Prepared in cooperation with the Bureau of Land Management

Effects of Culverts on Habitat Connectivity in Streams—*A Science Synthesis to Inform National Environmental Policy Act Analyses*

Scientific Investigations Report 2023–5132

U.S. Department of the Interior
U.S. Geological Survey

Cover. Many public lands are managed for diverse resources, uses, and values, including recreation, wildlife habitat restoration, conservation, energy production, and livestock grazing. This series of science syntheses is bringing together relevant science to inform decisions about managing these public lands into the future.

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Center image:

Photograph of a sub-alpine stream flowing through a perched culvert. Photograph by Zachary Lafaver, Battelle Memorial Institute, September 18, 2023.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)

Abbreviations

AOP	aquatic organism passage
BLM	Bureau of Land Management
DCI	Dendritic Connectivity Index
FIPEX	Fish Passage Extension
GIS	geographic information system
NEPA	National Environmental Policy Act
USGS	U.S. Geological Survey

Species Names

Common name	Scientific name
bluehead sucker	*Pantosteus discobolus* (referred to as *Catostomus discobolus* in Compton and others, 2008)
brook trout	*Salvelinus fontinalis*
Chinook salmon	*Oncorhynchus tshawytscha*
coho salmon	*Oncorhynchus kisutch*
flannelmouth sucker	*Catostomus latipinnis*
leopard darter	*Percina pantherina*
roundtail chub	*Gila robusta*

Effects of Culverts on Habitat Connectivity in Streams—A Science Synthesis to Inform National Environmental Policy Act Analyses

By Richard J. Lehrter,[1] Tait K. Rutherford,[2] Jason B. Dunham,[2] Aaron N. Johnston,[2] David J.A. Wood,[3] Travis S. Haby,[3] and Sarah K. Carter[2]

Executive Summary

Background: The U.S. Geological Survey is working with Federal land management agencies to develop a series of science synthesis reports. These reports synthesize science information to support environmental effects analyses that agencies perform per the National Environmental Policy Act (NEPA). In this report, we synthesize science relevant to the effects of culverts on habitat connectivity and aquatic organism passage (AOP) in streams, and we focus particularly on freshwater fish of the western United States.

How this report can inform a NEPA analysis: We organized the sections of this synthesis to inform the standard elements of NEPA environmental effects analyses. The report presents science information relevant to characterizing the proposed action and alternatives (section 1 of this report), characterizing the affected environment (section 2 of this report), and identifying issues for analysis and potential environmental effects for each issue using a clear analytical method (sections 3 and 4 of this report). We have developed a flowchart illustrating an example quantitative environmental effects analysis by gathering data about existing culverts, determining existing habitat connectivity in a watershed, and determining potential effects to habitat connectivity from a proposed culvert, which can be used to infer biological effects on fish that are present in the watershed (fig. 1).

Effects of culverts on habitat connectivity in streams: Human effects to the habitat connectivity of stream systems can occur from any type of action involving the alteration of the geomorphic or hydrologic characteristics of the stream. Dams are an obvious and well-documented barrier to habitat connectivity and AOP, and effects to habitat connectivity from small, numerous barriers such as culverts are also well known. Culverts are commonly installed on stream crossings due to their low cost and ease of placement. Loss of habitat connectivity commonly occurs because of poor planning, poor construction, or degradation of culverts through time.

Culverts can alter many natural geomorphic and hydrologic processes, and their capacity to allow AOP is frequently cited as a concern. There are several mechanisms by which a poorly constructed or degraded culvert can prevent AOP. Undersized culverts often constrict flow, causing an increase in velocity that is impassable for many species. Erosion through time can lead to perched culverts, where the outlet of the culvert is located above the stream surface. The height of this perch often exceeds the jumping ability of fish or other organisms, particularly smaller bodied individuals. Natural streams have substrate that provides reduced-velocity zones for upstream migrating fish—a feature missing from poorly designed or degraded culverts.

Culverts have been shown to have a variety of effects on freshwater fish across species and at different spatial scales. Because of the interconnectedness of streams and watersheds, each stream crossing can affect fish population dynamics at local, watershed, and larger landscape scales. For example, decreased habitat connectivity caused by poorly designed culverts can lead to habitat fragmentation within stream systems. Decreased habitat connectivity has numerous well-documented effects on freshwater fish populations and communities and is recognized as a leading cause of declining freshwater diversity. When culverts are not complete barriers to upstream movement, they can have substantial effects on seasonal movements of fish. Several studies have documented the effects of culverts on preventing access to refuges and overwintering habitat, which can reduce population resilience to seasonal habitat variability. By preventing upstream movement, culverts also slow colonization after disturbance, such as a fish kill, relative to an unimpaired stream reach.

Land management agencies have outlined methods for assessing and designing culverts, and there are established methods for estimating their effects to habitat. The U.S. Department of Agriculture Forest Service has published a stream simulation guide, which is a comprehensive source of information for constructing ecologically and hydrologically

