RESEARCH ARTICLE

A dynamic dendritic connectivity assessment tool for the planning and design of barrier mitigation strategies in river networks

Myron King · **Michael van Zyll de Jong** · **Ian G. Cowx**

Abstract

Context Increasing fragmentation of rivers caused by barriers continues to impact watersheds, especially disruption of fish migration patterns and loss of access to spawning and nursery habitats. Infrastructure expansion and ageing installations exacerbate the problem, reducing effectiveness of management in addressing barriers. Reduction in watershed connectivity requires effective tools capable of guiding river managers in remediation actions.

Objectives Our objective was to develop a watershed dynamic connectivity assessment tool (D-CAT), a customizable geospatial tool capable of river analyses at varying watershed scales. The tool uses proven watershed connectivity modelling combined with an effective evaluation approach to provide measurable change model outcomes.

Methods Three different barrier encounter scenarios were examined using the D-CAT tool to study watershed connectivity. The tool was tested on a watershed area of the River Derwent, a major tributary of the River Trent system in the United Kingdom.

Results For each barrier scenario tested, the D-CAT tool indicated which barriers could be removed or modified to provide the greatest watershed connectivity improvement. The tool provided a prioritized list of barriers for each scenario under varying choices for the number of barriers to remove, demonstrating the utility of the D-CAT tool to planning and design.

Conclusions The D-CAT tool is built to handle geographical data and variable user input, allowing in-depth watershed connectivity analysis. The tool forecasts the cumulative effects of alternative change scenarios for watershed connectivity, providing prioritization and optimization of removal strategies. The D-CAT tool offers significant support for landscape management towards better barrier removal/remediation decisions.

M. King (✉) · I. G. Cowx
Hull International Fisheries Institute, University of Hull, Hull HU6 7RX, UK
e-mail: mking@grenfell.mun.ca

M. King · M. van Zyll de Jong
Environmental Policy Institute, Memorial University, Corner Brook, NL, Canada

M. van Zyll de Jong
Department of Biological Sciences, University of New Brunswick, Saint John, NB, Canada

Introduction

Globally, river fragmentation, caused by construction of barriers, has profound effects on watershed connectivity, habitat accessibility, and the natural diversity of ecosystems (Grill et al. 2019). Fish populations are increasingly under pressure due to these barriers, facing a disruption in access to spawning and nursery areas. Rivers that were once well connected in a network of branches, are now fragmented into multiple, often isolated, river sections within the watershed (Grill et al. 2019). The problem of barrier fragmentation affects most rivers, altering fish migration (Gouskov and Vorberger 2016; Jager et al. 2001) and compromising distribution of aquatic plants and animals, especially fish (Ribolli et al. 2021; Radinger & Wolter 2015; Werth et al. 2014; Andersson et al. 2000). It is estimated that nearly two-thirds of all large rivers are now heavily fragmented (Birnie-Gauvin et al. 2020), and the full effects of fragmentation on rivers may also be underestimated (Jones et al. 2019; Fuller et al. 2015). While the connectivity of rivers continues to deteriorate, only limited efforts are taken to mitigate the problem outside the USA and EU countries. Economic drivers tend to control barrier mitigation and reversal efforts, leading to limited improvement against an overwhelming need. Installations such as culverts, weirs, dams and other barriers are now common-place, resulting in considerable fragmentation of river ecosystems (Timm et al. 2017; Goerig et al. 2016; Favaro & Moore 2015; Jeeva et al. 2011; Gibson et al 2005). The continuing development of new roads along with the ageing of many culverts also exacerbates this condition in many jurisdictions (Park et al. 2008).

With increasing human population pressure and the push to access remote resources, it is important to consider a widening scale of factors within river network management with respect to barriers. The need for forest products, mineral resources and urbanization helps drive our economics-based activities further into watersheds, as our industries strive to compete at any cost. Efforts to mitigate impacts from barriers are limited, especially in rural areas, with development pressures outstripping traditional management approaches and regulatory control (Park et al. 2008). The result is a de-prioritization of rivers and river connectivity in the face of such pressures. This proliferation of barriers to fish movement disrupts ecological connectivity, reducing the quantity of available suitable habitat necessary for life-history processes or dispersal (Fraik et al. 2021; Perkin et al. 2015; Nunn et al. 2008; Roni et al. 2002). This reduction in river connectivity alters fish assemblages, reduces population resilience to environmental disturbances and reduces genetic mixing (Jones et al. 2021; Rolls et al. 2013; Nunn and Cowx 2012). To understand the effect of cumulative impacts of barriers in river ecosystems, managers require an evidence-based, scientific approach. Such an approach should integrate a 'systems' view that gives attention to both the values of stakeholders and the necessary scientific information, allowing the potential consequences of intervention to be described. These are explicitly value-laden and decision-driven needs based on the best available information that can link values to facts (King et al. 2021; Gregory et al. 2012). The approach should allow for a series of integrated models or tools to be developed that allow managers to predict the behavior of systems and the consequences of various interventions. The resulting tools should have the ability to describe the connection between physical processes, evaluation of key attributes, and the impact of any intervention scenarios. The ability to look at the consequences of different alternatives is crucial in the decision-making, and planning and design processes.

Several authors have developed modelling approaches to quantify river connectivity and predict the impact of barrier removal scenarios, including using GIS-based platforms (e.g., O'Hanley & Tomberlin 2005; Cote et al. 2009; O'Hanley et al. 2013; Buddendorf et al. 2019; Rodeles et al. 2021). Despite the development of theoretical approaches there are few examples of the application of these models to forecast the effects of intervention scenarios on river systems for management and mitigation purposes. Meixler (2021) used a GIS framework to model physical barrier characteristics, hydraulic conditions and water temperature to express the likelihood that dams and other obstructions act as barriers to fish species. While considerably detailed, the complex datasets used in the study may limit its usefulness in places where data are scarce. Bonetti et al. (2016) examined fish movements across barriers to model flow rate hydraulics for passage facilitation (using tagging technology (i.e. acoustic telemetry), along with channel and barrier digital imaging. O'Hanley &

Tomberlin (2005) used integer programming optimization to optimize barrier removal in relation to budgeted cost. Branco et al. (2014) used spatial graphs along with a habitat suitability concentration to prioritize barrier removals, showing how removal of just one barrier can have greater impact overall than removing several barriers if appropriately chosen. In general, however, past modelling approaches tend to be limited to describing the theoretical element without real-world fitment or actual tool product development. Yet mangers need more than methodologies to use towards the improvement of rivers, they need a flexible format that is both customizable and simplified. Dynamic programming can offer this flexibility, while still having an evolved GIS platform structure that helps deliver enhanced results more simply. This is important as managers also need a toolset capable of handling an increasing number of watershed differences with minimal effort, and with varying amounts of available datasets that accompany the watersheds from one scenario to another.

