



# A new index to quantify longitudinal river fragmentation: Conservation and management implications

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## ABSTRACT

The proliferation of river infrastructure projects has altered aquatic longitudinal connectivity, posing a growing threat to riverine biodiversity and ecosystem processes worldwide. Effective methods to quantify loss of river connectivity across spatiotemporal scales and in data-limited landscapes are important to understand and inform basin-wide conservation and development planning. Here we introduce a Catchment Area-based Fragmentation Index (CAFI) and its derivative, the Catchment Area- and Rainfall-based Fragmentation Index (CARFI) as new metrics to quantify river fragmentation. These indices use catchment area as a proxy for riverine habitat availability, avoiding the drawbacks of existing metrics that rely on river length and associated derivatives. CAFI/CARFI can be computed across spatiotemporal scales, incorporate barrier passability values, assesses the cumulative impact of multiple barriers, and be applied even in data-limited environments.

We first applied CAFI and CARFI to a simulated network to illustrate their properties with respect to the number and location of barriers and compared these results to the widely applied Dendritic Connectivity Index (DCI). While all indices varied with barrier addition, CAFI and CARFI were more sensitive to both barrier number and location. Next, we illustrated the utility of CAFI and CARFI through case studies in two contrasting settings: the Klamath River in California, where dam building has ceased (and dam removals are being considered) and the Netravathi River in India, where dam building is ongoing, with 65 dams proposed for future development. Results indicate that CAFI and CARFI can effectively quantify trends in fragmentation across spatial scales and temporal scenarios of dam development (i.e. descriptive applications) and can aid the prioritization of sites for dam removal, restoration, or conservation (i.e. prescriptive applications). Overall, these indices can quantify the impacts of individual dams and assess a range of development scenarios to inform basin-wide conservation and development planning.

## 1. Introduction

The loss of connectivity is a ubiquitous threat facing rivers worldwide (Grill et al., 2015; Nilsson, 2005). In addition to the approximately 140,000 large and small dams across the world (McCully, 1996; Nilsson, 2005), tens of thousands of additional undocumented river infrastructure projects (RIPs) exist worldwide (Belletti et al., 2020). Furthermore, thousands of dams and other RIPs continue to be commissioned to meet humanity's growing demands for hydropower, flood control, and water

supply (Zarfl et al., 2015). Not surprisingly, freshwater ecosystems are among the most altered and threatened globally. Existing dams regulate over half the world's major river systems (Nilsson, 2005) and allow only 23% of large rivers (>1000 km in length) to flow uninterrupted into the ocean (Grill et al. 2019).

The primary impact of RIPs is the loss of river network connectivity through the construction of a physical barrier. This can impede the movement of sediments, nutrients, water, and aquatic organisms along the river network, thereby altering riverine habitat structure and

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ecosystem processes and functions (Nel et al., 2009; Poff and Hart, 2002; Pringle, 2003; Richter et al., 1996). Dams and other RIPs also pose direct barriers to the movement of aquatic biological communities, most notably on fish species that migrate along dendritic networks to access feeding or spawning grounds (Poff and Zimmerman, 2010). This loss of connectivity can lead to isolation of fish populations (Schick and Lindley, 2007), reduced potential for recolonization and metapopulation persistence (Fagan, 2002; Fullerton et al., 2010), decreased access to feeding, spawning and/or nursery habitats (Godinho et al., 2007; Hu et al., 2015), change in species composition (Consuegra et al., 2021; Jumani et al., 2018), and even extirpation of isolated fish populations (Hamilton et al., 2005; Winston et al., 1991).

To better understand and quantify the impacts of RIPs on river connectivity, several metrics of river fragmentation or connectivity have been proposed (see Jumani et al. 2020 for a review). These methods can be categorised into actual, structural, and potential connectivity metrics (Calabrese and Fagan, 2004). While numerous methods describe actual connectivity (i.e. based on observed or measured processes), their application across spatiotemporal scales can be constrained by data and resource limitations and analytical complexity. On the other hand, many structural metrics (such as barrier densities and longest free-flowing river length), though easy to compute, are descriptive, spatially implicit, often insensitive to the addition or removal of barriers, and incapable of quantifying the individual and cumulative impact of every dam (Jumani et al., 2020; Kemp & O'Hanley, 2010). As a middle ground, potential connectivity metrics are spatially explicit and can be used to robustly characterize connectivity with minimal data and resource requirements.

Habitat-weighted structural or potential connectivity indices such as the Dendritic Connectivity Index (DCI) (Cote et al., 2009) and indices derived from it, like the River Connectivity Index (Grill et al. 2014), can quantify the cumulative effects of multiple barriers on river connectivity across spatiotemporal scales. Such indices are also used to inform basin-wide conservation, restoration, and development plans (Cote et al. 2009; Bourne et al. 2011; Grill et al. 2014). These indices not only consider the extent of habitat available (as measured by river length or volume), but also the spatial configuration of barriers across the river network. Furthermore, increasing access to GIS capabilities and spatial datasets make these indices readily applicable across large spatiotemporal scales and data-deficit landscapes. Consequently, such metrics are gaining rapid popularity and widespread implementation.

Although such potential connectivity metrics can quantify structural river fragmentation, most use river lengths as a measure of habitat availability. This reliance on river lengths and the implicit treatment of river reaches across longitudinal gradients as ecologically equivalent poses serious drawbacks (detailed in Section 2). Examining and addressing these issues is important since numerous assessments use connectivity indices like the DCI to quantify river fragmentation in response to dam development (Anderson et al., 2018; Atkinson et al., 2020; Buddendorf et al., 2017; Choy, et al., 2018; Edge et al., 2017; Jaeger et al., 2014; McManamay et al., 2015) and prioritize barrier removal, under the assumption that an increase in structural connectivity (as quantified by an index) will improve biotic communities (Bourne et al., 2011; Kemp & O'Hanley, 2010; Perkin et al., 2015).

Here, we discuss the strengths and drawbacks of existing connectivity metrics (Section 2). We adopt a similar habitat-weighted approach to introduce a new index of longitudinal river fragmentation – the Catchment Area-based Fragmentation Index or CAFI (Section 3) – that addresses some of the drawbacks associated with existing metrics while retaining their advantages. We then examine the characteristics of the CAFI through simulations by varying the location and number of barriers in a hypothetical watershed and compare these results to those obtained using the DCI (Section 4). Finally, we apply our index to the Klamath River basin (USA) and the Netravati River basin (India) to illustrate its application in quantifying river fragmentation across spatiotemporal scales, and in spatial prioritization analyses to inform

basin-wide conservation and development planning (Section 5).

## 2. Strengths and drawbacks of existing potential connectivity metrics

Longitudinal connectivity is crucial in determining habitat availability for river-dependent fauna and hence determines the composition and distribution of aquatic biological communities (Cote et al., 2009; Fagan et al., 2002). Since connectivity in rivers is water-mediated through dendritic pathways, barriers cannot be considered in isolation of other barriers on the river network. Consequently, graph-theoretic approaches are an emerging method to quantify the cumulative impact of several barriers on network connectivity (Grill et al., 2014). Such approaches consider not just the number of barriers, but also their spatial configuration relative to each other and the river network by representing the river as a network of links and nodes. Data on habitat availability and other variables of interest can also be assigned to such networks. Various connectivity indices have been described using these techniques, the majority of which use river length as a measure of available habitat (Cote et al., 2009; Diebel et al., 2015; McKay et al., 2013; Segurado et al., 2013), though others use river-length dependent variables like river volume (Grill et al. 2014) and stream order (Díaz et al., 2019). The DCI by Cote et al. (2009) is among the most widely used connectivity metrics within this family of metrics. It is an index of river connectivity calculated from stream length, which assesses the probability that a fish may move between two points in a river network (Cote et al. 2009). The DCI can be calculated for both potamodromous (DCIp) and diadromous (DCId) life histories, and values range from 0 (no connectivity) to 100 (fully connected). Assuming each barrier is impassable and splits the river into distinct segments, the DCIp and DCId can be calculated as:

$$DCIp = \sum_{i=1}^n \frac{l_i^2}{L^2} * 100 \quad (1)$$

$$DCId = \frac{l_m}{L} * 100 \quad (2)$$

where, 'n' is the number of segments; 'l<sub>i</sub>' is the river length of the segment 'i' that is disconnected by one or more dams; 'l<sub>m</sub>' is the length of the segment closest to the mouth of the system; 'L' is the total length of the entire river network.

Furthermore, the DCI can incorporate directional barrier passabilities. Since these metrics can be readily computed across spatiotemporal scales, even in data-deficit environments, they have gained rapid popularity and widespread implementation (Jaeger et al., 2014).