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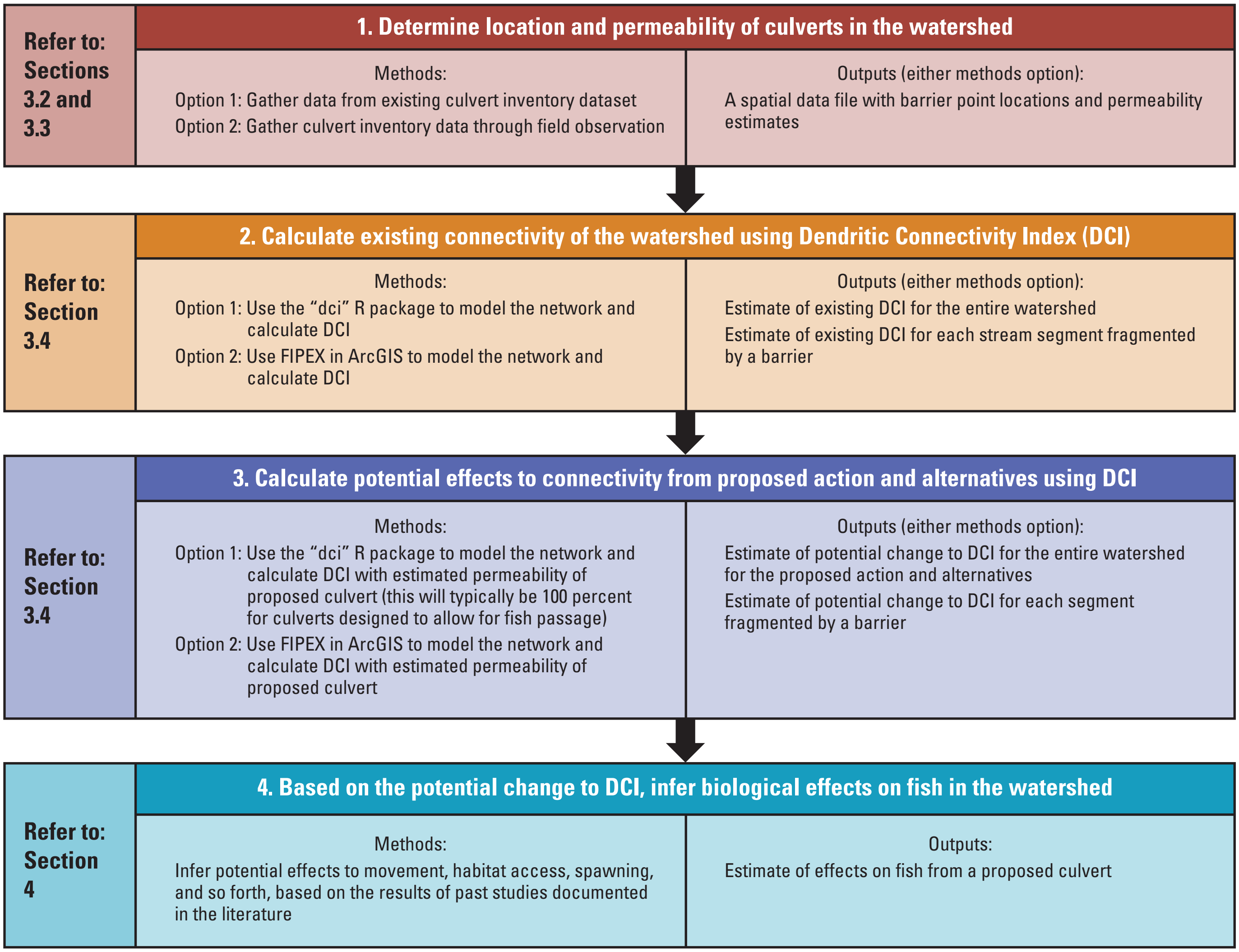

Figure 1. Flowchart illustrating an example environmental effects analysis of the effects of culverts on fish with references to the sections of this report that synthesize science information relevant to each methods step. [DCI, Dendritic Connectivity Index; FIPEX, Fish Passage Extension]

functional culverts. The permeability, or passability of a culvert, can be estimated using quantitative methods. The Dendritic Connectivity Index is a commonly used quantitative metric that incorporates measures of culvert permeability to estimate habitat connectivity of entire stream systems. The Dendritic Connectivity Index can inform existing habitat connectivity of a system and quantify the effects to connectivity that may result from installing, modifying, or removing a culvert.

Conclusion: Information in this document draws from a broad sample of scientific literature covering assessments of individual culverts to habitat connectivity across watersheds. This document can be incorporated by reference in NEPA documentation, cited as supplemental information, or provide a general reference for understanding and identifying literature about the effects of culverts on habitat connectivity in streams.

Methods for developing this synthesis: Rutherford and others (2023) introduced a methodology for developing science syntheses to inform analyses conducted under the NEPA, and relevant text from that report is reproduced herein. This and other syntheses build on that foundation and methodology and apply it to new topics of management concern on western lands.

We conducted a structured search of scientific literature to find published science about the effects of culverts on habitat connectivity in streams, the resulting effects on aquatic organisms, and methods for analyzing culvert condition and quantifying stream habitat connectivity. This report was prepared in cooperation with staff from the Bureau of Land Management, U.S. Fish and Wildlife Service, and U.S. Geological Survey.

Purpose of This Report

Federal land management agencies permit and plan for many uses and activities on public lands across the United States. Per the National Environmental Policy Act of 1969 (NEPA; 42 U.S.C. 4321 et seq.), Federal agencies must analyze and disclose the potential environmental effects of major Federal actions that may significantly affect the quality of the human environment. Regulations for implementing the NEPA require the integrated use of the natural and social sciences in agency planning and decision processes (40 CFR §1501.2). Science is foundational to understanding how proposed Federal actions may affect natural resources, ecosystems, and human communities.

The purpose of this document is to synthesize scientific information about the effects of **culverts** (see the “Glossary” section of this report for definitions of bolded words) on habitat connectivity and **aquatic organism passage (AOP)**. Science syntheses can be a useful mechanism for sharing science information with resource managers to inform their decisions (Seavy and Howell, 2010; Ryan and others, 2018). Science syntheses integrate knowledge and research findings to increase the generality, applicability, and accessibility of that information (Wyborn and others, 2018).

Although instream barriers can affect multiple components of stream systems such as floodplain connectivity, sedimentation, and woody debris transport—and have associated effects on the organisms that depend on them—this synthesis focuses primarily on how culverts alter freshwater fish habitat connectivity. Several comprehensive reviews provide information on the multitude of other effects of small instream barriers to river systems (Cocchiglia and others, 2012; Hoffman and others 2012; Frankiewicz and others, 2021). In perennial and intermittent river systems, culverts can, depending on their design and condition, serve as barriers to passage of aquatic organisms. Much of the aquatic infrastructure in the United States is aging and degrading, therefore negatively affecting habitat connectivity and limiting the movement of instream organisms (Perrin and Jhaveri, 2004; Park and others, 2008; Perkin and others, 2020). Implementing quantitative methods to estimate the effects of a barrier on habitat connectivity and following scientifically established, fish-friendly design can help maintain or improve habitat connectivity when constructing or modifying a culvert.

