ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

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Environmental Research Letters

OPEN ACCESS

RECEIVED
2 August 2020

REVISED
1 November 2020

ACCEPTED FOR PUBLICATION
17 November 2020

PUBLISHED
14 December 2020

TOPICAL REVIEW

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

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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 km^3 (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 head-waters 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, Wiens 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, Wiens 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, Wiens 2002, Cote *et al* 2009). However, being able to effectively assess and predict the impacts of RIPs is crucial to inform project-specific and basin-wide conservation, restoration, and development plans. Recognising this gap, numerous methodological advancements have been made to better assess metrics of river fragmentation and flow alteration based on several types of remotely sensed and field-based data (Nilsson 2005, Cote *et al* 2009, Grill *et al* 2014).

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 (Rodríguez-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, Pringle 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

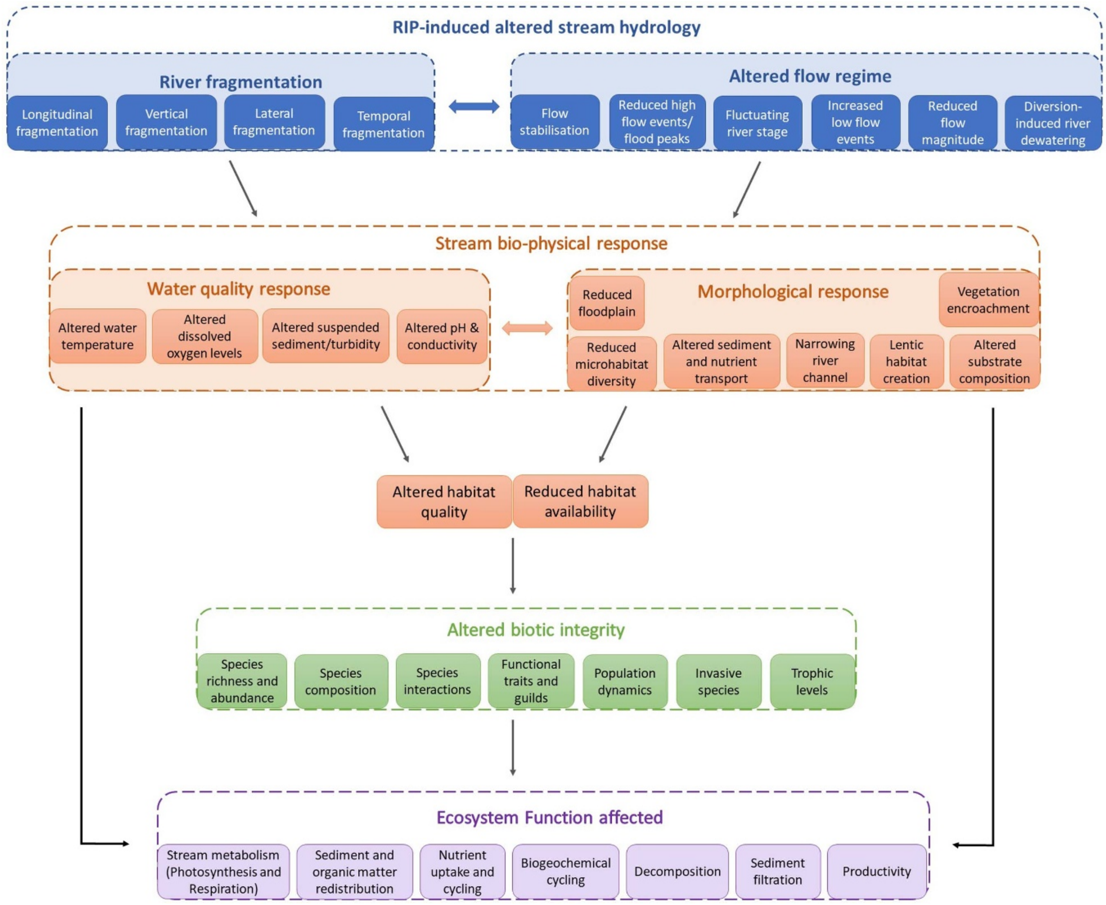

Figure 1. Schematic model illustrating morphological and water quality responses (orange boxes) to river infrastructure project (RIP) induced altered stream hydrology (blue boxes), and their influence on biotic integrity (green boxes) and ecosystem function (purple boxes). Arrows indicate pathways or directionality of influence. Dashed boxes represent distinct levels of impact, and solid coloured boxes within them represent the main components pertaining to that theme (adapted from Poff *et al* 1997).