Despite these strengths, river-length dependent indices have a few drawbacks. **First**, when river lengths are used without other weights, the underlying assumption is that stream reaches across a longitudinal gradient are ecologically equivalent. For example, the DCIp can produce the same value for dams located upstream or downstream in a watershed as long as the lengths of the resultant river fragments are the same, despite these scenarios presenting different ecological impacts (Grill et al. 2014). This can be particularly problematic when applied to the prioritization of dam mitigation or removal. **Second**, headwater dams that lie beyond the delineated river network are often excluded from the analysis when river-length dependent metrics are used. For example, Anderson et al. (2018; Supplementary Material) excluded about 70 dams from their analysis that were beyond the mapped river network. This is further illustrated in Supplementary Figure S1, which shows how variable flow accumulation thresholds can include or exclude dams on low-order reaches. Since headwater streams tend to harbour greater number of endemic species (Colvin et al., 2019; Meyer et al., 2007) and a large number of ongoing and proposed RIPs are being commissioned on headwater streams (Couto and Olden, 2018), omission of such dams from connectivity analyses poses a significant problem. **Lastly**, river-

length dependent indices can vary in value based on the spatial extent of the delineated river network (Baker et al., 2007). This, in turn, depends on the threshold set for flow accumulation to river lines, and to a lesser extent, the resolution of the underlying digital elevation model (DEM) (Dark and Bram, 2007; Murphy et al., 2008), and the flow direction and accumulation algorithm used (Erskine et al., 2006). The area threshold to convert flow accumulation rasters to river polylines can drastically change the extent of river branching and river length, which yields inconsistent and non-uniform changes in connectivity index values. To illustrate this, we examined DCIp and DCId values for a river network delineated across three different flow accumulation thresholds (Fig S1 in Supplementary Material). Resultant inconsistencies in values and number of dams excluded from the analysis render DCI values incomparable across the three networks. In terms of the underlying DEM resolution, fine-scale elevation data more accurately represent the contours of the landscape (Dark and Bram 2007), yielding more accurate hydrologic derivatives compared to coarser resolution DEMs (Murphy et al., 2008). Errors from coarse resolution DEMs are enhanced in headwater reaches and smaller catchments; smaller study regions thus need to be characterised by input data that appropriately capture landscape heterogeneity.

### 3. Catchment Area-based fragmentation index (CAFI) as a fragmentation metric

To address the above issues, we propose the Catchment Area-based Fragmentation Index (CAFI) as a new metric of river network fragmentation. Building from the DCI (Cote et al., 2009), this spatially explicit index of fragmentation replaces river length with cumulative catchment area as a measure of habitat quantity. Notably, upstream catchment area is an excellent predictor of discharge, a measure of habitat availability (Ziv et al., 2012), with a unit increase in contributing area generally yielding a unit increase in water volume under the simplifying assumption that all parts of the catchment contribute the same volume of water (Galster et al. 2006; Deitch and Kondolf 2012; Burgers et al. 2014). Assuming each barrier is impassable, the CAFI is calculated as the sum of the ratio of the catchment area of each dam to the total catchment area of the entire river network (Eq. (3)). In cases where barrier passability is known, the CAFI can be weighed by barrier passabilities as shown in Eq. (4).

$$CAFI = \sum_{i=1}^n \frac{a_i}{A} * 100 \quad (3)$$

$$CAFI = \sum_{i=1}^n \frac{a_i \cdot c_i}{A} * 100 \quad (4)$$

where, 'n' is the number of dams; 'a<sub>i</sub>' is the total catchment area of dam 'i'; 'c<sub>i</sub>' is the barrier impassability score ranging from 1 (impassable) to 0 (completely passable); 'A' is the catchment area of the entire river network

In catchments characterised by uniform spatial distribution of rainfall, drainage area is an adequate predictor of discharge. However, for rivers in mountainous terrains having strong orographic or latitudinal rainfall trends, incorporating spatially explicit information about precipitation may improve metric performance. In such cases, we propose the Catchment Area- and Rainfall-based Fragmentation Index or CARFI (Eq. (5))

$$CARFI = \sum_{i=1}^n \frac{a_i \cdot r_i}{A \cdot R} * 100 \quad (5)$$

where 'r<sub>i</sub>' is the average annual rainfall intensity in 'a<sub>i</sub>'; 'R' is the average annual rainfall intensity in the entire catchment area 'A'.

Like the DCI, the CAFI and CARFI also use network analysis to quantify the cumulative impact of each barrier relative to its location on

river fragmentation. It is important to note that, while the DCI is a measure of *connectivity*, CAFI is a measure of *fragmentation*, with higher values indicating greater fragmentation. Since contributing areas increases from upstream to downstream, a dam's impact on fragmentation will be greater the further downstream it is located. Based on the species or ecosystem process being considered, this may better reflect expected conditions since barriers located further downstream isolate greater proportions of available upstream habitat compared to headwater dams (Fagan et al., 2002; Nilsson, 2005). The CAFI has a lower limit of 0 (indicating complete connectivity), and for a basin with a single dam, the CAFI can range between 1 and 100 (low to high levels of fragmentation). However, as the number of barriers increase, the CAFI can surpass 100, with increasing values corresponding to increasing levels of fragmentation.

The CAFI and CARFI are relatively easy to compute even in data-deficit regions since catchment area can be delineated with any surface elevation model on a GIS platform and rainfall can be ascertained through global datasets such as WorldClim (Fick and Hijmans, 2017). Since these metrics rely on catchment area, all dams can be incorporated in the analysis, including those on headwater streams beyond delineated river networks. Furthermore, although the extent of contributing areas varies based on DEM resolution, the magnitude of error associated with areal measures tends to be lower when compared to errors in drainage network length (Ghaffari, 2011; Sukumaran and Sahoo, 2020; Tan et al., 2018). While CAFI/CARFI addresses some of the drawbacks of the DCI, they are limited in not being restricted to a maximum value.

### 4. Application of the CAFI and CARFI in a simulated drainage network

To examine the properties of these metrics, we calculated the CAFI and CARFI across a simulated second-order catchment (similar to Cote et al. 2009) and examined the areas of convergence and divergence between the DCIp, DCId, CAFI and CARFI. To enable better comparison with CAFI/CARFI values, DCIp and DCId were visualised as their inverse (100-DCI). The simulated network was characterised by a total drainage length of 1000 km (Fig. 1a), a catchment area of 10,000 square kilometres, and total annual rainfall of 2000 mm (Fig. 1b) with 20 impassable barriers distributed across its longitudinal length (Table S1 in Supplementary Material). Rainfall was simulated to be orographic such that rainfall intensity decreased from headwater to downstream reaches. We calculated index values under three scenarios: (1) a single barrier at decreasing distances from the river mouth, (2) directional increase in the number of barriers, and (3) varying the spatial configuration and number of barriers from 0 to 20. All simulations were conducted in R 4.0.5 (R Core Team, 2021). R code and associated data are provided in the Supplementary Information.

#### 4.1. Simulation 1- Variation in metric based on the location of a single barrier

Here index values were computed for a single barrier (barriers A to T in Fig. 1) to evaluate the effect of barrier location on fragmentation. Since the DCIp treats all stream reaches as functionally equivalent, regardless of their position on the river network, dams located upstream and downstream at similar distances from the headwater or river mouth, respectively, produce the same connectivity values, yielding a bell-shaped distribution (Fig. 2). On the other hand, DCId inverse, CAFI, and CARFI values show a monotonic decline with increasing distance of barrier to the mouth (Fig. 2). The DCId, CAFI and CARFI indicate that fragmentation caused by a single dam is highest near the mouth of the river and decreases as distance to mouth increases. For basin-wide processes, this reflects the expected trend where a downstream barrier isolates larger portions of the upstream habitat compared to a headwater dam (Fagan et al., 2002; Fullerton et al., 2010). On the other hand, DCIp generates maximum fragmentation when a dam splits a river network