How to Use This Report

The content, structure, and section numbering of this report are designed to support NEPA analyses and reflect the steps of project planning and NEPA analyses (table 1). This report is meant to be a general reference and could be used, for example, as follows:

- incorporated by reference in NEPA documentation or to directly provide language for use in NEPA documentation (when incorporating this document by reference or drawing language from this report, please use the Lehrter and others [2023] suggested citation on page ii of this report),
- included as supplemental information, or
- used as a resource to gather literature and identify gaps in available science related to the management decision and context.

Caveats to Use of This Report

Please note this report is a science synthesis rather than a comprehensive literature review. In addition, this report does not provide all information necessary to conduct a full environmental effects analysis or make conclusions regarding the significance of environmental effects. Resource planners and managers may need to supplement the information contained in this synthesis with local information. Information about specific design elements of the proposed project, local landscape conditions, and potential environmental effects from factors other than culverts can complement the information contained in this synthesis. Additionally, this synthesis focuses on the effects of a culvert on connectivity and does not discuss the variety of other effects that a culvert can have on stream conditions and aquatic organisms.

We note that this document focuses on data about culverts and does not provide information about how to obtain aquatic organismic data. Information and data about the distribution and status of local aquatic taxa and their populations are crucial to informing the spatial extent of the analysis and understanding what species and how much habitat might be affected by altered connectivity.

Table 1. How the information in this report can inform steps in project planning and National Environmental Policy Act (NEPA) analysis.

Steps in project planning and NEPA analysis	Relevant information in this science synthesis	Section of this report
Identify issues for analysis	This report synthesizes science regarding the alteration of habitat connectivity by the installation of culverts and its effect on aquatic organisms, which may inform understanding of the need for detailed analysis regarding potential effects of a proposed action.	Section "4. Potential Effects of Altered Connectivity by Culverts on Fish"
Identify and refine project design features	This report provides information about using culvert design to avoid, minimize, or mitigate potential effects to habitat connectivity where roads intersect streams.	Section "1. Culvert Installation or Modification"
Describe the affected environment	This report describes tools and sources of data that can be used to analyze existing habitat connectivity within a stream segment or watershed.	Sections "2. Characterizing Existing Connectivity" and "3. Tools for Assessing Habitat Connectivity"
Estimate the environmental consequences	This report provides tools that can be used to analyze effects to habitat connectivity resulting from a proposed action and alternatives. This report then synthesizes science regarding the alteration of habitat connectivity and its effects on aquatic organisms, which may inform environmental effects analyses related to a proposed culvert addition or modification.	Sections "3. Tools for Assessing Habitat Connectivity" and "4. Potential Effects of Altered Connectivity by Culverts on Fish"

Science Synthesis—Effects of Culverts on Habitat Connectivity in Streams

The following numbered sections are the science synthesis content of this report. The science synthesis sections are numbered to reflect a potential overall analysis workflow, as shown in figure 1, and facilitate internal referencing among sections. Our methods for conducting the literature search and synthesizing the science appear after this science synthesis section in the "Methods for Developing this Science Synthesis" section.

1. Culvert Installation or Modification

Culverts are a type of permanent, low-cost flow control structure that can be found at road-stream intersections. Because roads commonly intersect streams, culverts are prevalent across watersheds. Culverts are frequently installed, replaced, or modified on Federal public lands during activities such as fluid minerals development, logging, mining, and rights of way.

1.1. Culvert Construction

Culverts are constructed in a variety of sizes, materials, and shapes to accommodate hydraulic characteristics of a stream. Three common culvert types are round pipe culverts, pipe arch culverts, and box culverts (fig. 2). Round pipe culverts, ranging in size from 15 to 155 inches in diameter, are the most common and are suitable for smaller streams. Materials are generally reinforced concrete or corrugated metal pipe (Schall and others, 2012). Pipe arches have similar sizes to round pipe culverts but have a higher hydraulic capacity, giving them an advantage by providing a wider stream channel during low flows. Larger pipe arch culverts can be constructed with reinforced concrete or by bolting together pieces of corrugated metal (Schall and others, 2012). Lastly, box culverts are large reinforced concrete structures that are built to accommodate high flows and fish passage in larger streams. Any of the three culvert types can be designed bottomless to maintain the natural characteristics of the streambed, which improves AOP (Schall and others, 2012).

1.1.1. Designing Culverts to Promote Habitat Connectivity

Several Federal agencies have published guidance for culvert design. The Bureau of Land Management (BLM) provides general technical guidance for culverts constructed during fluid minerals development. The BLM's Gold Book states that culverts should "be designed for a 25-year or greater storm frequency and allow fish passage in perennial streams where fish are present" (U.S. Department of the Interior and U.S. Department of Agriculture, 2007, p. 27).

The Federal Highway Administration requires that any culvert that spans at least 20 feet of horizontal distance on any public land must comply with the National Bridge Inspection and Reporting Standards (23 CFR §650). The Federal Highway Administration also published a detailed guide outlining culvert design for maintaining habitat connectivity and AOP. The guide provides ecological and hydraulic information relevant to the design and construction of large culverts (Kilgore and others, 2010).

Figure 2. Images of three common types of culverts. Culvert *A* is a round pipe culvert constructed of corrugated metal. Culvert *B* is a bottomless pipe arch culvert constructed of corrugated metal. Culvert *C* is a box culvert constructed of reinforced concrete. Images courtesy of RoadXStr (a road-stream crossing database), Emily Heaston, U.S. Geological Survey.