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).

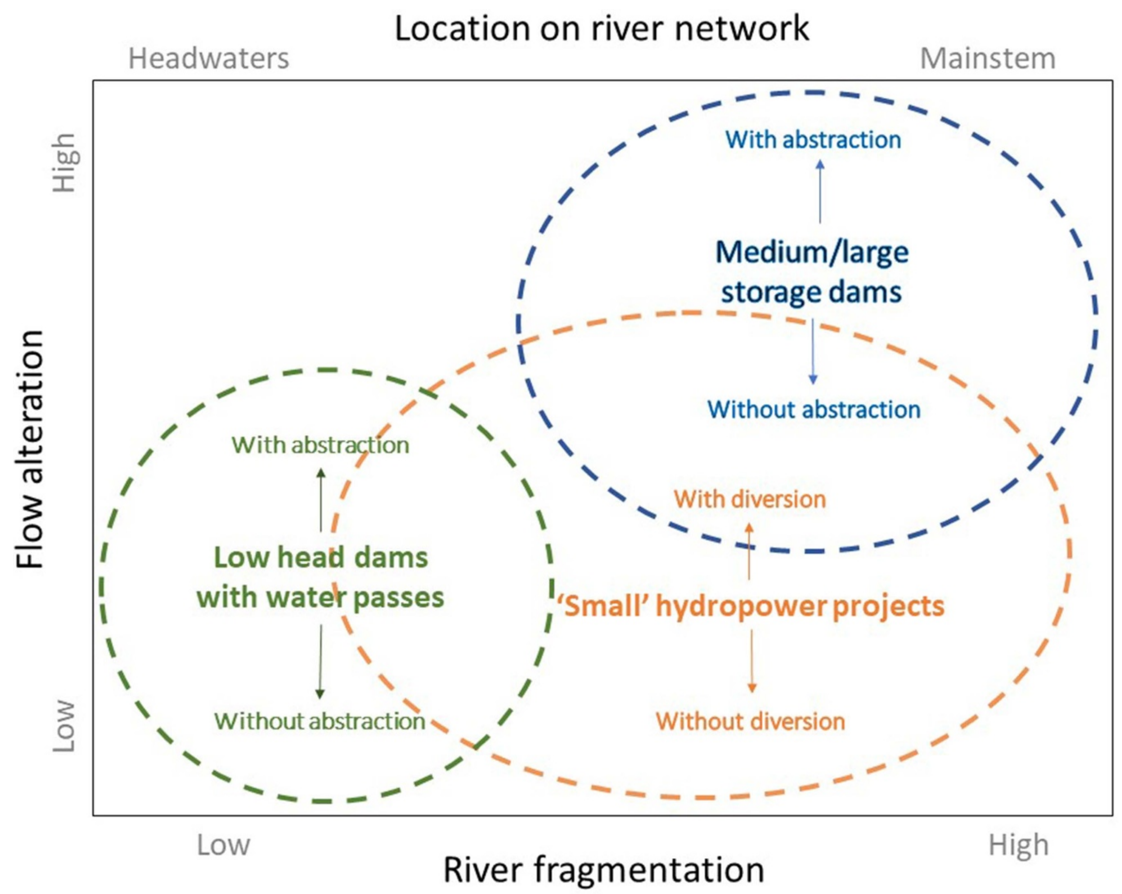

Figure 2. Expected location and impact of an individual project across different RIP types (medium/large storage dams, small hydropower projects, and low head dams) on river network fragmentation and flow alteration.