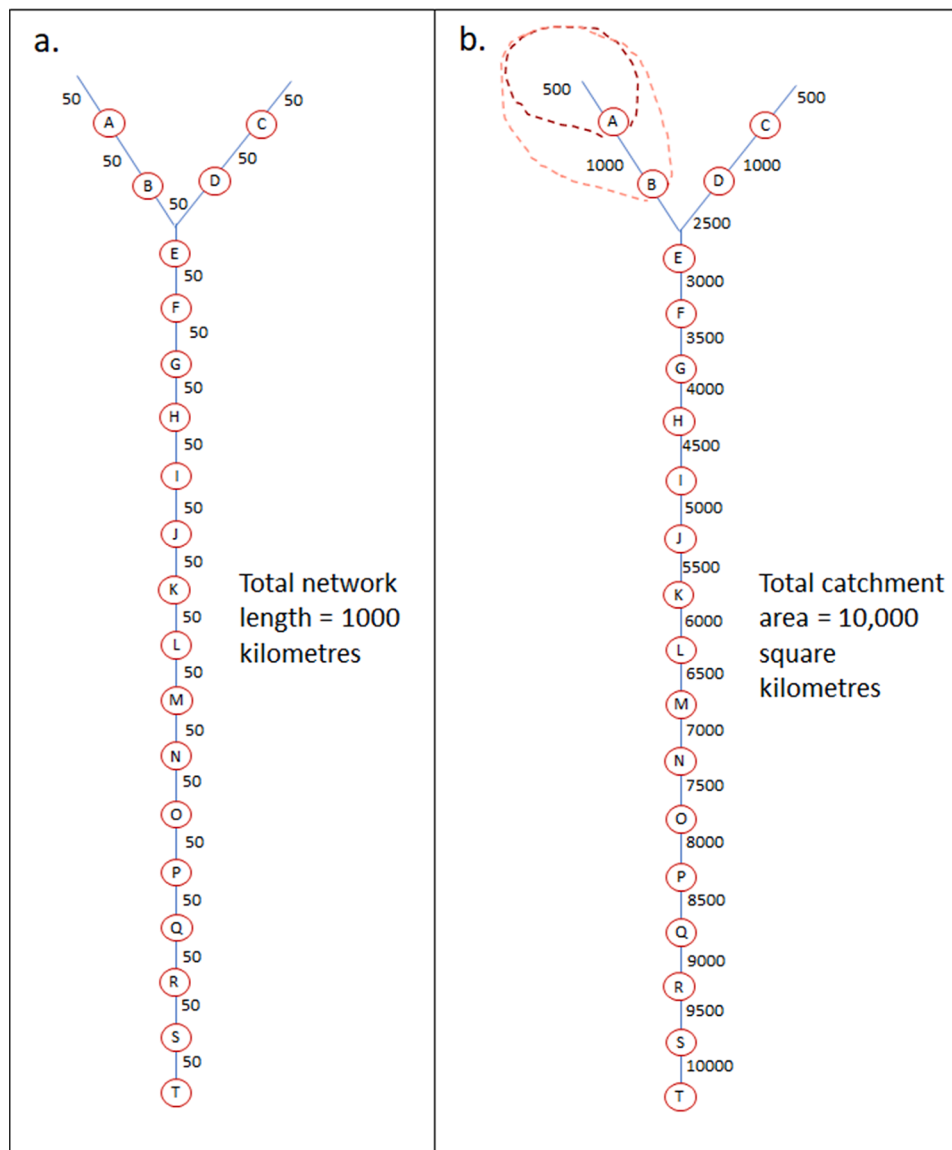


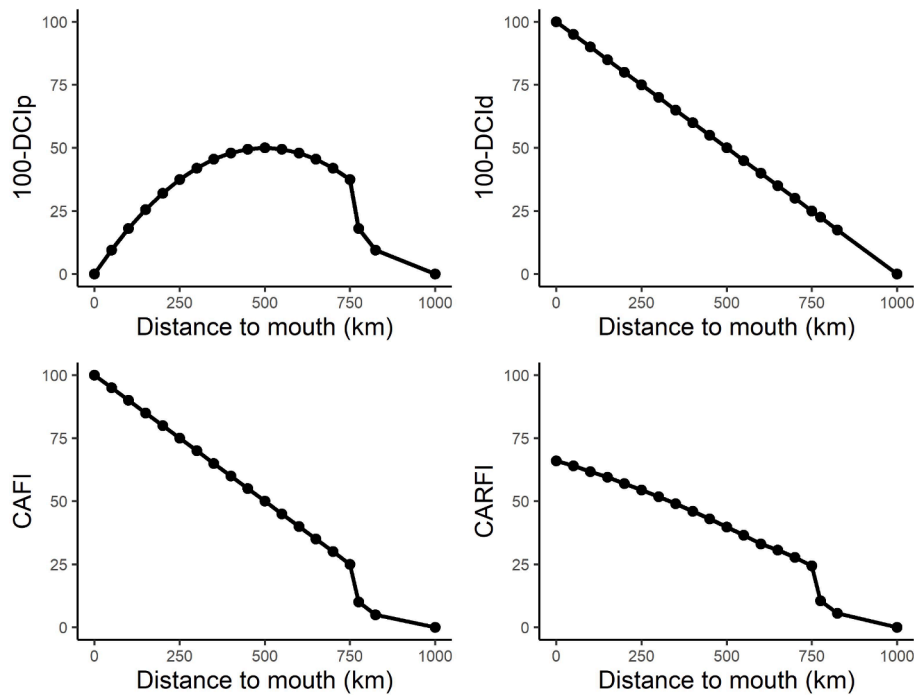
Fig. 1. Simulated drainage network and location of barriers along its path. Numbers in left panel correspond to the length of each river segment. Numbers in the right panel refer to the catchment area of each barrier, as illustrated with the dashed lines.

into equal fragments. This may be better suited to measure fragmentation for potamodromous species and other non-directional processes. CARFI values are generally lower than CAFI. This difference increases from upstream to downstream dams because in instances of orographic rainfall, catchments of headwater dams have higher annual rainfall intensities compared to those of downstream dams.

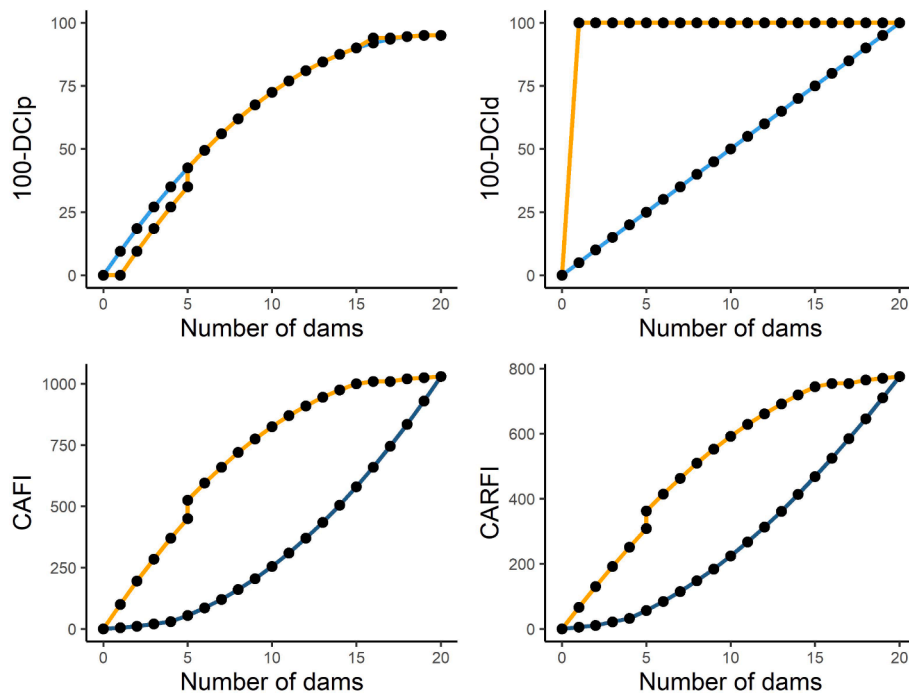
#### 4.2. Simulation 2- Variation in metric based on directional increase in the number of dams

Here, index values were calculated for an increasing number of barriers cumulatively added to the network. This increase was done in two ways, first with successive barriers added in the upstream to downstream direction (i.e. starting with barrier A in Fig. 1) and next with barriers added to the network in the reverse order (i.e. starting with barrier T in Fig. 1). While DCI<sub>p</sub> inverse increased with an increase in the number of barriers, similar trends of change were exhibited in the upstream and downstream direction of dam addition, with the extent of change (as indicated by the slope of the line) decreasing after the addition of the first 10–12 barriers (Fig. 3). Although DCI<sub>d</sub> inverse

showed differential trends of change based on the direction of barrier addition, values do not change with the addition or removal of barriers above the most downstream dam. Consequently, the addition of dams in the downstream to upstream direction did not show any change after the first dam ‘T’ (orange line, Fig. 3). On the other hand, for CAFI and CARFI, the direction and location of dam addition were reflected in the index value. When moving from upstream to downstream (blue lines, Fig. 3), the index increases gradually at first and then more rapidly as successive dams are added further toward the basin outlet; the opposite is true for dam addition from downstream to upstream (orange lines, Fig. 3), with the largest impacts for those first few dams farthest downstream. Overall CAFI and CARFI yielded smaller increases in fragmentation for barriers added further upstream, irrespective of the direction of increment. This trend reflects the increase in basin-wide fragmentation caused by the addition of headwater dams versus dams on the mainstem.