The U.S. Department of Agriculture Forest Service stream simulation guide provides detailed guidelines for designing and constructing road-stream crossings that maintain a high level of habitat connectivity and AOP (Cenderelli and others, 2011). Stream simulation aims to facilitate design of culverts that mimic the slope, structure, and dimensions of the natural streambed to minimize effects to **longitudinal connectivity**, hereafter referred to as “habitat connectivity.” The guide also includes a broad overview of managing watersheds for habitat connectivity, how to perform a site assessment to determine if the stream simulation approach is appropriate, preconstruction and postconstruction site assessment considerations, and many other details useful for culvert design.

1.2. Culvert Degradation

Culverts have a finite lifespan and can degrade to the point that they do not allow for AOP (Perrin and Dwivedi, 2006; Eisenhour and Floyd, 2013). Failing culverts incur economic costs, leading to a need for government agencies to regularly assess culvert condition (Perrin and Jhaveri, 2004; Perrin and Dwivedi, 2006). Case studies have documented that large concentrations of degraded culverts within a watershed affect AOP. In Alberta’s boreal forest, Park and others (2008) assessed 374 culverts and found that 50 percent were hanging, or “perched,” above the stream surface at the outlet of the culvert.

1.3. Culvert Removal and Replacement

Removing or replacing dilapidated or poorly designed culverts is a technique for restoring habitat connectivity and AOP (Amtstaetter and others, 2017). Projects that involve removing or replacing a culvert are situation-specific in their requirements but often involve many of the same hydrologic considerations (for example, temporarily redirecting flow, placing gradient control structures, and stabilizing stream banks) as constructing a new culvert (Bureau of Land Management, 2010; Bureau of Land Management, 2017).

2. Characterizing Existing Connectivity

Section 2 Highlights

- Habitat connectivity and its importance: Habitat connectivity refers to the ease or hindrance of movement of organisms and materials within a watershed. In aquatic riverine systems, movement—particularly for aquatic species like fish—occurs longitudinally along the river channel and within the watershed. Habitat connectivity plays a crucial role in supporting individual species and species assemblages.
- Types of barriers affecting connectivity: Natural and human-induced features can impede habitat connectivity. Movement can be hindered by natural barriers such as waterfalls, cascades, and seasonal drying. Human-made barriers, including dams, weirs, low-water crossings, and culverts, may significantly affect habitat connectivity. The effects of dams on stream biota are well documented, and smaller barriers at road crossings, like culverts, are prevalent and collectively have a substantial effect on habitat connectivity.
- Prevalence of small barriers: Studies have shown that the number of culverts can far exceed that of dams in certain North American watersheds. Therefore, the cumulative effects of these small barriers may be greater than those of larger dams, emphasizing the importance of addressing culverts' effects on habitat connectivity.

2.1. Habitat Connectivity Basics

Habitat connectivity describes the degree to which the landscape facilitates or impedes movement of organisms and materials between different locations in the watershed (McGarigal and Cushman, 2002). In aquatic riverine systems, movement (for aquatic obligates such as fish) is longitudinal (in other words, running upriver and downriver) along the river channel and within a watershed (Cote and others, 2009). Benda and others (2004) and Brown and Swan (2010) applied many existing landscape ecological concepts to aquatic ecosystems, noting that habitat connectivity within watersheds controls the distribution of available habitats, which in turn supports individual species and species assemblages. Fragmentation from human activity is a leading cause of freshwater biodiversity loss (Fischer and Lindenmayer, 2007; Perkin and others, 2015).

2.2. What Types of Barriers Can Affect Habitat Connectivity?

Natural and human-made features can impede habitat connectivity. Examples of natural barriers include waterfalls, cascades, seasonal drying, and unsuitable conditions such as excessively warm temperatures. Movement barriers associated with stream drying, unsuitably warm temperatures, or other altered instream conditions can also be related to human effects. Human-constructed barriers to habitat connectivity include flow control structures such as dams, weirs, low-water crossings, and culverts. The effects of dams on stream biota are well documented (Baxter, 1977; Murchie and others, 2008; Bellmore and others 2017), but researchers have also extensively documented the effects of smaller barriers that are often at road crossings (Anderson and others 2012; Hoffman and others 2012). Because of their prevalence, the effects of these smaller barriers on habitat connectivity may collectively far exceed those of dams (Januchowski-Hartley and others, 2013; Diebel and others, 2015). Respectively, Januchowski-Hartley and others (2013) and Diebel and others (2015) documented a ratio of 38 times and 24 times more culverts than dams in two separate North American watersheds.

3. Tools for Assessing Habitat Connectivity

Several modeling techniques are available to quantify habitat connectivity related to barriers in a watershed. Comparing estimated habitat connectivity in the watershed with and without current barriers can help resource managers understand the cumulative effects of human-made barriers in the watershed (for example, Mims and others, 2019).

Section 3 Highlights

- Factors affecting extent of analysis: When conducting habitat connectivity analysis, the spatial extent should align with the typical movement range of fish populations. Life history characteristics like species-specific differences in movement behavior also affect the extent of the analysis.
- Data requirements: Conducting a baseline habitat connectivity analysis using tools like the "dci" R package (Arkilanian, 2023) or the ArcMAP Fish Passage Extension (FIPEX; Oldford and others, 2022) requires comprehensive data on existing barriers in the watershed. Culvert location, condition, and other characteristics can be obtained from various sources such as online databases or field data collection.
- Assessing culvert permeability: Permeability assessment involves evaluating culvert characteristics that affect fish movement. Although no standardized method exists, tools like FishXing (Furniss and others, 2006) and resources from the North Atlantic Aquatic Connectivity Collaborative offer guidance for estimating culvert permeability.
- Estimating fish habitat connectivity: The DCI can be measured using the "dci" R package or FIPEX. Accurate results depend on the quality and completeness of the barrier inventory data within the study area.