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 Baigún 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 • Various development scenarios can be assessed • Helps identify important reaches that maintain basin-level connectivity • Can be assessed using integral index of connectivity (IIC) or probability of connectivity (PC) metrics (see below) • Can incorporate natural barriers (waterfalls)	• 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 • Treats stream reaches across a longitudinal gradient as ecologically equivalent • Connectivity treated as a binary value • Does not incorporate any other ecological characteristics	Bodin and Saura 2010; Segurado *et al* 2013
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 • Easy to compute • Modalities of connection can be assessed based on field observations or satellite imagery • Minimal data requirements • Seasonal and historical changes over times can be assessed • Can be quickly assessed across spatial scales	• Descriptive classes; does not monitor the duration and intensity of the actual hydrological connection • Assessing modalities of connectivity for each side channel and waterbody can be challenging • Side channels of different sizes and attributes (and hence having different levels of resilience) may be classified under the same category	Lasne *et al* 2007

(Continued)

Table 1. (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 • Dam locations	Five fragmentation classes (very low to very high)	Sub-basin to basin	• Easy to compute • Minimal data requirements • No primary data needed • Various development scenarios can be assessed • Can assess connectivity across spatial scales	• Subjective classification • Not spatially explicit • Values may not change even with the addition/removal of dams • Cannot incorporate barrier permeabilities • Treats stream reaches across a longitudinal gradient as ecologically equivalent • Does not incorporate any other ecological characteristics	Díaz *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 • Number of barriers	Density of barriers per length of river	River reach to basin	• Can incorporate natural barriers • 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 • 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 • Does not incorporate any other ecological characteristics	Jones *et al* 2019; Atkinson *et al* 2020

(Continued)

Table 1. (Continued).

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

(Continued)

Table 1. (Continued).

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 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

(Continued)

Table 1. (Continued).

Connectivity/ fragmentation metric	Description	Inputs/Data requirements	Outputs	Spatial scale of application	Advantages	Disadvantages	Applications
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 lengths • Dam locations • Length of dam-impacted river reaches	Index of impact from 0 to 100	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 • Can be calculated across spatial scales	• Not spatially explicit • Measuring the length of dam-affected upstream and downstream river reaches can be subjective • Treats stream reaches across a longitudinal gradient as ecologically equivalent • 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 • Does not incorporate any other ecological characteristics	Latrubesse *et al* 2017
River channel connectivity index (Li *et al* 2018)	Quantifies the unobstructed degree of river flow based on the concept of time accessibility. It is calculated as the ratio of the time accessibility of a given volume of streamflow without any barriers to that with 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	Index ranging from 0 (disconnected) to 1 (connected)	River reach to tributary	• Incorporates aspects of streamflow • Barriers treated individually to assess blocking degree • Various development scenarios can be assessed • No primary data needed • Values range between 0 and 1 and are easy to interpret	• 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 • Requires expert knowledge on barrier impacts to score barriers • Cannot incorporate natural barriers	Li *et al* 2018

(Continued)

Table 1. (Continued).

Connectivity/ fragmentation metric	Description	Inputs/Data requirements	Outputs	Spatial scale of application	Advantages	Disadvantages	Applications
Potential Connectivity Metrics							
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 RIPs 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

(Continued)

Table 1. (Continued).

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[a]	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

(Continued)

Table 1. (Continued).

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

(Continued)

Table 1. (Continued).

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 (Jaeger 2000)	• River network lengths • Dam locations • Directional dam passability values[a] • Waterfall locations[a]	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 • 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 • 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	Perkin and Gido 2012; Anderson *et al* 2018

(Continued)

Table 1. (Continued).

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[a] • Waterfall locations[a]	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

(Continued)

Table 1. (Continued).

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)	stimate 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 stimate 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

(Continued)

Table 1. (Continued).

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[a]	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

(Continued)

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 meta-populations • 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

(Continued)

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

(Continued)

Table 1. (Continued).

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[a]	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

(Continued)

Table 1. (Continued).

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[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 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 reach-level habitat volume (computed as reach length[a] wetted width[a] 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	Grill *et al* 2015

(Continued)

Table 1. (Continued).

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/ecoregion (RCI_{class}) or species-specific migration ranges (RCI_{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 reach-level habitat volume (same as RCI) • 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	Grill *et al* 2014

(Continued)

Table 1. (Continued).

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[a] • Dam locations • Waterfall locations[a] • 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 RIPs that lie beyond the delineated river network are often excluded from analysis • More data-intensive	O'Hanley *et al* 2013

(Continued)

Table 1. (Continued).

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

(Continued)

Table 1. (Continued).

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[a] • 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 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	Isaak *et al* 2007; Schick and Lindley 2007; Leibowitz and White 2009

(Continued)

Table 1. (Continued).