The objective of this paper is to describe the development of the Dynamic Connectivity Assessment Tool (D-CAT). D-CAT is built to assess the impact of river barriers on watershed connectivity, habitat accessibility and fish population dynamics. The D-CAT tool can also be used to predict the outcomes of barrier removal/mitigation strategies on these key ecosystem attributes, and may be customized to evaluate the connectivity effects of barrier degradation over time. The tool is adaptable to river systems anywhere around the globe. A case study from the River Derwent, a major tributary of the River Trent, in the UK is used to illustrate the tool's operation and utility.

Methods

The D-CAT modelling approach is based on extensive Python programme coding within the ESRI ArcGIS ArcMap (version 10.3) application, designed to evaluate watershed connectivity using spatial GIS layer representations. ArcGIS is appropriate because it has built-in capabilities for hydrological analysis and customized GIS layer analysis available. ArcGIS offers the capability for a developer to use the built-in layer analysis toolbox, and also fine-tune the GIS modelling with customized programming approaches.

With Python programming available directly in ArcGIS, analysis of key variables and components of the watershed and river network aids tool design, functionality and final outcomes. The multi-function GIS Python code at the core of the tool was developed to study river connectivity change for a watershed. It comprises 400 lines of written Python code, including 11 separate functions forming a full program delivery. The code is designed to work at a GIS watershed level with potential barriers from a GIS barrier database, while handling input layers and output reporting altogether. D-CAT analyzes the watershed (or selected portion of the watershed) initially without any watershed or barrier changes (reference point), and then recalculates multiple times depending on the changes possible. The calculations are programming subroutines, which can feed specialized calculation methods into the tool sequence to calculate and gauge outcomes. Input to the D-CAT tool includes the watershed rivers, barrier locations, and data regarding the rivers and barriers (for example the segmented river lengths, and the individual barrier upstream and downstream species passability rating). As a customizable tool, there is flexibility with input formats, including GIS vector or raster input layers. While the primary calculation is barrier passability, the tool programming can also be expanded to handle additional calculations on other key ecosystem values (i.e., habitat, fish production).

The D-CAT tool primary calculation uses a river connectivity (or fragmentation) methodology that is expanded from the Dendritic Connectivity Index (DCI) approach initially proposed by Cote et al. (2009). and is integrated into GIS. The DCI mandates the use of river segment lengths, along with barrier passability calculations, for each potential barrier as the connectivity analysis. The calculation is one that is now well-established, and field-tested (see Bourne et al. 2011). The DCI approach can be applied to two differing fish life history strategies: potadromous (DCI_P) and diadromous (DCI_D). The potadromous application is primarily concerned with watershed connectivity where fish are making migrations within freshwater environments, and is calculated using:

$$DCI_P = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} \frac{I_i}{L} \frac{I_j}{L} * 100 \tag{1}$$

where the probability of observing c_{ij} is dependent on the section lengths i and j, identified by I_i and I_j as the fraction of the total watershed drainage network L (Cote et al. 2009). The diadromous application is primarily concerned with watershed connectivity where fish are making migrations between freshwater and marine environments, and is calculated using:

$$DCI_D = \sum_{i=1}^{n} \frac{I_i}{L} \left(\prod_{m=1}^{M} p_m^u p_m^d \right) * 100 \quad (2)$$

where L is again the length of all stream sections in the watershed drainage network, I_i is the section i length, p_m^u and p_m^d are upstream and downstream passabilities of the mth barrier between the mouth of the river and river section i (Cote et al. 2009).

The DCI subroutine of the D-CAT tool is built to calculate a value representing the connectivity of the river segments that are separated by multiple barriers. Each barrier has an impact on successful passage of various fish species both upstream and downstream, and this impact is cumulative with each barrier that needs to be passed to reach the important habitat. It is vital to account for the cumulative effects of barriers when doing an analysis of barrier impacts on rivers. The DCI considers cumulative effects by accounting for multiple barrier impacts. This takes shape when multiple barriers are handled in product form within the calculation, such that the upstream/downstream individual passability of each barrier contributes to the passability of the series. The accumulating deleterious effects on overall habitat availability, through disruption of river connectivity by impediment of passability across barriers forms the basis of the analysis. This is vital because habitat connectivity plays a central role in aquatic community development (King et al. 2021; Cote et al. 2009). Small differences in the overall connectivity of a watershed system, may be achieved through improvements in passability to any of the individual barriers in the analysis. Using the initial DCI calculation as a reference connectivity value, it is possible to examine, and consequently gauge, multiple scenarios of watershed barrier changes for restoration targeting and watershed connectivity improvements.

The D-CAT tool analyzes connectivity of the watershed system under changing conditions within a GIS framework with python programming to calculate all possibilities of projected multi-barrier changes. These changes are derived via the theoretical improvement of barrier combinations that are a part of the watershed network under investigation. The projected scenarios of connectivity improvements are based on direct barrier interventions, such as when passability scores are altered for one or more barriers through removal or easement activities resulting in changes to watershed connectivity. Every possible scenario is checked, such that barrier interventions with the highest benefit under the DCI treatment of the watershed network are prioritised. (Fig. 1)

At the beginning of the change analysis, a numeric choice for the number of barriers in one combination set is chosen. This numeric value r determines how many barriers are to be targeted for change within the full group of 'problem' barriers n, and may be related to economic mitigation costs or any other factors. Pre-filtering can also be done at this point if necessary, and to limit the number or area of barriers. After setting the conditions and variables as needed for the watershed, the program is started. The tool calculates all the possible combinations using the popular combinations formula:

$$nCr = \frac{n!}{r!(n-r)!} \quad (3)$$

and cycling through each combination set, stores the identity of each barrier that is an actual candidate for removal or mitigation in a subset for the program. The tool then enacts the change by adjusting targeted barrier elements, and in relation to the unchanged barriers, calculates an output for each set appending it to the particular combination set. For example, in the case of the DCI_P subroutine on a group of barriers in the watershed impacting a potadromous fish species, the tool expands Eq. (1) above into multiple equation parts where barrier upstream and downstream passabilities and associated lengths of habitat are processed:

$$DCI_P = \left[\frac{I_A}{L} \frac{I_A}{L} + \frac{I_B}{L} \frac{I_B}{L} + \frac{I_C}{L} \frac{I_C}{L} + \ldots + 2p_X^u p_X^d \frac{I_X}{L} \frac{I_Y}{L} \right. $$
$$\left. + 2p_X^u p_X^d p_Y^u \frac{I_X}{L} \frac{I_Z}{L} \right] + \left[2p_Y^u p_Y^d \frac{I_Y}{L} \frac{I_Z}{L} \right] \times 100 \quad (4)$$

The tool frames the representative barrier components and calculates a DCI_P outcome for the 'no barrier changes' reference condition, and additionally calculates every alternative multiple barrier