The Dendritic Connectivity Index (DCI; Cote and others, 2009) models watersheds as networks of habitat in which the absence of barriers yields a DCI value of 100. The DCI is affected by the number, location, and **permeability** of barriers within the watershed. As impermeable barriers are added, the DCI declines from its maximum value of 100, indicating total connectivity, to as low as 0, indicating minimum connectivity. An application of the DCI in the Great Plains indicated that the DCI is sensitive to the effects of fragmentation by road crossings; DCI decreases with increasing fragmentation (Perkin and Gido, 2012).

3.1. Choosing the Spatial Extent of the Habitat Connectivity Analysis

The spatial extent at which an individual barrier affects aquatic organisms, and subsequently the spatial extent at which to conduct a habitat connectivity analysis, varies. An important factor to consider is the extent of the ranges of the populations that move through the location of the barrier. For example, if a fish population typically moves within a 10-digit hydrologic unit watershed, the analysis should cover that entire watershed.

The movement of individual fish species is dependent on life history characteristics, which should be considered when determining the extent of the analysis. Body size is directly correlated with swimming speed, making it more difficult for juveniles and smaller species to overcome fast flow rates (Ojanguren and Braña, 2003; Cano-Barbacil and others, 2020). Differences in propensity to movement also differ among species and populations; for example, some fish require long migration distances while others can adopt a resident strategy (Hoffman and others, 2012; Brodersen and others, 2014).

3.2. Data Needed to Estimate Habitat Connectivity in a Watershed

To conduct a baseline habitat connectivity analysis, a comprehensive dataset of existing barriers within the proposed watershed is needed. Culvert location and condition information can be obtained either from existing sources or field data collection. Although systematic inventories of human-constructed barriers to habitat connectivity are missing or lacking in many North American watersheds (Januchowski-Hartley and others, 2013), particularly in the Intermountain West (Dunham and others, 2023), several barrier inventory databases are available. For example, the Southeast Aquatic Resources Partnership provides a growing list of human-made barriers to habitat connectivity for every State except Hawaii. Their Aquatic Barrier Prioritization Tool is a geospatial web interface that summarizes road crossings and dams as barriers to habitat connectivity within specific States, hydrologic units, or ecoregions (National Aquatic Barrier Inventory and Prioritization Tool, 2023). This tool also provides downloadable spatial data for more in-depth analyses. However, because the tool is based on inventoried barriers, areas with high concentrations of barriers may simply reflect areas with more complete inventories. Other tools such as RoadxStr (a road-stream crossing database) are also in development to meet needs for rapid surveys to address large numbers of crossings in a short timeframe (Emily Heaston, U.S. Geological Survey, written commun., 2023).

When field data are feasible to collect, they can supplement or provide more up-to-date information than online databases. The Oregon/Washington BLM office recently published a spatial data standard for collecting data related to culverts (Bureau of Land Management, 2020). The data standard provides detailed definitions of all data to be collected regarding culverts, details of data collection and input, and other relevant information.

If field data are not available or financially or logistically impractical to collect or analyze, case studies may be cited and used to infer the potential effects of changes in habitat connectivity on watersheds. Several example habitat connectivity analyses are included in section "4.2.2. Responses of Fish Populations to Altered Habitat Connectivity" of this document.

3.3. Assessing the Permeability of a Culvert

Permeability is an estimate of the ability of an organism to pass through a potential barrier culvert. The spatial extent of the connectivity analysis may affect the intensity of the sampling approach chosen for assessing permeability. Although there is no standardized method for assessing the permeability of culverts, common survey methods assess many of the same culvert characteristics. These characteristics often include road condition, hydrologic information, culvert material, stream substrate, and characteristics of the inlet and outlet such as grade, dimensions, and drop distance to the water surface.

The North Atlantic Aquatic Connectivity Collaborative provides instruction manuals, data forms, and a scoring system for assessing culverts on their website (University of Massachusetts Amherst, 2023). In addition, they provide online training for field assessment, a database of assessed crossings, and web-based tools for identifying high-priority watersheds, crossings, and assessments.

An older but common tool for estimating permeability is FishXing, which was published by the U.S. Department of Agriculture Forest Service (Furniss and others, 2006). The tool models culvert hydraulics and fish swimming performance, providing an estimate of permeability that can be incorporated into a habitat connectivity analysis. Data required for estimating permeability consist of basic site information, culvert data, and demographic information about fish species (in other words, species present or potentially present, at minimum). The tool models the estimated permeability (0–100 percent) of the culvert with user-entered data for the species of interest. It also estimates other barrier-specific metrics, including passable and impassable flow ranges and whether there is an outlet drop that serves as a barrier for the species of interest.

3.4. Estimating Fish Habitat Connectivity in a Stream or Stream Network with Culverts

The DCI can be measured using one of several tools. The "dci" R package is being actively developed and provides a straightforward, programmable method of calculating the DCI for a watershed (R Core Team, 2023; Arkilanian, 2023). ArcMap Fish Passage Extension (FIPEX; Oldford and others, 2022) is another tool that allows a user to calculate and visualize the DCI within ArcMap. Regardless of method, the quality of a habitat connectivity analysis depends on the quality and completeness of the existing inventory of barriers within the study area. We describe these two quantitative methods in more detail in appendixes 1 and 2 and provide an example script for running an analysis of connectivity using the "dci" R package in appendix 3.