**Fig. 2.** 100-DCIp, 100-DCId, CAFI and CARFI values for a single dam across varying distances from the mouth of a simulated network. The sudden change at the point close to 750 m corresponds to dam 'E' located below the confluence of two tributaries, where fragment length and catchment area vary by a higher margin.



**Fig. 3.** 100-DCIp, 100-DCId, CAFI, and CARFI values for an increasing number of dams, added in the upstream to downstream (blue lines) and downstream to upstream (orange lines) directions. The sudden change at the point close to 750 m corresponds to dam 'E' located downstream of the confluence of two tributaries, where fragment length and catchment area vary by a higher margin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

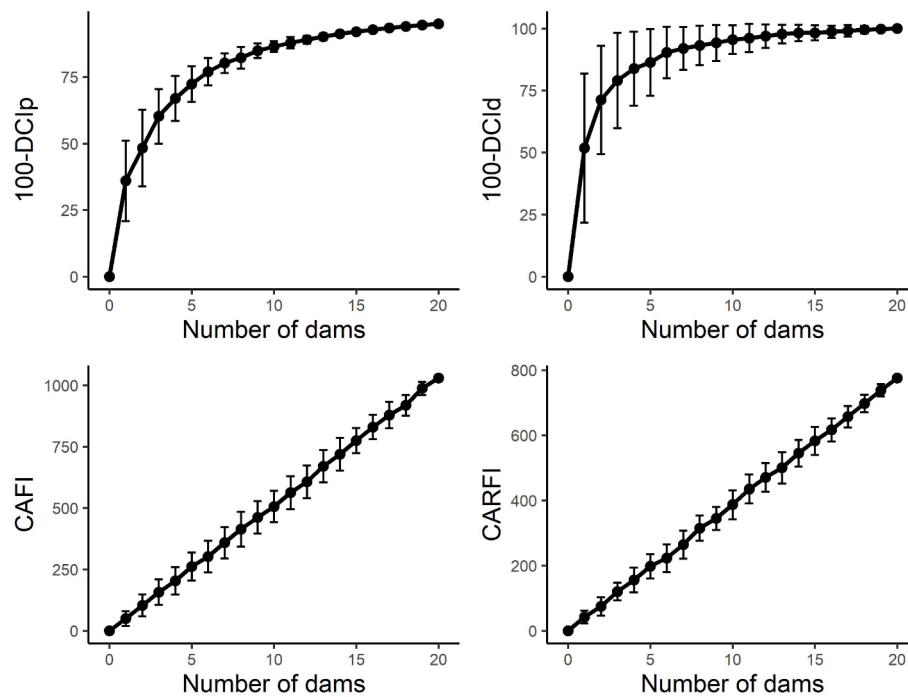
**4.3. Simulation 3 - Variation in metric based on the number and spatial configuration of barriers**

Here, index values were calculated for an increasing number of barriers (ranging from 1 to 20) across 100 random iterations of barrier locations on the simulated river network. This simulation illustrates the sensitivity of these indices to the incremental addition of a dam across varying spatial configurations (Fig. 4). DCIp and DCId values were most sensitive to the addition of the first 5–10 and 3–5 barriers respectively.

CAFI and CARFI, on the other hand, retained sensitivity to the incremental addition of more barriers. This difference may make the CAFI/CARFI better suited to measure changes in fragmentation, especially in previously dammed basins.

In our second simulation, we addressed the potential for thresholds in connectivity associated with the number of barriers and changes in watershed topology. Passage rate was held constant at 0.5, while watershed topology, the number of barriers, and the locations of the barriers were varied. As anticipated, we observed a strong non-linear





**Fig. 4.** Simulation of 100-DCIp, 100-DCId, CAFI, and CARFI values for an increasing number of dams across 100 random iterations of barrier locations. The error bars denote standard deviation.

decline in connectivity associated with the number of barriers. For instance, the median connectivity (HCIU value) over 500 watershed topologies and 20 dam configurations reduces from 1.00 at 0 barriers to 0.52 at 3 barriers, 0.36 at 5 barriers, and 0.17 at 10 barriers. Fig. 5 demonstrates this nonlinearity, stratified by network diameter, where three classes of diameter were identified to contain nearly equal sample size (34.0% of samples have diameters of 6–15, 31.7% of samples have diameters of 16–21, and 34.3% of samples have diameters of 22–39). This figure shows that watersheds with low branching topology and high diameter are more susceptible to disconnection by lower numbers of barriers. In our second simulation, we addressed the potential for thresholds in connectivity associated with the number of barriers and changes in watershed topology.

The above simulations illustrate the properties of the CAFI, CARFI, DCIp and DCId in relation to barrier location, number of barriers, and sensitivity to additional barriers in a river network. The DCIp, CAFI, and CARFI share common trends of curvilinear responses to barrier addition (Fig. 3). While the DCId is sensitive to the location of a single barrier (Fig. 2), CAFI and CARFI are more sensitive to both barrier location (Fig. 2) and a varying number of dams (Fig. 3). While DCIp and DCId values begin to plateau after the addition of the first few dams, CAFI and CARFI retain sensitivity to the incremental addition of barriers (Fig. 4).

##### 5. Case study applications of the CAFI and CARFI

We applied the CAFI to the Klamath River Basin in the USA and the CARFI to the Netravathi River Basin in India to illustrate the application of these indices in different settings. The Klamath is a large river originating in southern Oregon, USA that traverses over 425 km before reaching the Pacific Ocean off northern California. The basin spans an area of ~ 31,340 km<sup>2</sup> and supports several endangered and threatened species such as the *Deltistes luxatus* (Cope, 1879) and *Chasmistes brevirostris* (Cope, 1879) (USFWS, 2012), and extensive anadromous fish runs for salmonids such as *Oncorhynchus kisutch* (Walbaum, 1792), *O. tshawytscha* (Walbaum, 1792), and *O. mykiss* (Walbaum, 1792). Up until the year 2000, the main river network of the Klamath had 62 dams along its course; eight dams have been removed since that time. Four

dams have been identified for further removal under the Klamath Hydroelectric Settlement Agreement (Gosnell and Kelly, 2010). Here, we compute the extent of longitudinal fragmentation under three scenarios: the past scenario based on the presence of all anthropogenic barriers ( $n = 62$ ), the present scenario based on the presence of existing dams ( $n = 54$ ), and the future scenario considering the removal of four large dams ( $n = 50$ ). These scenarios were examined at the spatial scales of the basin and sub-basin (defined by the 8-digit hydrologic code of the USGS Watershed Boundary Dataset (Simley & Carswell, 2009)) under the assumption that every barrier is impassable. We also use CAFI to identify priority dam removal sites to best improve longitudinal connectivity.

The Netravathi River is a small west-flowing river originating in the mountains of the Western Ghats of Karnataka State in India. The basin receives an average rainfall of 4063 mm and experiences strong orographic rainfall trends, with rainfall intensity varying between 6433 mm and 2780 mm from upstream to downstream reaches (Fig S2 in Supplementary Material). The basin encompasses an area of approximately 3470 km<sup>2</sup> and the river flows over 104 km before emptying out into the Arabian Sea. This region is part of the Western Ghats global biodiversity hotspot (Myers et al. 2000) and UNESCO world heritage site. This river is also identified to be a potential freshwater key biodiversity area (Molur et al. 2011), characterised by exceptionally high levels of species richness and endemism and intense anthropogenic pressures. The river has 24 current dams along its network, and 65 small hydropower dams (those that produce < 25 MW) have been proposed for further development. Hence, CARFI values were examined across two scenarios – the present scenario characterised by all existing dams ( $n = 24$ ), and the future scenario characterised by the presence of all existing and proposed dams ( $n = 89$ ). These scenarios were examined at the spatial scales of the basin and sub-basin (defined by level 8 of the HydroBASINS dataset (Lehner et al., 2008)) under the assumption that every barrier is impassable. Additionally, ‘optimised’ strategies of dam development were identified to minimize fragmentation while maximising human gain with respect to hydropower capacity.