Fig. 1 The D-CAT connectivity tool processing diagram. Solid lines represent current tool structure while dotted lines represent potential tool expansion areas. Blue lines represent data inputs and user inputs, red lines represent internal processing, and black lines represent final tool outputs
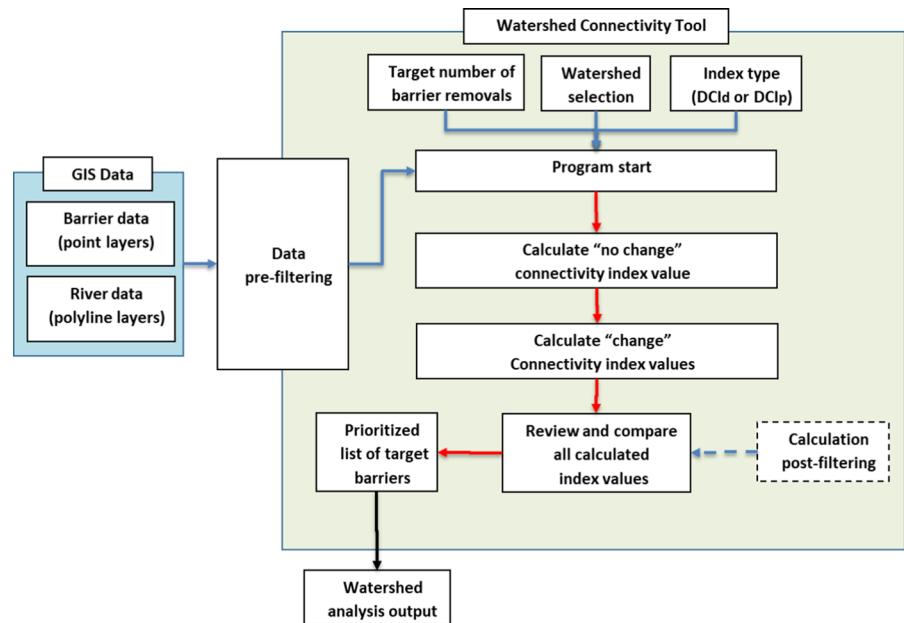
remediation projection. Each combination set along with the new calculation is output to a text file for the watershed being analyzed. The output of the 'change' calculations, along with the initial 'no changes made' calculation, are then further analyzed in the program. Barrier removal combinations are ranked based on their calculated improvements to DCI, and the list of prioritized combination outputs are saved for reviewing. The overall programming structure and interactivity of the D-CAT tool is designed in a way that allows for modelling expansion. This is possible at various stages of the tool procedure, including inputs, control variables, calculations, and outputs. The tool is created to model change to the environment, following the GeoDesign based RRPAT (King et al. 2021) approach that enables a detailed and controlled evaluation of potential outcomes.

Case study

River systems in the UK have been heavily modified over centuries of development, especially since the Industrial Revolution. Barriers have been constructed in river channels to power industry, aid navigation, support water abstraction infrastructure and alleviate flooding, amongst other uses, and in recent years there has been an increased demand to retrospectively install small-scale hydropower units on the weirs.

Weirs and other obstructions have compromised the ability of migratory species to reach upstream spawning and nursery habitat areas for centuries and many structures are now ageing and in disrepair. As a consequence, movement of migratory fish species, especially salmon, trout, eel, potadromous cyprinids, and lamprey, has been compromised, and many rivers are failing EU Water Framework designation because of fish. To alleviate this problem there is drive to provide fish passage easement measures on barriers, or in some cases remove the barriers. The main problem is identifying the key barriers that impede both upstream and downstream migration to achieve the most effective outcome of remedial works.

The River Derwent watershed in the Derbyshire area of the United Kingdom (East Midlands Region) was chosen to trial the D-CAT tool because it has numerous barriers to fish migration, many of which have been in place for decades, and there is drive to reintroduce natural breeding populations of Atlantic salmon into the system. Five tributary rivers were evaluated for the case study, viz.: the Upper and Lower Amber, Alfreton Brook, Press Brook, and Ogston Reservoir. In database form, these river sections contain 27 identified barriers (Fig. 2), with varying lengths of river (9.8 m up to 108 km, average 11.8 km) restricted beyond each barrier. Four-digit identification numbers geo-spatially linked to
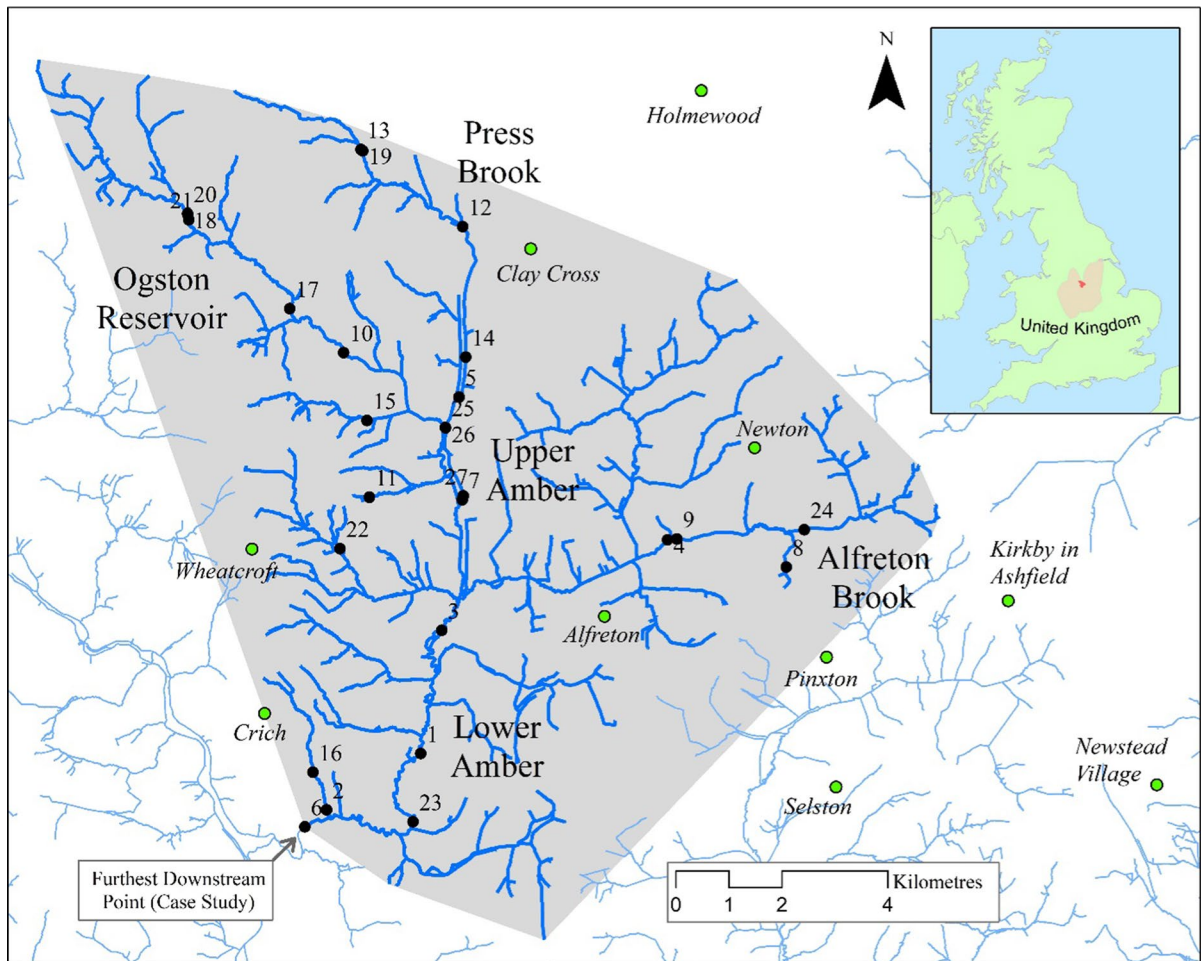
Fig. 2 The case study area (shaded) is part of the River Derwent watershed system located in the Derbyshire Region, United Kingdom. Numbered black dots are the 27 barriers with associated dark blue river segments. The study rivers include Upper and Lower Amber, Alfreton Brook, Press Brook, and Ogston Reservoir. For the purposes of demonstrating the D-CAT tool, barrier #6 was taken to be at the mouth of the river system