Photograph of gizzard shad (*Dorosoma cepedianum*) by Rick Lehrter, Bureau of Land Management

4. Potential Effects of Altered Connectivity by Culverts on Fish

Section 4 Highlights

- Culvert characteristics blocking aquatic organism passage: Culverts can impede the movement of aquatic organisms, particularly fish, and significantly affect stream hydrology, geomorphology, and biota. Channel constriction, perched outlets, and extreme flow velocities are key culvert characteristics that hinder aquatic organism passage.
- Effects on fish: Culverts serve as barriers to the daily and seasonal movements of fish, disrupting their access to habitat and essential resources like cold water refuges. The fragmentation caused by culverts leads to disconnected habitats and isolated subpopulations, ultimately contributing to biodiversity loss.
- Responses of fish populations to altered connectivity: Fragmentation by culverts reduces community resilience and can result in lower fish species richness and abundance at affected sites. Properly designed culverts can enhance habitat connectivity and improve access for fish.
- Special considerations: Culverts can also play a role in managing aquatic invasive species. Intentionally impeding habitat connectivity using culverts may limit competition between native and invasive species, prevent hybridization, and help control the spread of invasive species. Management decisions and assessments regarding culvert use as an invasive species management tool should be considered carefully because of the potential of a culvert to affect native species.

4.1. What Characteristics of Culverts Block Aquatic Organism Passage?

Culverts can prevent the movement of aquatic organisms (Warren and Pardew, 1998) and have major effects on stream hydrology, geomorphology, and biota (Frankiewicz and others, 2021). Warren and Pardew (1998) conducted a thorough mark-recapture study of the ability of three families of small-bodied fish to pass through a variety of culvert designs (pipe culvert, slab, open-box) relative to an unimpaired, natural reach. They demonstrated that (1) fish passage, expressed as mean daily movement, was significantly reduced at pipe culverts relative to open-box culverts, ford crossings, and natural reaches and (2) water velocity at crossings was inversely related to fish movement. Further studies have confirmed that increases in flow velocity due to constriction by pipe culverts reduce or prevent AOP (Schaefer and others, 2003; Macdonald and Davies, 2007). More recent research has acknowledged that fish often use reduced-velocity zones to lower energetic costs. Roughness in a culvert can improve a fish's ability to pass through by creating reduced-velocity zones that lower energetic costs (Amtstaetter and others, 2017; Rodgers and others, 2017).

When streamflow is low, some culverts may be perched above the stream surface. Perched culverts can be particularly difficult to navigate for small-bodied fish (Anderson and others, 2012). Shallow depths resulting from low flows through a culvert can prevent fish movement. Even when high streamflow is sufficient to submerge the outlet, the constricted flow through the culvert may be too fast for small-bodied fish to swim against (Furniss and others, 2000). Examples of culverts in various conditions can be seen in figure 3.

4.2. Effects of Culverts on Fish

Fish move within a river system on a daily and seasonal basis for many reasons, such as finding resources, accessing refuges, spawning, and colonization. Culverts can serve as barriers to movement and dispersal and fragment habitat. Broadly, increased habitat fragmentation in river systems often results in disconnected habitat and isolated subpopulations of organisms through time, leading to a loss of biodiversity (Perkin and Gido, 2012).

4.2.1. Daily and Seasonal Movement of Freshwater Fishes

Fish engage in movements at different temporal scales, all of which are susceptible to interruption by culverts (table 2). Three dominant families of small-bodied fish (*Centrarchidae* [sunfishes and black bass], *Cyprinidae* [minnows and carps], and *Fundulidae* [topminnows and killifishes]) were documented making daily movements through stream crossings seeking different habitat patches (Warren and Pardew, 1998). Daily and seasonal movements are also important for maintaining the capacity of fish to use diverse habitats that meet their needs for feeding, migration, refuge, and reproduction (Schlosser, 1995). For example, habitat fragmentation by instream barriers has been shown to reduce access to cold water refuges (Schaefer and others, 2003; Petty and others, 2012), which is of particular concern as the effects of climate change, such as extended drought, warmer waters, reduced base flows, and increased flooding (Reidmiller and others, 2018), continue to become more prevalent (Ebersole and others, 2020). Seasonal fish movements to suitable overwintering habitat can also be blocked by impassable dams and culverts (Chisholm and others, 1987; Sethi and others, 2021). Lastly, culverts can prevent upstream migration for the many freshwater fish species that migrate long distances for spawning (Crowe, 1962; Fausch and Young, 1995; Compton and others, 2008).

A

B

C

Figure 3. Images of culvert outlets in various conditions. Culvert *A* is a bottomless, corrugated metal pipe-arch culvert that maintains a natural substrate through the outlet. Culvert *B* is a corrugated metal pipe culvert with a perched outlet and increased flow rates due to flow constriction. Culvert *C* is a corrugated metal pipe culvert with a perched outlet and obvious degradation (rusting) through the bottom of the culvert. Images courtesy of RoadXStr (a road-stream crossing database), Emily Heaston, U.S. Geological Survey.

Table 2. Literature describing specific effects of barrier culverts to fish.

[Each table spanner contains an effect of a barrier on fish. The rows below the spanners list the taxa for which each effect has been studied, the barrier type assessed in the study, and relevant citations. We note that this is not a comprehensive list of literature about these specific topics, but rather a set of illustrative examples (see Hoffman and others [2012] for additional examples)]

Study taxa	Barrier type	Citation
Effect—Reduce daily access to habitat patches		
Sunfishes and black bass (*Centrarchidae*), minnows (*Cyprinidae*), and topminnows and killifishes (*Fundulidae*)	Culvert	Warren and Pardew (1998)
Effect—Reduce access to refuges		
Brook trout (*Salvelinus fontinalis*)	Unspecified	Petty and others (2012)
Leopard darter (*Percina pantherina*)	Culvert	Schaefer and others (2003)
Effect—Prevent access to overwintering habitat		
Coho salmon (*Oncorhynchus kisutch*)	Culvert and dam	Sethi and others (2021)
Brook trout (*Salvelinus fontinalis*)	Natural barriers	Chisholm and others (1987)
Effect—Decrease recruitment to spawning habitat		
Bluehead sucker (*Catostomus discobolus*), flannelmouth sucker (*Catostomus latipinnis)*, and roundtail chub (*Gila robusta*)	Dam	Compton and others (2008)
Chinook salmon (*Oncorhynchus tshawytscha*)	Dam	Deriso and others (2001)
Effect—Prevent or slow colonization or recovery after a disturbance		
Temperate stream fish communities (both studies)	Culvert	Freeman and others (2021)
	Unspecified	Detenbeck and others (1992)