5.1. Quantifying longitudinal fragmentation across spatial and temporal scales

**Klamath River Basin:** Change in basin-scale CAFI scores between 1800 and 2025 is shown in Fig. 5a. Dams constructed between 1840 and 1910 contributed to low levels of basin-wide fragmentation as they were located on headwater streams. Fragmentation increased steeply in the 1920 s and 1960 s. The last dam was constructed in 1991, after which defragmentation occurred. The removal of eight dams between 2002 and 2012 marginally decreased basin-wide CAFI from 281 to 271 (red solid line, Fig. 5). The future removal of four large dams (Iron Gate, Copco 1, Copco 2, and JC Boyle) will decrease basin-wide CAFI by more than half to 94.8 (red dotted line, Fig. 5). Comparing this chronosequence to the inverse DCip and DCId (Fig. 5b and 5c) reveals some similarities, such as the first peak of fragmentation around the 1920 s. However, some important dissimilarities remain. First, the rate of increase in fragmentation for the first few dams (1800–1900) is greater for DCip and DCId. Additionally, after 1925, DCip and DCId values tend to plateau despite the subsequent building of over 40 dams, although DCId values varied more than those of DCip. Hence, the second peak of dam building (as seen in case of CAFI around the 1960 s) is not as apparent. Furthermore, the proposed removal of four large dams, which will free up ~ 400 km of upstream river length, has a smaller impact on improving connectivity as per DCip and DCId, in stark contrast to CAFI.

At the sub-basin scale, the removal of eight dams between 2002 and 2012 improved sub-basin level connectivity along the mid- and downstream sections of the river (Fig. 6). Specifically, fragmentation decreased in the Shasta, Trinity, Salmon, and Sycan river sub-basins (Table 1). This decrease was greatest in the Shasta river sub-basin, where the removal of just two dams decreased the CAFI from 143 to 19 (Table 1). The removal of four dams in the Upper Klamath will drastically improve connectivity in the future scenario.

**Netravathi River Basin:** Dam building on the Netravathi began in 1990, and a steep increase in fragmentation was seen in the years following 2010 due to the construction of five dams along mainstem channels (Fig. 7a). The present scenario, characterised by 24 dams, resulted in a basin-level CARFI score of 281.8; the addition of 65 proposed dams will increase basin-level CARFI to 958.9. A similar increasing trend is apparent with the inverse DCip (Fig. 7b). However, the DCId, which is sensitive to the most downstream dam, exhibited a much smaller extent of change with the addition of 65 proposed dams. Both, DCip and DCId indicated sharper increases in fragmentation after the addition of the first few dams and a smaller response to the future

addition of 65 dams as compared to the CARFI.

At the sub-basin scale, all sub-basins show an increase in fragmentation from the present to the future scenario, except for the Gowri river sub-basin (Fig. 8; Table 2). Currently undammed sub-basins of middle and lower Kumaradhara will be subjected to severe increases in fragmentation if proposed dams are built. For the Yettinahole sub-basin, CARFI levels before the construction of the controversial Yettinahole Diversion Project (YDP) was 94. After the construction of eight dams of the YDP in 2019, the CARFI increased to 158.

5.2. Sensitivity analysis to prioritize dam mitigation/removal

**Klamath River Basin:** To prioritize dams for removal or mitigation efforts, a sensitivity analysis of existing dams was conducted. Using the first scenario with 116 dams as the starting point, all projects were iteratively removed to determine the individual effect of removing a single dam (Branco et al., 2014). At each step, we first identified the dam that caused the greatest decrease in fragmentation upon its removal, after which it was permanently dropped. This process was repeated until all the dams were ranked (Fig. 9). The removal of just seven dams can reduce basin-level fragmentation to pre-1920 levels, from 252 to 44.5. The four dams (Iron Gate, Copco 1, Copco 2, and JC Boyle) identified for removal are also ranked the highest in the sensitivity analysis and will result in the highest possible decrease in basin-level fragmentation. On the other hand, the eight dams removed between 2002 and 2012 have had a significantly lower impact on decreasing fragmentation (Fig. 9).

**Netravathi River Basin:** To aid the planning and prioritization of proposed dams, a sensitivity analysis was conducted using the existing scenario as the starting point. Each individual proposed project was iteratively added to the river network with all existing dams to determine the individual effect of adding a single dam on CARFI. At each step, the dam with the lowest impact was added to the river network and the process repeated until all the dams were ranked in increasing order of impact. Fig. 10 represents the range of CARFI values for each added dam across all simulations. The lower end of the boxplot represents the “better” option that causes the lowest possible increase in basin-level CARFI, while the upper end represents the “worst” option that causes the greatest increase in basin-level CARFI.

The ranked proposed dams were overlaid with their hydropower capacity to assess the utility of each dam. Dams were grouped into four categories based on their impact (high versus low fragmentation) and output (high versus low utility) (Fig. 11a). Dams with a low impact but high utility are generally considered ‘better’, while those with high

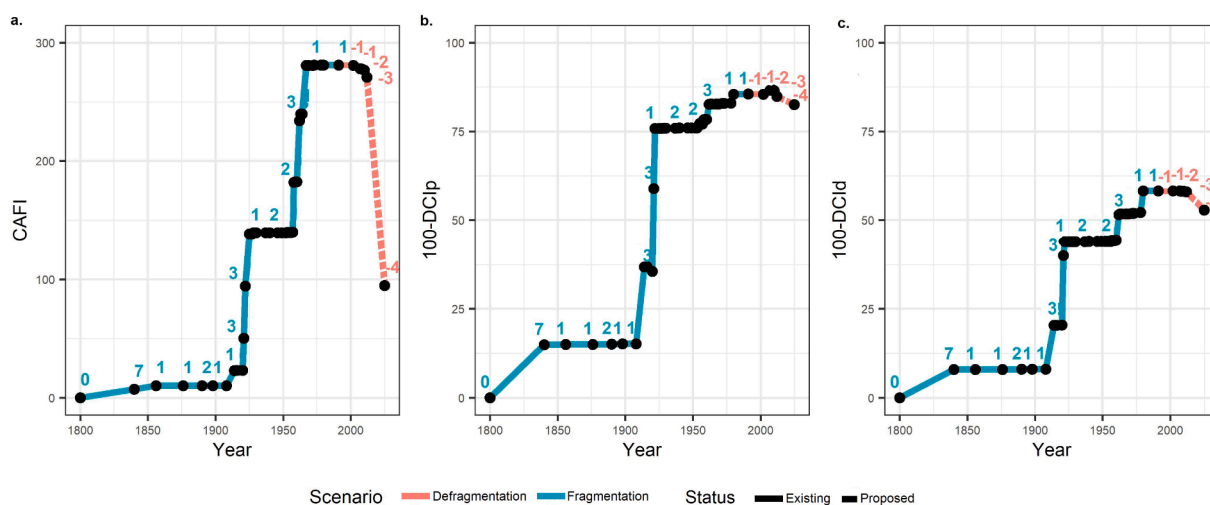
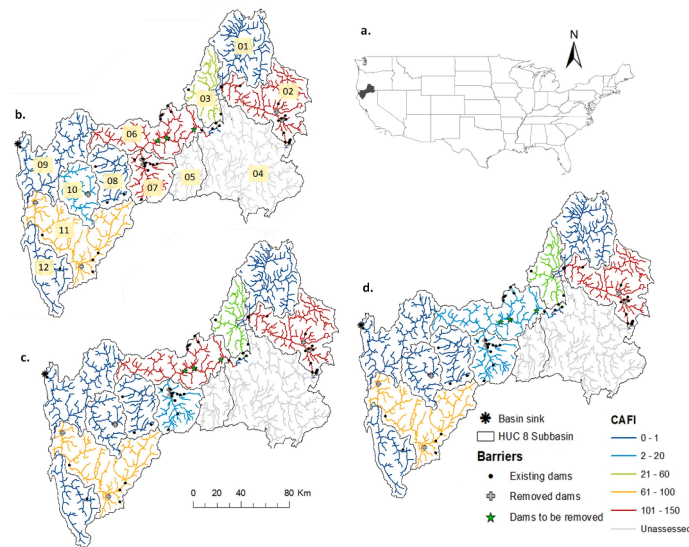


Fig. 5. Chronosequence of basin-level CAFI (a), 100-DCip (b), and 100-DCId (c) in the Klamath. Numbers indicate the number of dams built or decommissioned on select years. Blue and red lines respectively indicate increases and decreases in fragmentation; solid and dashed lines represent present and future scenarios respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** Sub-basin level change in CAFI in the Klamath Basin (shaded area in (a)) across three scenarios: past scenario with 62 dams (b), present scenario with 54 dams (c) and future scenario involving the removal of four dams (d). The last two digits of the HUC8 sub-basin code are illustrated in panel b. ‘Unassessed’ areas include parts of the river that do not connect to the main network via surface connections.

**Table 1**  
Sub-basin level CAFI scores across three scenarios for the Klamath River Basin. Numbers in parentheses represent the number of barriers.