the next downstream barrier are used in the database (Table A1), but for ease of reference for the case study the barriers were numbered 1 through 27 for processing and mapping.

The total river network length in the study area was 319 km, with barriers (weir installations) relatively evenly distributed throughout the river system. Experts rated upstream passability of the barriers between 0 (no passability) and 1 (fully passable) and downstream passability from 0.8 to 0.95, in relation to Atlantic salmon fish species.

Three different scenarios were examined in the case study watershed using the D-CAT tool. We first

examined the simple watershed-level connectivity for diadromous conditions. This was followed by studying the potadromous condition using two different scenarios: 1) a downstream-only approach where all river segments analysed were based on barriers located one after another in the downstream direction; and 2) a downstream-upstream approach where some river segments in the analysis followed barriers in a downstream order, followed by river segments where the barriers were ordered one after another in the upstream direction. The latter condition occurs when the segment-to-segment pathway must crossover a confluence point (i.e. the point where one river meets

another, such as tributary meeting the main river stem). These two scenarios were chosen to showcase the D-CAT tool capability in handling the only two arrangements that occur when studying a straight sequence of barriers along a river. The terms 'downstream-only' and 'downstream-upstream' are used to denote these scenarios as a choice for physical river orientation. It is acknowledged that 'upstream-only' as a scenario is also possible, and would be exactly the same as our 'downstream-only' scenario for the connectivity calculation methodology being applied.

Diadromous condition

Diadromous fish migrate between the freshwater zone of the rivers and the ocean. The connectivity of the watershed considers the accessibility of all areas of the watershed, including all barriers and their passability values. For this case study the DCI_D was calculated based on all $n = 27$ barriers (barrier numbers 1 through 27), and using all the segmented river lengths associated to each individual barrier. The D-CAT tool was initially applied to calculate the connectivity changes for diadromous condition under the option of choosing '2' as the number of barriers (r) to remove. Additional scenarios where the number of barriers were 3, 4, and 5 are analyzed and reported for comparison.

Potadromous condition

Potadromous fish do not migrate to the ocean, but instead spend their life in the rivers, moving about within the freshwater system. Under this circumstance, the connectivity of the river system is measured from one segment to another within the watershed by analysing the fragmentation between the segments. The wider a fish may travel within the river system the more river branches must be included in the connectivity calculation. Consequently, there is higher probability of encountering more barriers with increasing potadromous distance traveled.

For the case study, two potadromous scenarios were tested. The first scenario examined the potadromous condition where one river segment is completely downstream of another river segment, while the second scenario examined the connectivity of two segments located on different river branches within the river network. These two scenarios were selected due to the physical differences in the river network representation, which translates into a different approach required during tool processing. Doing this test shows the versatility of the tool in calculating projections under both types of segment-to-segment scenarios for any river network.

Downstream-only scenario

As before, the D-CAT tool was applied to calculate the connectivity changes for potadromous condition—downstream scenario. The first analysis in this scenario was processed by again choosing '2' problem barriers initially as the number of barriers r to remove (Fig. 3). There are seven barriers in the downstream pathway between the two chosen segments (A and B), are 7 barriers in the downstream pathway, barrier numbers 13, 19, 12, 14, 5, 26, and 1. There are also a few barriers that are close-by, but not involved in the calculation (see Fig. 3 inset views for clarity).

Downstream-upstream scenario

The next criteria applied the D-CAT tool to calculate the DCI_P changes for the potadromous condition—downstream-upstream scenario (Fig. 4). While similar to the downstream-only scenario in terms of barrier-to-segment ratio, the calculations involved are different due to the branch-to-branch river connection point, requiring a different tool calculation approach.

The tool was tested under this scenario choosing $r = $ '2' again initially as the combination number of problem barriers to remove. There are 10 barriers in the downstream-upstream pathway between the two chosen river segments (A and B), barrier numbers 13, 19, 12, 14, 5, 10, 17, 21, 18, and 20. In this barrier test group, five of the barriers are downstream and five are upstream. While these are important physical properties of this particular test river stretch, the operation of the tool to calculate the connectivity is not dependent on end-segment choice for A or B, nor in regards to how many barriers are downstream or upstream. The tool can handle the connectivity calculation in both directions and with a change in river flow occurring in any barrier-to-barrier pathway segment.