4.2.2. Responses of Fish Populations to Altered Habitat Connectivity

Freshwater fish respond to altered habitat connectivity in multiple ways. In Georgia, only 3 of 11 fish species recolonized a headwater stream 18.5 months after a chemical spill at the headwaters of a highly culvert-fragmented watershed, indicating decreased community resilience resulting from fragmentation by culverts (Freeman and others, 2021). In a study of 97 sites in southeast Oklahoma, fish species richness (a count of unique species) was lower at culvert-affected sites compared to free-flowing sites, and the most highly degraded culverts had the greatest effects on species abundance and richness (Fleming and Neeson, 2020). Chelgren and Dunham (2015) modeled habitat connectivity for a watershed in Oregon by comparing replaced crossings with existing crossings, concluding that the new crossing design increased fish passage for the multiple fish species considered.

4.2.3. Special Considerations—Culverts and Aquatic Invasive Species

Culverts may also affect the diversity, abundance, resilience, and reproduction of invasive aquatic species (for example, see Kerby and others, 2005), making culverts an invasive species management tool in some circumstances. Intentionally impeding habitat connectivity using a culvert may prevent competition between native and invasive fish species (Fausch 1989; Bowie and others, 2018), prevent unwanted hybridization (Behnke, 1992; Neville and Dunham, 2011), and limit the spread of invasive species (Milt and others, 2018). Fausch and others (2006, 2009) provided an extensive discussion of this issue with reference to management decisions and assessments.

Methods for Developing this Science Synthesis

Rutherford and others (2023) introduced a methodology for developing science syntheses to inform analyses conducted under the National Environmental Policy Act (NEPA). This and other syntheses build on that foundation and methodology and apply it to new topics of management concern on western lands. Therefore, relevant text from these reports is reproduced herein.

We used a literature search to gather science relevant to culverts and habitat connectivity. We sought information relevant to conducting environmental effects analyses per the NEPA (Carter and others, 2023), including background data, studies that describe the effects of culverts on habitat connectivity or aquatic organisms, methods for analyzing culvert condition and habitat connectivity, and effective culvert design.

We used the Python-based BiblioSearch tool developed by the U.S. Geological Survey (Kleist and Enns, 2021) to conduct a scientific database search to gather recent (2017–22) literature relevant to the effects of culverts on habitat connectivity and aquatic organisms. We used the search terms “'culvert' AND ('stream' OR 'river' OR 'lotic') AND ('AOP' OR 'passage' OR 'barrier' OR 'connectivity')” to search three databases (Web of Science, Scopus, and ScienceBase) for relevant literature published within the last 5 years (2017–22). This search yielded 147 publications, which we reviewed to confirm their relevance to culverts, habitat connectivity, and AOP. We then used a backwards snowballing method (Wäldchen and Mäder, 2018) starting from the most relevant, highly cited studies to identify seminal publications related to the topic of our literature search. This method allowed us to obtain a core list of literature to better understand the current (2017–22) state of the science and seminal studies that provided foundational information. We sought studies related to fish passage in river systems that gave no preference to **diadromous** or **potamodromous** taxa. Finally, we synthesized the scientific information from the search into this document with the goal of informing environmental effects analyses for resource management on Federal public lands.

We synthesized information returned in these searches according to our objective to inform NEPA analyses. Rather than reporting all literature we found, we synthesized only the literature applicable to informing analyses of the potential effects of culvert installation or modification on connectivity and aquatic organisms. As such, this synthesis does not constitute a comprehensive literature review of all effects of culverts on aquatic organisms, and it is possible that we may have missed articles not identified through our literature search methods.

Throughout the development of this report, we worked with staff from the BLM, U.S. Fish and Wildlife Service, and U.S. Geological Survey to coproduce this document (Beier and others, 2017). We refined the structure and content of the report through close collaboration with multiple BLM staff throughout scoping, writing, and review.

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Glossary

aquatic organism passage (AOP) "AOP/Fish Passage is the removal of barriers to movement through and between bodies of water. This can include dam removal, road removal, or enlargements of culverts and tide gates to allow more natural flows through these barriers." (American Fisheries Society, 2023 [webpage])

culvert "A conduit or passageway, not classified as a bridge, under a road, trail, or other facility usually consisting of a round pipe, a pipe-arch, or an open or closed bottom box or arch." (U.S. Department of Energy, 2023 [webpage])

diadromous "Of a fish: migratory between salt water [sic] and fresh water [sic]" (Merriam-Webster, 2023a [webpage])

longitudinal connectivity "Within the stream system, longitudinal connectivity refers to the pathways along the entire length of a stream." (Minnesota Department of Natural Resources, 2023 [webpage])

permeability "* * * the degree of impairment a barrier presents to fish passage or longitudinal connectivity of the river system. It is used in various analyses as a 'weight' to help assess the relative impacts of barriers." (Oldford and others, 2022, p. 51)

potamodromous "Of a fish: migratory in fresh water [sic]" (Merriam-Webster, 2023b [webpage])

Appendix 1. Option 1: “dci” R Package

The “dci” package in R uses the “sfnetworks” package to model geospatial network data and calculate various forms of the Dendritic Connectivity Index (Arkilanian, 2023). This tool can be run by someone with basic geographic information system (GIS) and R experience; a sample script that can be adapted to any stream network is provided in appendix 3.

Installing the package and running the basic analysis in R requires three input shapefiles that can be created in geospatial software prior to the analysis. The first of these is the stream network, which can be obtained from the National Hydrography Dataset and clipped to the watershed or hydrologic unit of interest. The second shapefile is point locations of culverts, which can be obtained from a variety of sources (see section 3.2). Optionally, each point can contain an associated permeability value in the culvert layer with permeability values between 0 and 1 (see section 3.3). If no permeability values are entered, R will assume that all barriers have a permeability of 0. The third shapefile is a single point location of the watershed outlet where all water flows out of the watershed.