Sub-basin	HUC 8 code	CAFI – past scenario (62)	CAFI – present scenario (54)	CAFI – future scenario (50)
Miller Creek	18,010,201	0.0 (0)	0.0 (0)	0.0 (0)
Sycan River	18,010,202	120 (18)	104.3 (16)	104.3 (16)
Fall Creek	18,010,203	31.9 (4)	31.9 (4)	31.9 (4)
Lost River	18,010,204	0.1 (2)	0.1 (2)	0.1 (64)
Upper Klamath River	18,010,206	115 (10)	115 (8)	5.6 (4)
Shasta River	18,010,207	143 (15)	19.6 (15)	19.6 (15)
Scott River	18,010,208	0.23 (3)	0.23 (3)	0.23 (3)
Lower Klamath River	18,010,209	0.11 (1)	0.11 (1)	0.11 (1)
Salmon River	18,010,210	3.09 (2)	0.0 (0)	0.0 (0)
Trinity River	18,010,211	71.7 (6)	69.7 (4)	69.7 (4)
South Fork Trinity	18,010,212	0.08 (1)	0.08 (1)	0.08 (1)

impact and low utility are poor options recommended to be avoided at all costs.

We also overlaid the ranked dams’ CARFI scores with their hydropower capacity to determine the least fragmenting combination of barriers to be built to achieve a given hydropower production goal (Fig. 12). For example, the existing 24 dams on the Netravathi have a cumulative installed capacity of 100 MW. Considering a hypothetical goal to double the hydropower generating capacity to 200 MW (dashed line, Fig. 12), the construction of 18 selected dams would achieve that goal whilst causing the lowest cumulative impact on basin-wide fragmentation as measured by the CARFI. It is important to note that this is an illustrative exercise; we intend for such applications to be used along with other socio-ecological considerations and site-specific characteristics to inform dam siting.

**6. Discussion**

Given the continued global development of river networks, there is a need to develop robust and flexible metrics of river fragmentation that

have the ability to: (a) assess the individual and cumulative impacts of multiple barriers; (b) be applied across spatial scales and scenarios; (c) incorporate dam passabilities; and (d) be easily and efficiently computed in data deficit regions with (e) computational ease and efficiency. The CAFI and CARFI are metrics of longitudinal river fragmentation that meet the above requirements.

As catchment areas increase from upstream to downstream, the CAFI/CARFI yields a higher impact for dams located further downstream (Figs. 2 and 3), incorporating an implicit sense of ‘directionality’. This differential impact along a longitudinal gradient of a river better reflects expected trends of impeded basin-wide ecosystem processes and the movement of diadromous species as barriers located further downstream isolate greater proportions of available upstream habitat compared to headwater dams, and impact the generally higher diversity of larger rivers (Fagan et al., 2002; Fullerton et al., 2010; Grill et al., 2014). Although the DCId tends to produce declining connectivity values for downstream dams, their values do not change with the addition or removal of barriers above the most downstream dam since it is calculated from the perspective of a diadromous fish arriving from the sea. This trend, while suitable for diadromous species, could pose a drawback for other applications.

The CAFI/CARFI is easy to compute, especially in data-deficit environments. This attribute is crucial since ongoing and future dam developments are mainly concentrated in tropical developing countries (Zarfi et al., 2015) that are often limited in hydro-ecological data availability and tend to overlap with areas of high freshwater biodiversity (Pandit and Grumbine, 2012; Tockner et al., 2016). In these scenarios, the CAFI/CARFI can be particularly useful in aiding science-based decision-making pertaining to basin-wide conservation and RIP management. The lack of reliance on river fragment lengths and their derivatives also makes the CAFI/CARFI more robust and easier to apply, especially with respect to dams on low-order tributaries. This is important since most proposed dam developments are geared towards small dams on headwater streams (Couto and Olden, 2018) where the derivation of channel length and stream order measures can be subjective and relative to thresholds for channel inception or DEM resolution. Further, unlike river-length dependent measures (such as river length to next barrier), contributing area values do not change with the removal or addition of dams. This improves the computational efficiency of these metrics, allowing users to evaluate a large number of scenarios and barrier combinations more quickly compared to recursive analyses in



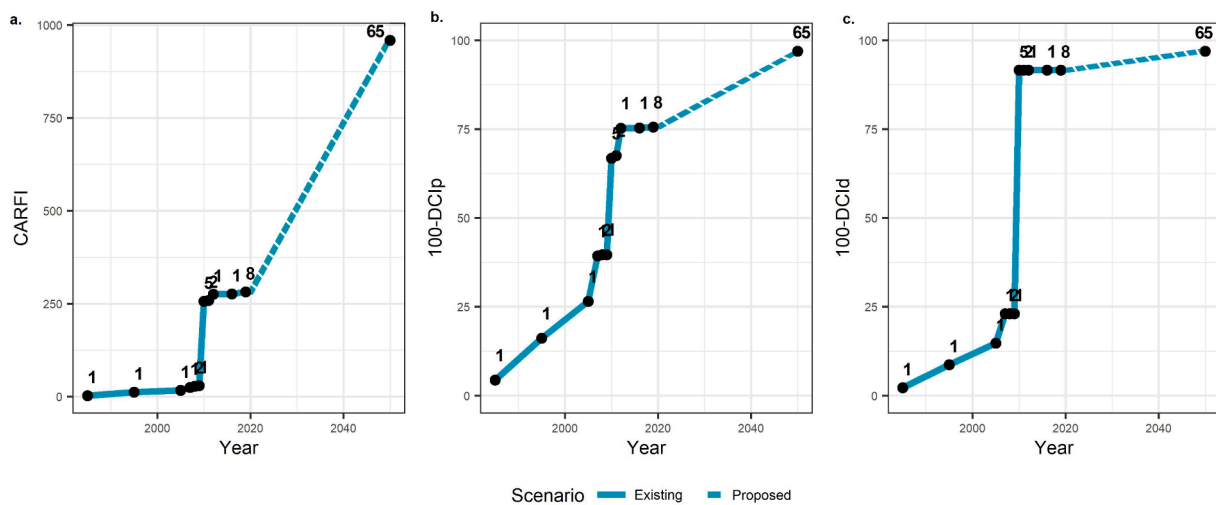


Fig. 7. Chronosequence of basin-level CARFI (a), 100-DCIp (b), and 100-DCId (c) in the Netravathi. Numbers indicate number of dams built each year. Solid and dashed lines represent present and future scenarios respectively.

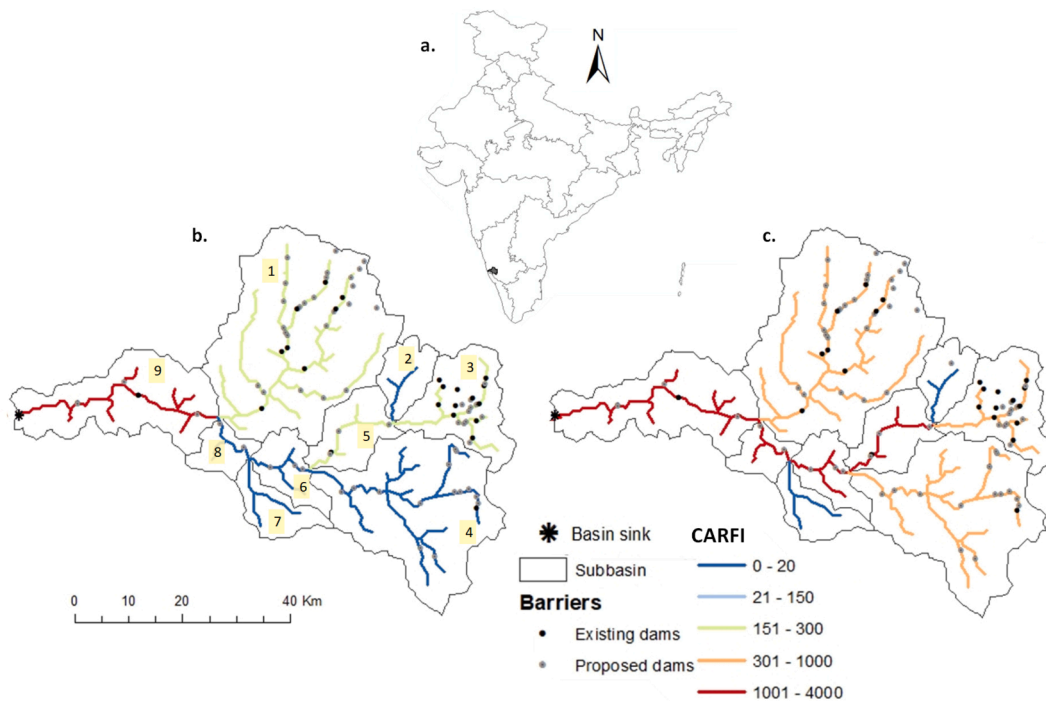


Fig. 8. Sub-basin level change in CARFI scores in the Netravathi Basin (shaded area in (a)) over two scenarios: present scenario with 24 built dams (b) and future scenario with 89 dams (c). The last digit of the sub-basin code is illustrated in panel b.

graph-theoretic river routing models.