Connectivity/ fragmentation metric	Description	Inputs/Data requirements	Outputs	Spatial scale of application	Advantages	Disadvantages	Applications
Actual connectivity metrics							
Lateral connectivity parameter (C_d) (Reckendorfer *et al* 2006)	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	• Quantifies the duration of actual hydrological connection based on flow data • Depends on flow pattern of the river and the position of these waterbodies relative to river height • Can be calculated across seasonal and temporal time scales • Waterbodies can be categorised into connectivity classes based on ranges of C_d values	• Reliance on multi-year flow data limits its application in data-deficit regions • Cannot assess impacts of proposed scenarios since it relies on flow data • Ability to calculate C_d values for a side channel depends on the availability of a gauging station at its upstream end • 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

(Continued)

Table 1. (Continued).

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 (snorkelling, filming)	Variable	River reach to tributary	• Detailed information on actual movement/connectivity and behaviour • Accurately represents the movement of animals	• Effort intensive • Smaller spatial scale of application • Data collection is limited by on-ground condition • Influenced by imperfect detections	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 • Can incorporate aspects of behaviour • Accurately represents the movement of animals • Influence of seasons and other habitat parameters can also be assessed	• High data processing • Limited application • Expensive • Effort intensive • Smaller spatial scale of application • Species/taxa specific	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 • Accurately represents the directionality and extent of movement, path of travel and passage efficiency • Influence of body size, sex, maturation and other variables on dam passability can be assessed	• Expensive • Data and effort intensive • Smaller spatial scale of application • Data collection is limited by on-ground condition • Species/taxa specific • Tagging may influence species behaviour, survival and growth, thereby confounding results	Schrank and Rahel 2004; Gosset *et al* 2006
Direct sampling (electroshocking, seining or trapping)	*In-situ* fish capture	Spatially 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 • Can measure ecological continuity based on composition dis(similarity) across sites • Can be linked to river infrastructure projects and other influencing variables • Influence of body size, sex, maturation and other variables on dam passability can be assessed	• Limited information on barrier passability • Effort intensive to collect data over spatiotemporal scales • Smaller spatial scale of application • Data collection is limited by on-ground condition • If not accounted for, variable gear efficiency and sampling effort can produce misleading results • Species/taxa specific	Merritt and Wohl 2006; Alexandre and Almeida 2010; Jumani *et al* 2018

(Continued)

Table 1. (Continued).

Connectivity/ fragmentation metric	Description	Inputs/Data requirements	Outputs	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	Genetic variation, diversity, differentiation or similarity	Subbasin to basin	• Quantifies metapopulation connectivity for a given site and species of interest • Fine spatiotemporal resolution • Can shed light on connectivity across temporal scales • Can distinguish between populations and even individuals	• Requires technical skill to analyse and interpret the data • Connectivity can be assessed at the scale of the populations or individuals • Often requires specialised mathematical and computer programming expertise to develop models • Requires collections of specimens or biotic samples • Significantly more expensive compared to other methods	Wofford *et al* 2005; Faulks *et al* 2011; Terotot *et al* 2014

[a] 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 unimpacted 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 RIPs with short post-dam hydrology or no flow gauges • Cannot assess impacts of proposed RIPs 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

(Continued)

Table 2. (Continued).

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 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 inter-correlated metrics can be redundant and complicated to apply in eflow assessments • Does not directly relate ecological responses to flow statistics	Mathews and Richter 2007; Timpe and Kaplan 2017

(Continued)

Table 2. (Continued).

Flow alteration metric	Description	Data requirements	Output	Spatial scale of application	Advantages	Disadvantages	Applications
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 hydrological 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	• 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)	Richter *et al* 1998; Mittal *et al* 2014

(Continued)

Table 2. (Continued).

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

(Continued)

Table 2. (Continued).

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 RIPs 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

(Continued)

Table 2. (Continued).