Fig. 3 The case study potadromous downstream scenario using the connectivity tool. The DCI$_P$ was examined for segment A to B (highlighted in red), where B is downstream from A. Inset maps show three A to B pathway interest points for clarity. Green arrows are river flow direction. The yellow points are the barriers encountered between A and B river segments
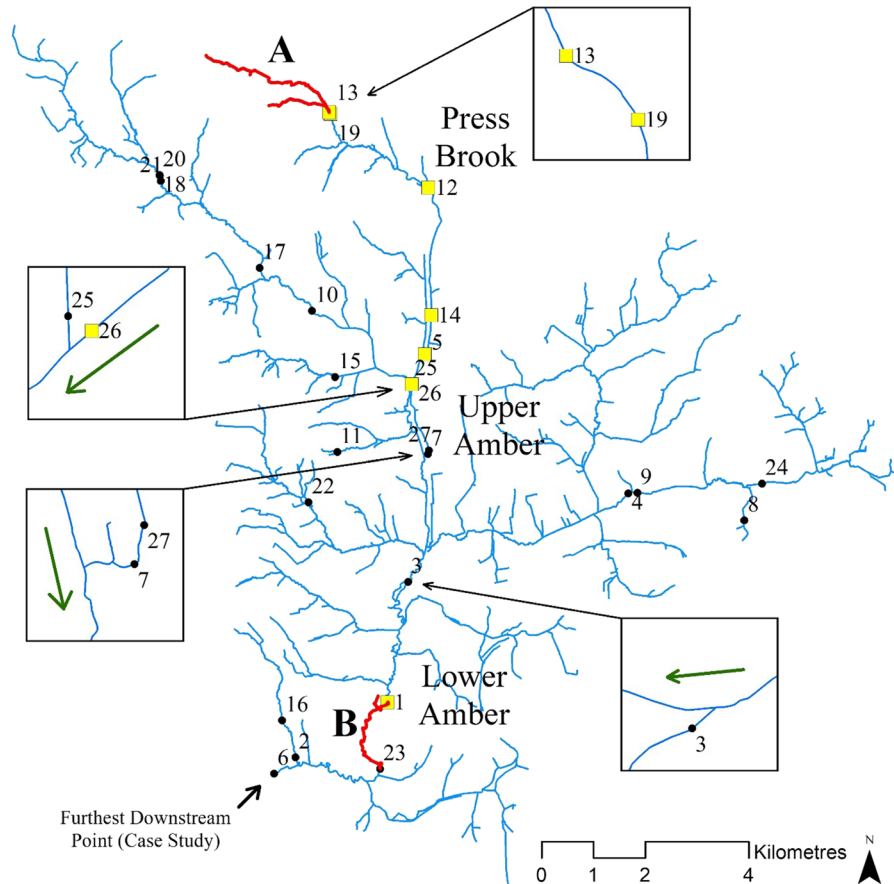

Results

Diadromous condition

The D-CAT tool cycled through 253 possible combinations of $r = $ '2' barrier choices, calculating the potential watershed connectivity change for each combination of the remediation candidate barriers. Barrier numbers 3, 14, 17, and 24 were eliminated from the remediation candidate list as part of the process filtering because they have a perfect (1) passability rating. The initial DCI$_D$ was calculated as 57.06 for the candidate barrier network if no barrier remediation was done. The greatest connectivity increases projected for the full watershed, under the diadromous condition with barrier combination size $r = $ '2' were: (1) barrier 1 and barrier 6 (DCI$_D = 73.87$); (2) barrier 1 and barrier 20 (DCI$_D = 71.15$); and (3) barrier 1 and barrier 26

(DCI$_D = 71.14$). The river segments associated with these barriers are shown in Fig. 5.

Potadromous condition—downstream-only scenario

For the potadromous condition—downstream-only scenario, 15 possible combinations of $r = $ '2' barrier choices were calculated, with barrier number 14 not included since it carries a perfect passability rating. The D-CAT evaluated all connectivity changes through the eight segments under the various barrier combination sets. The DCI$_P$ was 66.58 when no remediation changes were made to the candidate barriers. When concentrating on these river segments, the combination choices providing the greatest connectivity improvement were (1) barrier 5 and barrier 26 (DCI$_P = 85.90$); (2) barrier 12 and barrier 26 (DCI$_P = 80.38$); and (3) barrier 1 and barrier 26 (DCI$_P = 80.09$). The range of all projected DCI$_P$

Fig. 4 The case study potodromous downstream-upstream scenario. The DCI$_P$ was examined for segment A to B (highlighted in red), where a downstream river flow and upstream river flow separate segments A and B. The pathway from A to B encounters five barriers downstream followed by five barriers upstream, shown with yellow points. River flow direction is indicated by green arrows
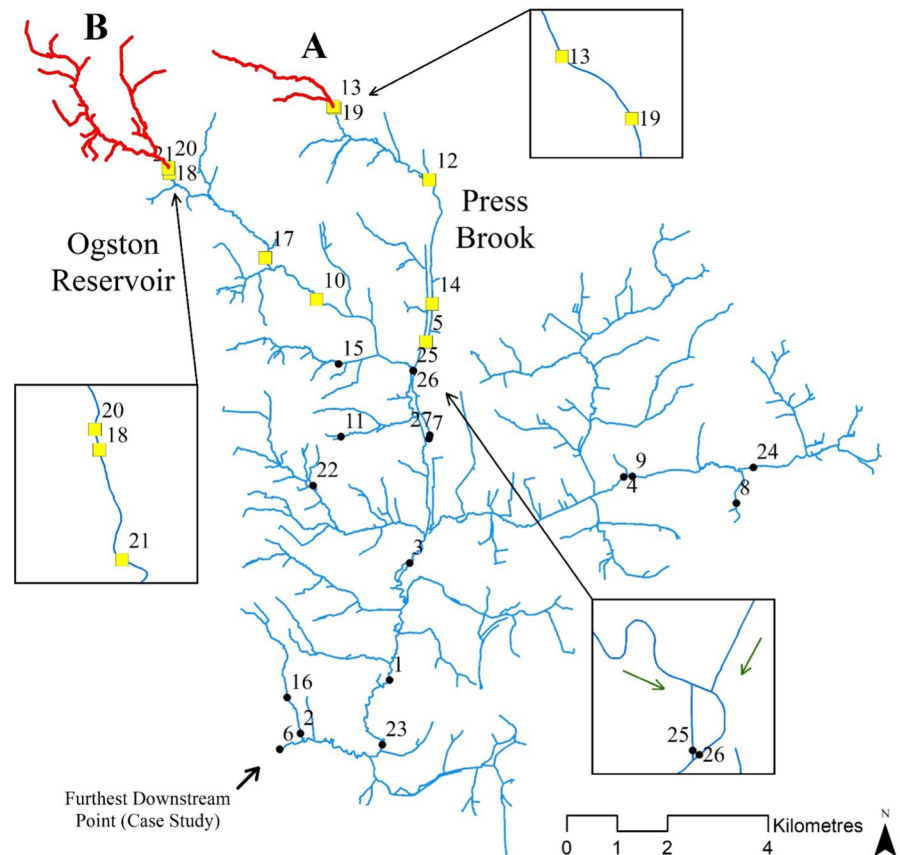
calculation outcomes for all possible 2-candidate-barrier remediation choices were from 67.16, less than 1% improvement of the connectivity to 85.90, a connectivity improvement of 29% (Fig. 6).

Potadromous condition—downstream–upstream scenario

For the potadromous condition—downstream-upstream scenario, the tool calculated 28 possible combinations of $r =$ '2' barrier choices, and evaluated connectivity changes through 11 segments under these various combinations. Barrier numbers 14 and 17 were eliminated during the tool processing due to perfect passability ratings. The DCI$_P$ calculation was 27.65 with no changes made to the candidate barriers. The D-CAT tool projected the combination choices providing the greatest connectivity improvements were (1) barrier 5 and barrier 10 (DCI$_P =$ 45.29); (2) barrier 10 and barrier 12 (DCI$_P =$ 38.67); and (3) barrier 10 and barrier 21 (DCI$_P =$ 37.91). Projected DCI$_P$

calculation outcomes for 2-candidate-barrier remediation choices in this scenario ranged from 28.84, a 4% improvement, to 45.29, which is a connectivity improvement of 64% (Fig. 7).

