2013 Prioritizing restoration of structural connectivity in rivers: a graph based approach Landscape Ecol. 28 1231–8
Shiau J-T and Wu F-C 2007 Pareto-optimal solutions for environmental flow schemes incorporating the intra-annual and interannual variability of the natural flow regime Water Resour. Res. 43 6
Simon A, Doyle M, Kondolf M, Shields F D, Rhoads B and McPhillips M 2007 Critical evaluation of how the rogen classification and associated ‘natural channel design’ methods fail to integrate and quantify fluvial processes and channel response J. Am. Water Resour. Assoc. 43 1117–31
Solans M A and Garcia de Jalón D 2016 Basic tools for setting environmental flows at the regional scale: application of the ELOHA framework in a mediterranean river basin: testing...
the ELOHA framework in the ebro river basin *Ecohydrology* 9 1517–38

Tharme R E 2003 A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers *River Res. Appi.* 19 397–411

Timpe K and Kaplan D 2017 The changing hydrology of a damned amazon *Sci. Adv.* 3 e1700611

Tischendorf L and Fahrig L 2000 How should we measure landscape connectivity? *Landscape Ecol.* 15 633–41

Tockner K, Bernhardt E S, Koska A and Zarfl C 2016 A global view on future major water engineering projects *Society - Water – Technology*, ed R F Hüttl, O Bens, C Bismuth and S Hochstetter (Cham: Springer International Publishing) 47–64

Torterotot J-B, Perrier C, Bergeron N E and Bernatchez L 2014 Influence of forest road culverts and waterfalls on the fine-scale distribution of brook trout genetic diversity in a Boreal watershed *Trans. Am. Fish. Soc.* 143 1577–91

Valle D and Kaplan D 2019 Quantifying the impacts of dams on riverine hydrology under non-stationary conditions using incomplete data and gaussian copula models *Sci. Total Environ.* 677 599–611

Vannote R L, Minshall G W, Cummins K W, Sedell J R and Cushing C E 1980 The river continuum concept *Can. J. Fish. Aquat. Sci.* 37 130–7

Vogel R M and Fennessy N M 1995 Flow duration curves ii: a review of applications in water resources planning *J. Am. Water Resour. Assoc.* 31 1029–39

Vogel R M, Sieber J, Archfield S A, Smith M P, Apse C D and Huber-Lee A 2007 Relations among storage, yield, and instream flow *Water Resour. Res.* 43 1–12

Vorosmarty C J, Green P, Salisbury J and Lambers R B 2000 Global water resources: vulnerability from climate change and population growth *Science* 289 284–8

Ward J V 1989 The four-dimensional nature of lotic ecosystems *J. North Am. Benthological Soc.* 8 2–8

Webb J A and Padgham M 2013 How does network structure and complexity in river systems affect population abundance and persistence *Limnologica* 43 399–403

Wiens J A 2002 Riverine landscapes: taking landscape ecology into the water *Freshwater Biol.* 47 301–15

Winemiller K O et al 2016 Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong *Science* 351 128–9

Wofford J E B, Gresswell R E and Banks M A 2005 Influence of barriers to movement on within-watershed genetic variation of coastal cutthroat trout *Ecol. Appl.* 15 628–37

Wohl E 2017 Connectivity in rivers *Prog. Phys. Geo.: Earth Environ.* 41 345–62

Woodrow K, Lindsay J B and Berg A A 2016 Evaluating DEM conditioning techniques, elevation source data, and grid resolution for field-scale hydrological parameter extraction *J. Hydrol.* 540 1022–9

World Commission on Dams, ed 2000 Dams and Development: A New Framework for Decision-Making (London: Earthscan)

Yang P, Ames D P, Fonseca A, Anderson D, Shrestha R, Glenn N F and Cao Y 2014 What is the effect of LiDAR-derived DEM resolution on large-scale watershed model results? *Environ. Modell. Softw.* 58 48–57

Yarnell S M, Petts G E, Schmidt J C, Whipple A A, Beller E E, Dahm C N, Goodwin P and Viers J H 2015 Functional flows in modified riverscapes: hydrographs, habitats and opportunities *Bioscience* 65 963–72

Zarfl C, Lamsdon A E, Berlekamp J, Tydecks L and Tockner K 2015 A global boom in hydropower dam construction *Aquat. Sci.* 77 161–70

Zhou Q and Liu X 2002 Error assessment of grid-based flow routing algorithms used in hydrological models *Int. J. Geogr. Inf. Sci.* 16 819–42