Flow alteration metric	Description	Data requirements	Output	Spatial scale of application	Advantages	Disadvantages	Applications
Hydroecological Integrity Assessment Process (HIAP) (Henriksen *et al* 2006)	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 hydrological data have been gathered	• Indicates the degree to which different flow components are being affected; mitigation measures can be tailored to target restoration • Analysis supported by the Hydrologic Index Tool and Hydrologic Assessment Tool • Where suitable hydrological data are unavailable or incomplete, simulated flow data can be used • Can assess the individual and cumulative impact of reservoirs • Useful for setting flow targets for regulated streams	• Reliance on long-term flow data limits its application in data-deficit regions • Designed to use USGS mean daily and peak flow discharges from the National Water Information System, and is hence most suitable for American rivers • Does not relate ecological response to the flow statistics • Extensive data processing to account for data-gaps • 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 • Ability to calculate cumulative impacts depends on the spatial configuration of dams and gauging stations • Assumes stationarity	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 inter-correlated metrics can be redundant and complicated to apply in environmental flow assessments	Morid et al 2019

(Continued)

Table 2. (Continued).

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 streamflow 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 RIPs 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

(Continued)

Table 2. (Continued).

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

(Continued)

Table 2. (Continued).

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

(Continued)

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

(Continued)

Table 2. (Continued).

Flow alteration metric	Description	Data requirements	Output	Spatial scale of application	Advantages	Disadvantages	Applications
Effective Degree of Regulation (EDOR) (Ehsani *et al* 2017)	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)