Results using the D-CAT tool to examine additional calculation combination choices 3, 4 and 5 are shown in Table 1. Each combination choice represented the targeted number of barriers for remediation amongst the total number of barriers for the scenario condition within the watershed.

For the diadromous condition, the D-CAT determined that increasing the number of barriers remediated to perfect passability from two barriers to five barriers, could increase the case study watershed connectivity by an additional 16%. The tool also calculated an additional 11% improvement in connectivity for the potadromous downstream-only scenario, and an additional 85% improvement for the downstream-upstream scenario when increasing the number of barriers restored from two to five.

Landsc Ecol (2023) 38:1431–1446

Fig. 5 The connectivity tool DCI_D calculations using a barrier combination choice '2' under the diadromous calculation scenario for the case study watershed. The segments of river associated with the indicated barriers are highlighted in red

Connectivity (DCI_D)	Barriers restored	Barrier map
57.06	(No change)	-
73.87 (connectivity improvement 29%)	1, 6	
71.15 (connectivity improvement 25%)	1, 20	
71.14 (connectivity improvement 25%)	1, 26	
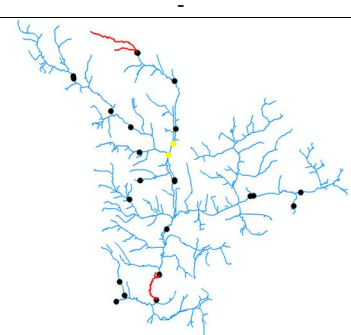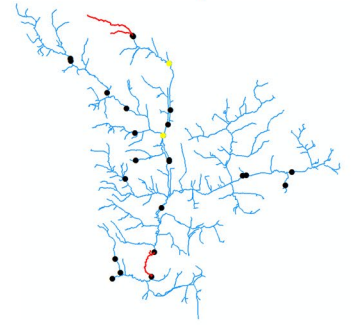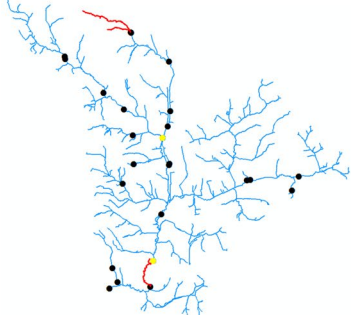
Discussion

D-CAT is designed as a dynamic tool to assess the impact of river barriers on watershed connectivity and to forecast the impact of various barrier removal/mitigation strategies. The tool was tested on a 27 multi-barrier concentration on the River Derwent in England. Processing time was minimal for the final test code to produce results, and changing inputs for the combination number, GIS layer, output filename, and necessary programming variables is designed to be minimal. The number of combinations nCr increases according to combination key r and the total number of barriers n, meaning the main limitation is processing power of the computer running the GIS

software. The tool can easily handle river networks several times this size or multiple river networks regionally.

In the Derwent case study, barrier number 1, with a passability rating of 0.6 upstream and 0.8 downstream figured prominently in the DCI_D calculations. Barrier number 1 was not the lowest passability ratings in the 27-barrier set, which had several barriers with passability rating of 0.3 upstream. The length of accessible habitat associated with barrier number 1 is, however, over 108 km, which is large compared to many of those barriers with the same passability. The amount of accessible habitat associated with barrier 1 that would be available under a projected remediation scenario, helps increase the DCI_D derived and raise

Fig. 6 DCI$_P$ calculation top 3 outcomes using a barrier combination choice '2' under potadromous condition, downstream scenario. The two end-segments involved for this calculation are shown in red. The barriers restored to achieve the change in connectivity are shown as yellow
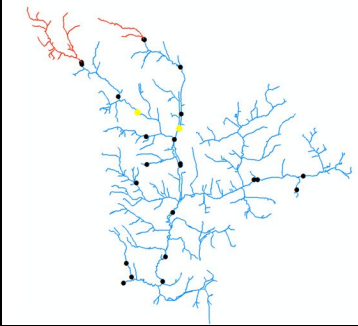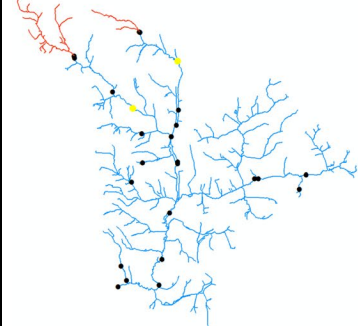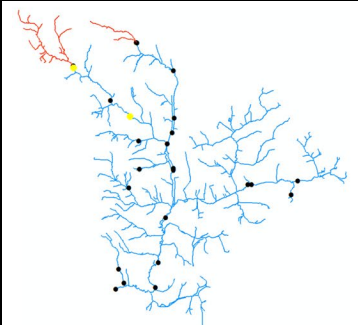
Connectivity (DCI$_P$)	Barriers restored	Barrier map
66.58 (A to B)	(No change)	-
85.90 (connectivity improvement 29%)	5, 26	
80.38 (connectivity improvement 21%)	12, 26	
80.09 (connectivity improvement 20%)	1, 26	

this barrier to the top of the priority list. In the additional analysis scenarios where the projected number of barriers remediated was increased to 3, 4 and 5, continued to give barrier 1 priority for all alternatives. Barrier number 6, which has a very poor passability rating of 0.0, also stood out with barrier 1 at the top of the DCI$_D$ outcome priority list, regardless of how many barriers are chosen as *r* for mitigation. Barrier number 6 is a strong remediation candidate based on both the passability rating and the nearly 20 km of currently inaccessible habitat associated with it.

Barrier number 5 figured prominently amongst both the downstream-only and the downstream-upstream remediation candidate DCI$_P$ calculations, and projected priority outcome alternatives. The passability rating for this barrier was 0.3 upstream and 0.95 downstream, while the habitat length associated with the barrier is just over 1 km. Both DCI$_P$ scenarios had other remediation candidate barriers with significantly more associated habitat even though the passability ratings were the same (e.g., barrier numbers 13 and 26 with 4.4 km and 15 km, respectively, in the downstream-only scenario: barrier numbers 13 again, and barrier 20 with 15 km in the downstream upstream scenario). The positioning of barrier 5 in the connectivity network in both scenarios is more central, which also causes the barrier to rise in importance within the scope of both scenarios. This highlights the importance of the DCI$_P$ calculation as well as the significance of testing multiple projected outcomes to optimize the scenario connectivity, to provide the best decision-making guidance possible.