The CAFI/CARFI is adaptable in that it can be weighted by user-defined variables of importance such as species richness, unique river classes, and habitat quality as illustrated by Grill et al. (2014) and Rodeles et al. (2021; 2020; 2019) based on study objectives or site-specific considerations. It can also account for differences between impermeable and partially permeable barriers through the barrier impassability score, although this does not implicitly account for the spatial relationship between dams. Given that these indices are not species- or taxa-specific, we expect them to represent fragmentation more holistically for biotic communities (particularly diadromous or migratory species) and connectivity-dependent river dynamics such as sediment redistribution. Since CAFI weighs barriers with smaller

catchments as having a smaller impact, we also propose the CARFI for rain-fed catchments experiencing orographic rainfall trends. In such cases, the impact of a barrier with a small catchment area but a higher rainfall intensity (as compared to that of the total basin) will be weighted higher.

The lack of an upper bound to CAFI/CARFI values poses certain advantages and disadvantages. This feature allows the index to retain sensitivity to the addition of new barriers, even in a previously dammed basin (Figs 4, 5a, 7a), making them particularly suited to analysing and visualizing spatiotemporal trends in fragmentation in response to increasing dam densities. Since the DCIp and DCId begin to plateau after the addition of the first few dams, in basins with high-dam densities, they do not adequately reflect changes in connectivity with additional

**Table 2**  
Sub-basin level CARFI scores for present and future scenarios for the Netravathi River Basin. Numbers in parentheses represent the number of barriers.

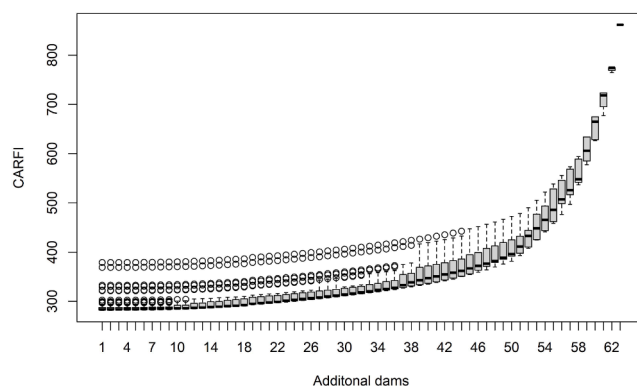
Sub-basin	Sub-basin code	CARFI – present scenario (24)	CARFI – future scenario (89)
Shishila River	NET1	184.38 (8)	366.48 (33)
Kumarahalli	NET2	0 (0)	10.19 (1)
Yettinahole	NET3	158.37 (12)	313.21 (24)
Upper Kumaradhara	NET4	4.19 (1)	339.18 (16)
Addahole	NET5	297.26 (1)	1077.14 (4)
Middle Kumaradhara	NET6	0 (0)	2165.79 (3)
Gowri River	NET7	0 (0)	0 (0)
Lower Kumaradhara	NET8	0 (0)	3260.95 (2)
Netravati River	NET9	1355.28 (2)	3429.67 (6)

dam building (Figs 4, 5b and c, 7b and c). However, the linear relationship between CAFI and additional dams may overestimate the impact of new barriers or their removal in heavily dammed basins. In other words, the potentially infinite increase in CAFI/CARFI values within a finite basin loses functional relevance beyond a threshold in basins with very high dam densities. The extent of loss of functional relevance will depend on the species or process being considered. Additionally, while CAFI/CARFI values can be compared across similarly sized basins or across various scenarios of barrier placement for a given basin, the lack of a mathematical upper limit makes it difficult to compare CAFI values across differently sized basins. Hence, we recommend that index values generally be interpreted relative to each other or within a basin, with increasing values corresponding to increasing levels of fragmentation.

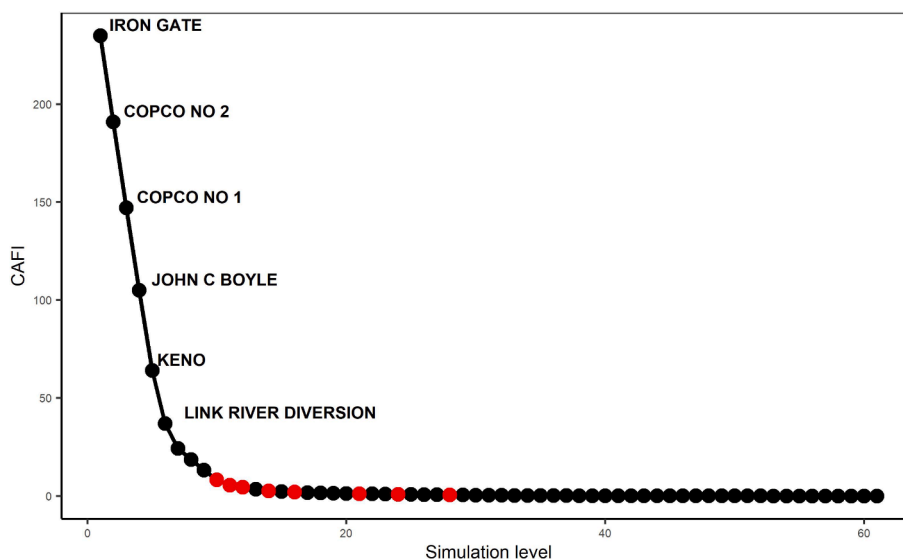
Through the applied case studies, we also illustrate the descriptive (Section 5.1) and prescriptive (Section 5.2) applications of CAFI/CARFI to study trends in fragmentation and inform management and conservation planning. We caution against the deterministic interpretation of these results, and rather use these as an illustrative exercise. The index does not replace ground-level studies or project-specific impact assessments. Instead, we suggest the index be used in conjunction with site-specific considerations to holistically inform river conservation and development planning. In terms of descriptive applications, the index can demonstrate the increases or decreases in fragmentation caused by varying number of dams across spatial scales due to its sensitivity to the

addition or removal of barriers (Figs. 5 and 7). The choice of scale should depend on the size of the basin and the process or subject of study. A combination of basin and sub-basin scale analyses is expected to produce the most comprehensive results, allowing users to analyse a range of scenarios and determine sub-basins of restoration or conservation interest.

The indices can also be used in optimization or sensitivity analyses (McKay et al., 2017) to better plan dam removal, mitigation action, or management. Ranking of dams based on their impact on fragmentation can help identify good and bad options for dam removal (Fig. 9) or placement (Fig. 10). The impact of individual and cumulative dams on fragmentation can be viewed against dam contributions to determine relatively “better” (low fragmentation and high benefit) and “worse” (high fragmentation and low benefit) projects (Fig. 11a). However, due to the way the index is defined, CAFI/CARFI emphasises the impacts of dams having larger catchment areas. Hence, when using CAFI/CARFI to inform dam placement (as in the case of the Netravathi), sites with smaller contributing areas tend to be prioritized (Fig. 11b). This could be problematic given the importance of headwater streams in providing breeding/nursery grounds and habitat for numerous endemic species of conservation value (Colvin et al., 2019; Meyer et al., 2007). Undammed tributaries also provide critical buffer to riverine ecosystem processes and function in dammed basins (Atkore et al., 2017). Hence, we caution against the use of this (or any) index as the sole determinant in



**Fig. 10.** Dam placement sensitivity analysis based on CARFI scores for 65 proposed barriers on the Netravati River basin.