Table 2. (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

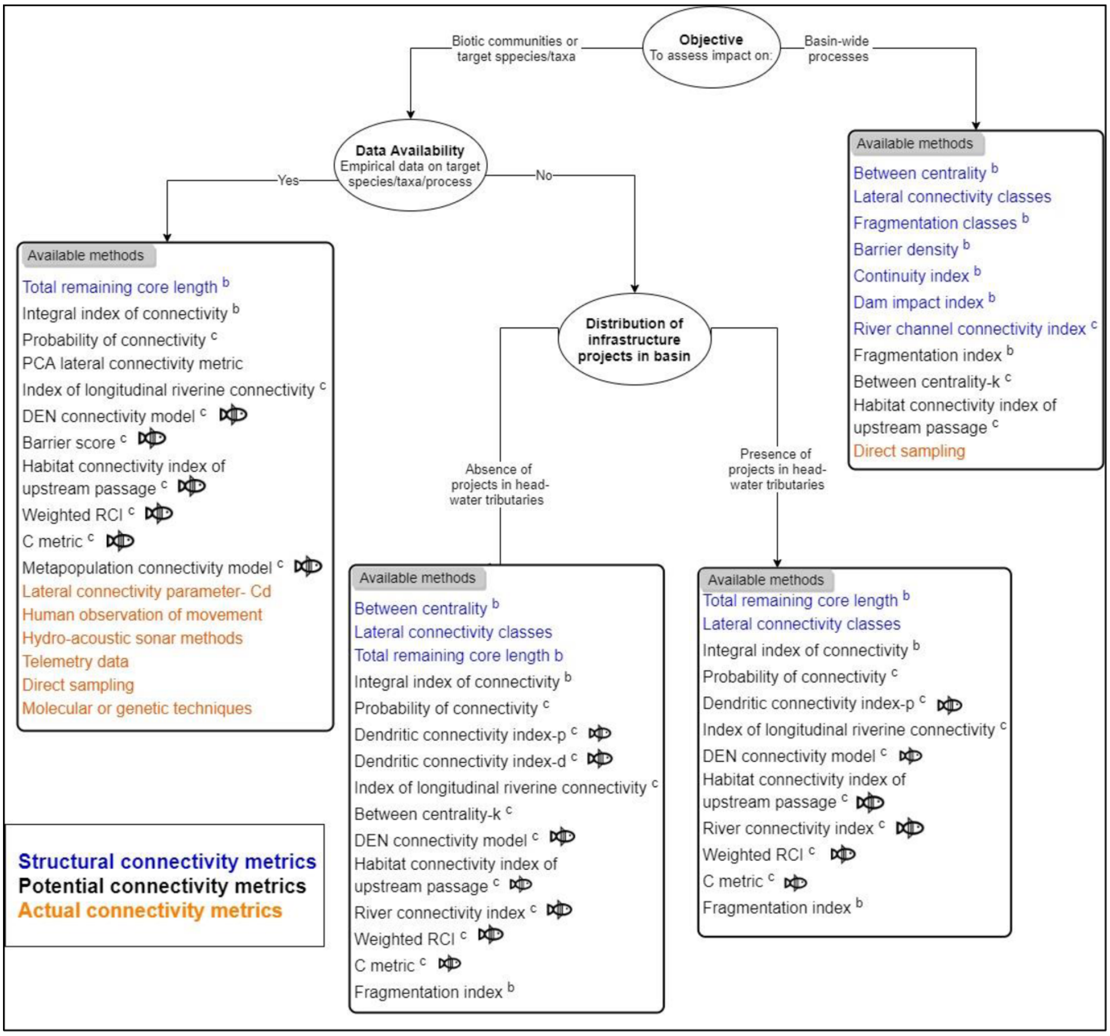

Figure 3. Decision-making tree for selection of river connectivity metrics based on objective, data availability, and distribution of infrastructure projects in the basin. Superscripts indicate barrier passability values to be binary (b) or continuous (c); The symbol [fish symbol] indicates method designed 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 furture research

The methodological advancements in characterizing river fragmentation and flow alteration described above provide a wide variety of tools for researchers

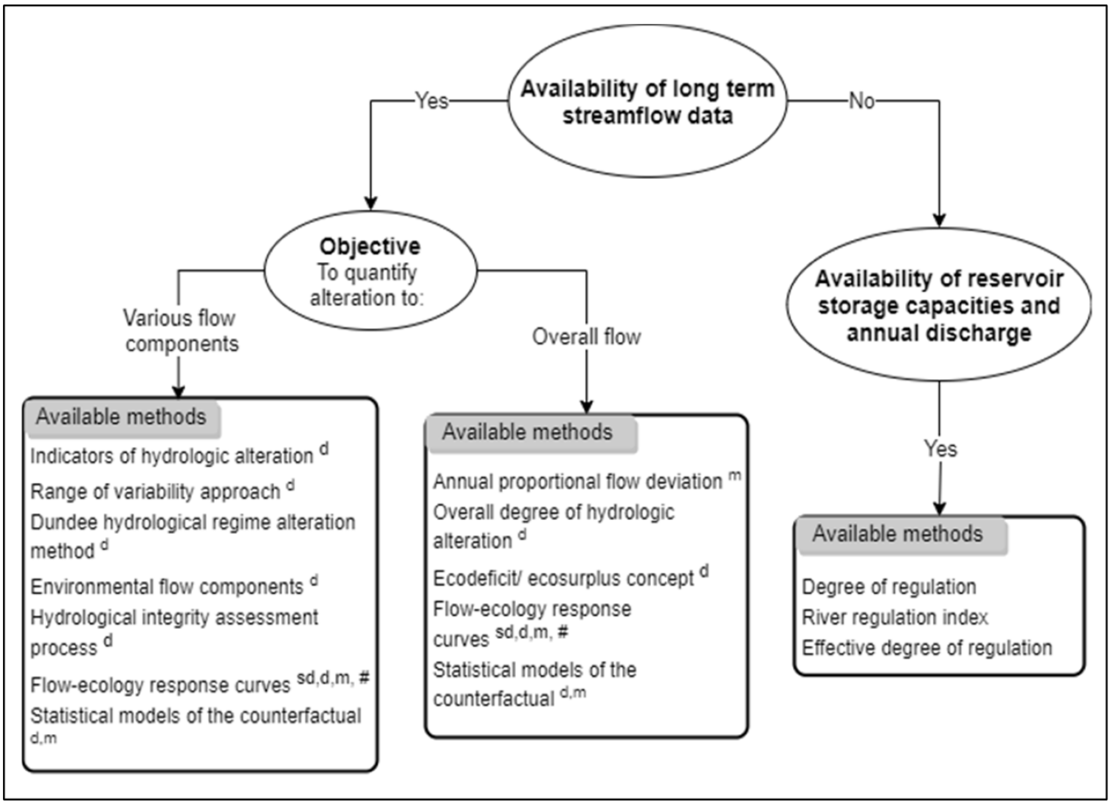

Figure 4. Decision-making tree for selection of flow alteration metric to be used based on data availability. Temporal scale of streamflow data required: sd = sub-daily, d = daily, m = monthly. # Incorporates ecological data of interest to build flow-ecology curves

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 maximising 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 Sáenz 2020), FHReD (Zarfl *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 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 (Mcmanamay *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, Gaucherel 2007, Llausàs 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, Llausàs 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.

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