Fig. 7 The connectivity tool DCI$_P$ calculations using a barrier combination choice '2' under potadromous condition, downstream-upstream scenario. The end-segments for this calculation are again shown as red, and the restored barriers as yellow for the achieved change in connectivity

Connectivity (DCI$_P$)	Barriers restored	Barrier map
27.65 (A to B)	(No change)	-
45.29 (connectivity improvement 64%)	5, 10	
38.67 (connectivity improvement 40%)	10, 12	
37.91 (connectivity improvement 37%)	10, 21	

While certain problem barriers are critical and rise to the top of the list for any combination key chosen, it is less intuitive that a particular combination of barriers may improve the connectivity more strongly than the individual barriers would provide alone under singular analyses approaches. For example, the top DCI$_P$ for a combination for key '4' barriers were barriers 10, 18, 20, and 21, yet barrier number 20 does not feature in the runner-up combination sets for the same key (Table 1). This again shows the power of the D-CAT tool, which could potentially show decision-makers a less obvious combination set that provides the greatest improvement. The optimization of targeted remediation barriers under the D-CAT tool could also evolve further when including other values, such as life-stage requirements, or production estimates, since these values could be linked to accessible habitat. Combine this with additional expert assessment of involved barriers and filtering the priority list can aide managers to narrow the targets significantly for actual barrier removal or mitigation.

The DCI$_D$ is a valuable approach for whole watershed systems, where the entire watershed is examined using details of each barrier to determine an overall indication of fragmentation. For an experienced GIS practitioner, the code is easily adjusted to use initial barrier exclusion factoring, or proportional measures for habitat quality, giving the tool versatility for local watershed customization. It allows optimization of the full barrier

Table 1 Three different combination choices (3, 4 and 5) were selected and run using the D-CAT connectivity tool for the three different conditional scenarios

Condition	Combination key (# of combinations)	Top barrier combinations	DCI result (% improvement)
Initial $DCI_D = 57.06$ (27 barriers) Diadromous Scenario	3 (1771)	1, 6, 20	77.04 (35%)
		1, 6, 26	77.03 (35%)
		1, 6, 25	75.79 (33%)
	4 (8855)	1, 6, 20, 26	80.19 (41%)
		1, 6, 20, 25	78.95 (38%)
		1, 6, 25, 26	78.94 (38%)
	5 (33649)	1, 6, 20, 25, 26	82.10 (44%)
		1, 6, 20, 22, 26	81.87 (43%)
		1, 6, 20, 22, 26	81.58 (43%)
Potadromous – downstream scenario 8 segments (7 barriers) Initial $DCI_P = 66.58$	3 (20)	5, 12, 26	89.77 (35%)
		5, 13, 26	87.08 (31%)
		1, 5, 26	86.90 (31%)
	4 (15)	5, 12, 13, 26	91.65 (38%)
		1, 5, 12, 26	90.80 (36%)
		5, 12, 19, 26	90.33 (36%)
	5 (6)	5, 12, 13, 19, 26	93.46 (40%)
		1, 5, 12, 13, 26	92.69 (39%)
		1, 5, 12, 19, 26	91.36 (37%)
Potadromous – downstream-upstream scenario 11 segments (10 barriers) Initial $DCI_P = 27.65$	3 (56)	5, 10, 12	50.84 (84%)
		5, 10, 13	47.55 (72%)
		5, 10, 21	46.94 (70%)
	4 (70)	10, 18, 20, 21	56.64 (105%)
		5, 10, 12, 13	54.10 (96%)
		5, 10, 12, 21	52.63 (90%)
	5 (70)	5, 10, 18, 20, 21	68.92 (149%)
		10, 12, 18, 20, 21	59.37 (115%)
		10, 13, 18, 20, 21	58.14 (110%)

Upstream length (in meters) is the length of river immediately upstream and associated to the specified barrier

set based upon the input criteria, which would be a significant support to decision makers with so many individual barriers with varying factors to consider. In the case study, applying the DCI_D calculation to 27 watershed barriers provided a priority list of problem barriers that could be recommended and potentially targeted for remediation measures. The DCI_P is a detailed assessment that could quickly highlight those barriers in a linear group or branch area causing the greatest impediment to end-to-end fish movement. Such a detailed result could help point practitioners, often working with little funds, towards the most effective barrier remediation solutions.

One benefit of creating a prioritized connectivity improvement list, is that other barriers in the list still represent a connectivity improvement for those barrier choices. This means the management team, assembled and dedicated to scenario review with minimal effort, could examine alternative barrier sets for intervention should the top-rated set be unsuitable for any reason, e.g. too expensive. For example, upon running the tool and seeing the top-rated set carries a total cost beyond the funds available to address those barriers, then the next top-rated set could be examined to determine if the total cost would allow the budget allocation to address them. The analysis-derived, high-level connectivity improvement list of barrier combinations can also be examined deeper to determine remediation impacts in more detail, and in relation to surrounding ecosystem factors. Such factors could be contextualized in a GIS system spatially or for time, allowing improved control of these influences when initiating a calculation scenario within the tool. The result therefore acts as a strong guide to management for timely decisions in a continuous manner, rather than relying solely on individual barrier conditions or lengthy manual assessment efforts. Effectively, the D-CAT tool is a model that links river process with change in river values (King et al. 2021). It is designed to examine impact on values (for example habitat quality and quantity, watershed connectivity) for various fish species. The tool is expandable, and can be used to test competing alternatives and optimize the system for more than one value over space and time.

Conclusion

The objective of this study was to develop a dynamic connectivity assessment tool (D-CAT); a dynamic change model designed to assess the effects of changes in process (i.e., passability) on key ecosystem attributes or values (i.e., river connectivity, habitat accessibility and fish population status). In addition to predicting impacts, D-CAT was designed to provide a forecast of alternative change scenarios (i.e., alternative barrier removal or mitigation strategies) on river values, thus providing mangers with the performance measures required to assess alternative actions and make evidenced based decisions. The results of the case study demonstrate the utility of D-CAT to planning and design. D-CAT is able to forecast the cumulative effects of alternative change scenarios (i.e., barrier removal/ mitigation strategies) on river connectivity of a watershed unit. In addition, the tool is scalable and can be used to assess a single river segment, an entire watershed unit, or can be used to assess multiple watersheds within a region. The ability to scale the analysis to a regional area is critical for prioritization and optimization of removal or mitigation strategies by conservation authority with limited operational capacity and budgetary constraints. This tool represents a significant addition to the river management toolbox. The next step in tool development is to use D-CAT to link changes in connectivity directly to other rivers values such as, accessible habitat to enable forecasts of changes in fish population status on varying scales.

Declarations

References

Andersson E, Nilsson C, Johansson ME (2000) Effects of river fragmentation on plant dispersal and riparian flora. Regulated Rivers 16(1):83–89.

Birnie-Gauvin K, Nielsen J, Frandsen SB, Olsen H-M, Aarestrup K (2020) Catchment-scale effects of river fragmentation: a case study on restoring connectivity. J Environ Manage 264:110408–110408.