**Fig. 9.** Dam removal ranking based on CAFI scores for 62 barriers on the Klamath. The red dots represent the eight dams removed between 2002 and 2012. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

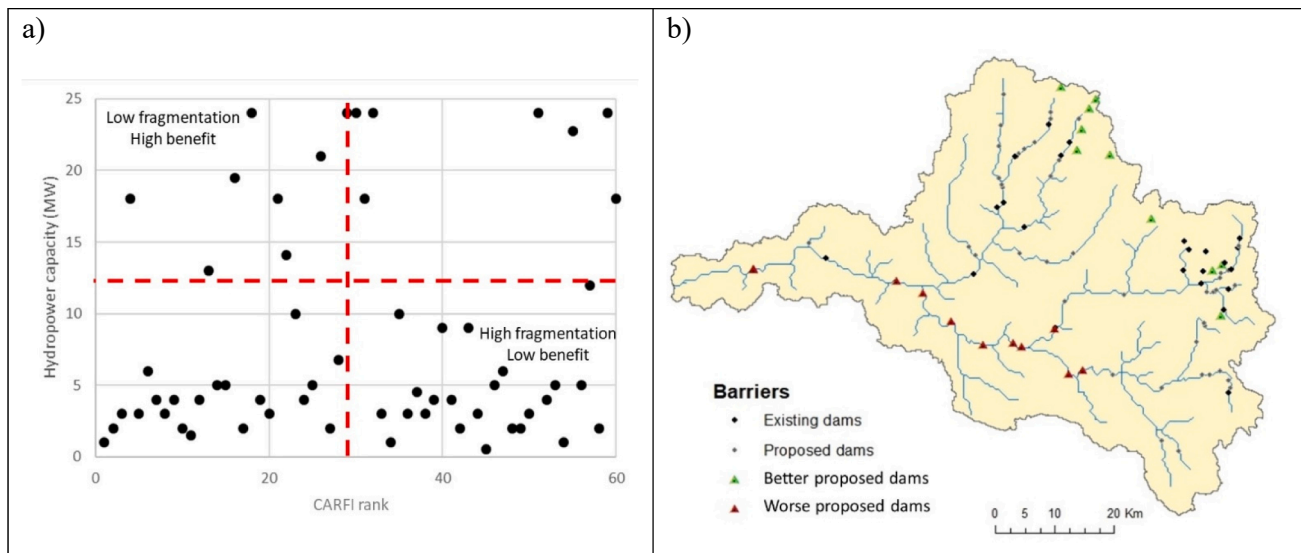


Fig. 11. (a) Proposed dams categorised based on their impact on fragmentation and hydropower capacity (b) The ten ‘better’ (green triangle) and ‘worse’ (red triangle) dams as selected by CARFI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

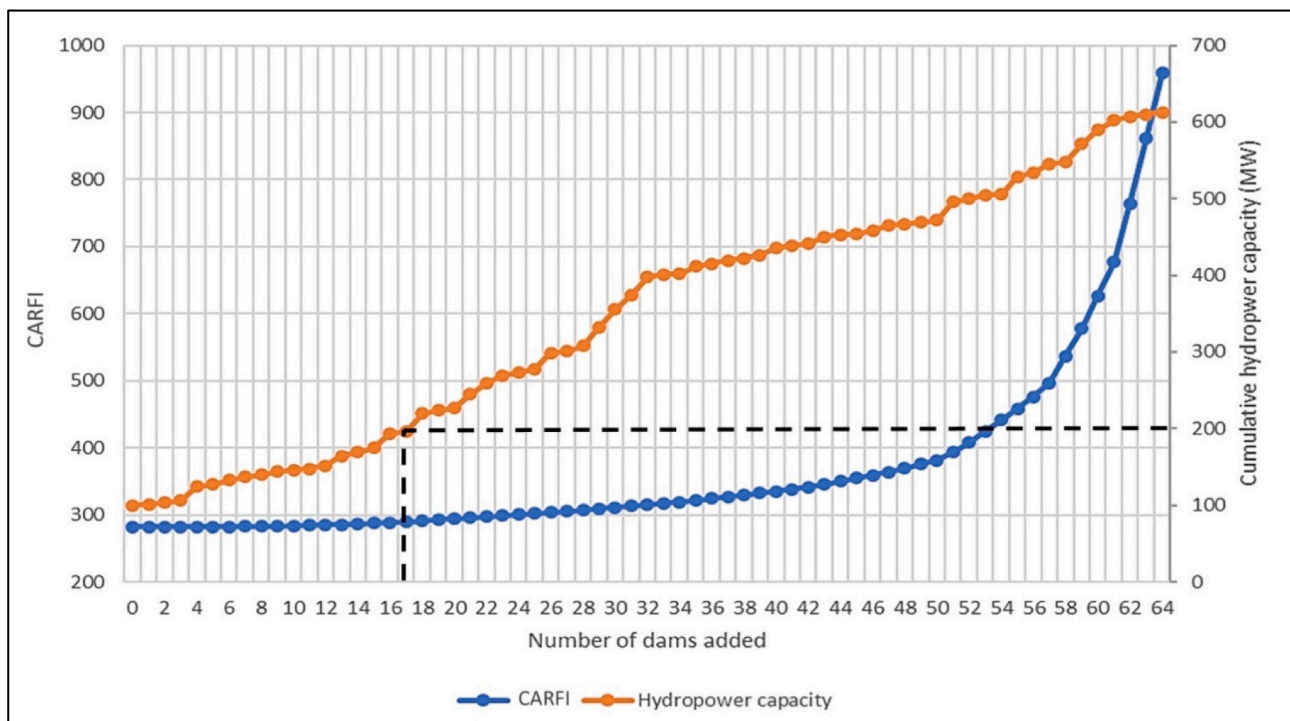


Fig. 12. Addition of proposed dams in order of increasing impact on fragmentation (blue line) overlaid with the cumulative increase in installed hydropower (orange line). The dashed line represents the number of dams to be considered to achieve a hypothetical goal of 200 MW generating capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prioritizing dam placement. In these cases, users are advised to incorporate additional rules such as retaining a fixed number of undammed tributaries and maintaining some minimum inter-dam distance. Given the complexities regarding the spatiotemporal scale of application and the analyses used, careful interpretation of results is also required. Since these indices measure only structural fragmentation, they are intended to guide conservation and management decisions along ground-level studies or impact assessments and social and ecological considerations.

An underlying assumption behind the application of all structural connectivity metrics is that an increase in fragmentation (as measured by a given metric) will correspond to a loss of functional connectivity

(with respect to biotic communities or ecosystem processes). However, the ecological relevance of most indices remains unknown, presenting an important frontier for further research. Since connectivity is dependent on the point of view of the species or process being considered, different indices may be better suited for different applications. For instance, potamodromous species may respond better to fragmentation measured by DCIp, while diadromous species or basin-wide connectivity dependent processes may correlate better with CAFI/CARFI. Hence, empirical, field-based studies are required to ecologically validate CAFI/CARFI and other connectivity metrics. Since different species and ecosystem processes perceive habitats and operate at different

spatiotemporal scales (Gauchere, 2007; Llausàs and Nogué, 2012), their response to fragmentation is also expected to be scale-dependent. Thus, research is also needed to identify the range of spatial scales over which the CAFI/CARFI can be meaningfully applied (Fullerton et al., 2010; Jumani et al., 2020). Since different metrics vary in their properties and assumptions, research on comparative assessments between various river connectivity or fragmentation indices can shed light on areas of convergence and divergence in metric performance. Coupled with information on the ecological relevance of different metrics, this can further inform metric selection given river habitat characteristics, extent of damming, and study objectives. Finally, research is also needed to better quantify barrier passability (Kemp & O'Hanley, 2010), incorporate spatial interdependence in barrier passabilities (Cote et al., 2009), and test the integration of the index with ecological information such as species diversity or habitat quality.

## 7. Conclusion

Metrics that evaluate the impacts of RIPs on fragmentation can play an important role in the conservation and management of riverine ecosystems. The widespread use of fragmentation metrics highlights the need for easily derived and ecologically relevant tools to make such evaluations. Though such metrics cannot substitute for empirically derived data, they can be effectively used by stakeholders to assess potential impacts of specific dams and provide a means to assess a range of conditions as a first step towards basin-wide conservation planning. Given their widespread utility, such metrics need to be sufficiently robust with respect to their underlying assumptions, properties, and ecological relevance to be meaningfully applied.

The results presented here demonstrate the descriptive and prescriptive utility of the CAFI/CARFI for conservation and management planning, as well as potential drawbacks that may constrain their value. Despite their limitations, these indices overcome some of the disadvantages associated with existing metrics. These improvements make the CAFI/CARFI a useful metric that can be applied across scenarios to quantify the individual and cumulative impacts of barriers on a river network. Their applications in quantifying fragmentation and in identifying 'good' and 'bad' dams, priority sites for dam removal or mitigation, and project locations that can have lower impacts on fragmentation make CAFI/CARFI a useful tool to guide conservation and restoration of rivers and the biodiversity they support.

### *CRedit* authorship contribution statement

**Suman Jumani:** Conceptualization, Funding acquisition, Writing – original draft. **Matthew J. Deitch:** Conceptualization, Writing – review & editing. **Denis Valle:** Conceptualization, Writing – review & editing. **Siddarth Machado:** Software, Writing – review & editing. **Vincent Lecours:** Writing – review & editing. **David Kaplan:** Writing – review & editing. **Jagdish Krishnaswamy:** Writing – review & editing. **Jeanette Howard:** Writing – review & editing.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2022.108680>.

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