Bonetti RM, Reinfelds IV, Butler GL, Walsh CT, Broderick TJ, Chisholm LA (2016) A multi-scale GIS and hydro-dynamic modelling approach to fish passage assessment: Clarence and Shoalhaven Rivers, NSW Australia. Geomorphology 260:79–90.

Bourne CM, Kehler DG, Wiersma YF, Cote D (2011) Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity. Aquat Ecol 45(3):389–403.

Branco P, Segurado P, Santos JM, Ferreira MT, Strecker A (2014) Prioritizing barrier removal to improve functional connectivity of rivers. J Appl Ecol 51(5):1197–1206.

Buddendorf WB, Jackson FL, Malcolm IA, Millidine KJ, Geris J, Wilkinson ME, Soulsby C (2019) Integration of juvenile habitat quality and river connectivity models to understand and prioritise the management of barriers for Atlantic salmon populations across spatial scales. Sci Total Environ 655:557–566.

Cote D, Kehler DG, Bourne C, Wiersma YF (2009) A new measure of longitudinal connectivity for stream networks. Landscape Ecol 24(1):101–113.

Favaro C, Moore JW (2015) Fish assemblages and barriers in an urban stream network. Freshw Sci 34(3):991–1005.

Fraik AK, McMillan JR, Liermann M, Bennett T, McHenry ML, McKinney GJ, Wells AH, Winans G, Kelley JL, Pess GR, Nichols KM (2021) The impacts of dam construction and removal on the genetics of recovering steelhead (*Oncorhynchus mykiss*) populations across the Elwha River Watershed. Genes 12(1):89.

Fuller MR, Doyle MW, Strayer DL (2015) Causes and consequences of habitat fragmentation in river networks. Ann N Y Acad Sci 1355(1):31–51.

Gibson RJ, Haedrich RL, Wernerheim CM (2005) Loss of Fish habitat as a consequence of inappropriately constructed stream crossings. Fisheries 30(1):10–17.

Goerig E, Castro-Santos T, Bergeron NÉ (2016) Brook trout passage performance through culverts. Can J Fish Aquat Sci 73(1):94–104.

Gouskov A, Vorburger C (2016) River fragmentation and fish population structure: a comparison of three Swiss midland rivers. Freshw Sci 35(2):689–700.

Gregory R, Failing L, Harstone M, Long G, McDaniels T, Ohlson D (2012) Structured decision making: a practical guide to environmental management choices. Wiley, Oxford

Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F, Babu S, Borrelli P, Cheng L, Crochetiere H, Macedo HE, Filgueiras R, Goichot M, Higgins J, Hogan Z, Lip B, McClain ME, Meng J, Mulligan M et al (2019) Mapping the world's free-flowing rivers. Nature 569(7755):215.

Jager HI, Chandler JA, Lepla KB, Van Winkle W (2001) A theoretical study of river fragmentation by dams and its effects on white sturgeon populations. Environ Biol Fishes 60(4):347–361.

Jeeva V, Kumar S, Verma D, Rumana HS (2011) River fragmentation and connectivity problems in the Gange River of the Upper Himalaya (India): the effect on the fish communities. Transylvanian Rev Syst Ecol Res 12:75–90

Jones J, Börger L, Tummers J, Jones P, Lucas M, Kerr J, Kemp P, Bizzi S, Consuegra S, Marcello L, Vowles A, Belletti B, Verspoor E, Van de Bund W, Gough P, Garcia de Leaniz C (2019) A comprehensive assessment of stream fragmentation in Great Britain. Sci Total Environ 673:756–762.

Jones PE, Champneys T, Vevers J, Börger L, Svendsen JC, Consuegra S, Jones J, Garcia de Leaniz C (2021) Selective effects of small barriers on river-resident fish. J Appl Ecol 58(7):1487–1498.

King M, van Zyll de Jong, M., Piercey, D., Nunn, A.D., & Cowx, I.G. (2021) An integrated decision driven design framework to support the ecological restoration of rivers. J Environ Planning Manage. https://doi.org/10.1080/09640568.2021.1932772

Meixler MS (2021) A species-specific fish passage model based on hydraulic conditions and water temperature. Eco Inform 65:101407

Nunn AD, Cowx IG (2012) Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys. Ambio 41(4):402–409

Nunn AD, Harvey JP, Noble RAA, Cowx IG (2008) Condition assessment of lamprey populations in the Yorkshire Ouse catchment, north-east England, and the potential influence of physical migration barriers. Aquat Conserv Mar Freshwat Ecosyst 18(2):175–189

O'Hanley JR, Tomberlin D (2005) Optimizing the removal of small fish passage barriers. Environ Model Assess 10(2):85–98

O'Hanley JR, Wright J, Diebel M, Fedora MA, Soucy CL (2013) Restoring stream habitat connectivity: a proposed method for prioritizing the removal of resident fish passage barriers. J Environ Manage 125:19–27

Park D, Sullivan M, Bayne E, Scrimgeour G (2008) Landscape-level stream fragmentation caused by hanging culverts along roads in Alberta's boreal forest. Can J for Res 38(3):566–575

Perkin JS, Gido KB, Cooper AR, Turner TF, Osborne MJ, Johnson ER, Mayes KB (2015) Fragmentation and dewatering transform Great Plains stream fish communities. Ecol Monogr 85(1):73–92

Radinger J, Wolter C (2015) Disentangling the effects of habitat suitability, dispersal, and fragmentation on the distribution of river fishes. Ecol Appl 25:914–927

Ribolli J, Zaniboni-Filho E, Machado CB, de Souza Guerreiro TC, de Freitas PD, Galetti Jr PM (2021) Anthropogenic river fragmentation reduces long-term viability of the migratory fish *Salminus brasiliensis* (Characiformes: Bryconidae) populations. Neotropical Ichthyology.https://doi.org/10.1590/1982-0224-2020-0123

Rodeles AA, Galicia D, Miranda R (2021) A simple method to assess the fragmentation of freshwater fish meta-populations: Implications for river management and conservation. Ecol Ind 125:107557

Rolls RJ, Ellison T, Faggotter S, Roberts DT (2013) Consequences of connectivity alteration on riverine fish assemblages: potential opportunities to overcome constraints in applying conventional monitoring designs. Aquat Conserv 23(4):624–640

Roni P, Beechie TJ, Bilby RE, Leonetti FE, Pollock MM, Pess GR (2002) A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest Watersheds. North Am J Fish Manag 22(1):1–20

Timm, A., Higgins, D., Stanovick, J., Kolka, R., & Eggert, S. (2017). Quantifying Fish Habitat Associated with Stream Simulation design culverts in Northern Wisconsin. https://www.semanticscholar.org/paper/QUANTIFYING-FISH-HABITAT-ASSOCIATED-WITH-STREAM-IN-Timma-Higginsb/25f00836ccae619f4e555019b17913d368403b81

Werth S, Schödl M, Scheidegger C (2014) Dams and canyons disrupt gene flow among populations of a threatened riparian plant. Freshw Biol 59(12):2502–2515