The sample script (app. 3) walks the user through loading the shapefiles to R, using “sfnetworks” to convert them to a spatial format, creating the river network using the “dci” package, and then calculating Dendritic Connectivity Index values for the entire watershed and individual stream segments. The script also provides basic visualizations for the data; these data can then be plotted using R or exported as a shapefile that can be mapped in geospatial software. Annotations in the script provide more specific direction and assistance, and more details can be found in the “dci” package documentation.

Reference Cited

Arkilanian, A., 2023, dci—Calculate the Dendritic Connectivity in river networks, R package version 0.0.0.9000: GitHub software release, accessed June 1, 2023, at https://github.com/aarkilanian/dci.

Appendix 2. Option 2: Fish Passage Extension

Fish Passage Extension (FIPEX; Oldford and others, 2022) is an ArcMap extension that can be used to model and analyze the habitat connectivity of a watershed with barriers. The Fish Passage Extension uses the modeled river network and permeability information for the modeled barriers to calculate the Dendritic Connectivity Index (DCI; Cote and others, 2009) for the watershed. Using FIPEX requires a moderate level of geographic information system (GIS) experience. This tool provides a method of assessing the individual and cumulative effects of a barrier on connectivity in a watershed while working solely in ArcMap and using R to process data in the background. We describe the tool and outline a basic analysis in this section; however, FIPEX documentation provides a detailed and authoritative walkthrough to installing and using the tool (Oldford and others, 2022). It is important to note that ArcMap will be retired by Esri in 2026 in favor of ArcGIS Pro, and that the current FIPEX tool will no longer be supported.

The Fish Passage Extension uses ArcMap's Network Utility Analyst to model the connectivity of a watershed with barriers. This tool takes, at minimum, the same three input datasets used in the "dci" R package to construct the model: a line shapefile of the watershed of interest, a point shapefile of barriers within the watershed of interest and their associated permeability values, and a watershed outlet location. If applicable, additional datasets of dams and sinks (in other words, ponds and lakes) can also be added to the analysis.

The user can then choose between a "One-Click" analysis (single-barrier) or an advanced connectivity analysis of the entire watershed. For a single-barrier analysis, the tool will analyze the conditions immediately upstream of the chosen barrier. The "Advanced Analysis" icon on the FIPEX toolbar will open an options menu where the user can select datasets and set the parameters for the DCI calculations. After running the analysis, the tool will return a table with DCI values for the entire network as well as DCI values for each individual river segment between barriers. Barriers can be activated or deactivated to include or exclude them from the analysis, facilitating comparison of the connectivity of a watershed with or without a proposed or existing barrier. See figure 2.1 for the results of an example analysis.

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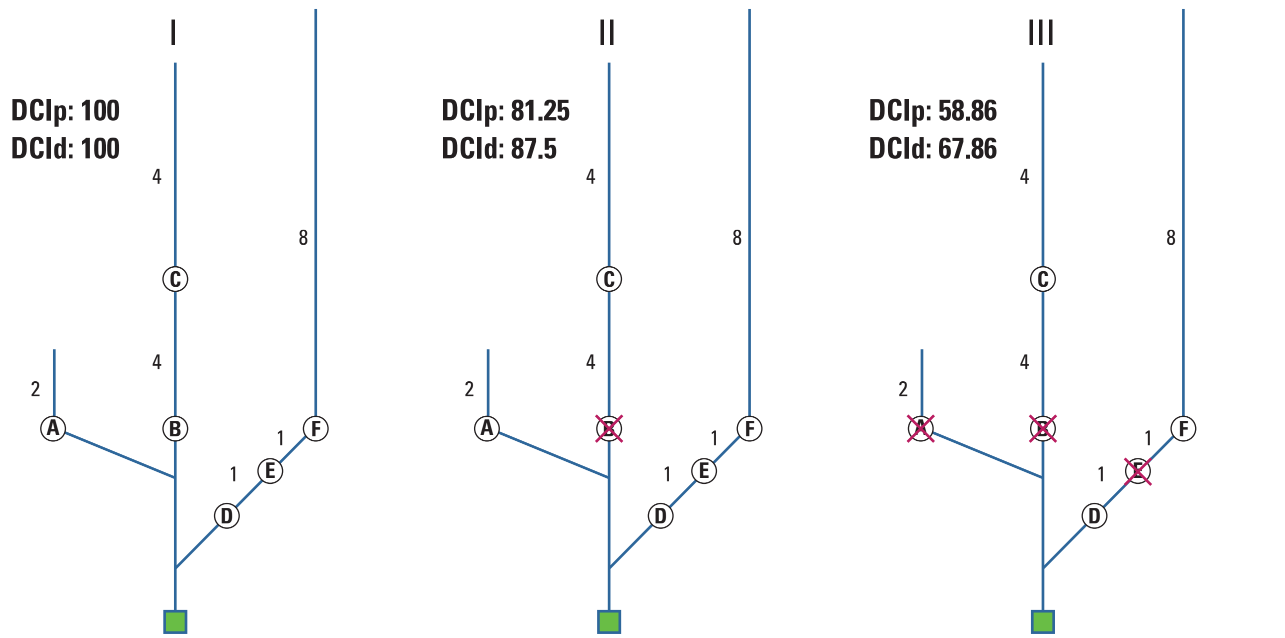

Figure 2.1. An example connectivity analysis from the Fish Passage Extension tool in ArcMap showing three scenarios of culvert placement with associated potamodromous Dendritic Connectivity Index (DCIp) and diadromous Dendritic Connectivity Index (DCId) values. The green box represents the "sink," or the location farthest downstream in the watershed being analyzed. Circled letters (A–F) represent possible barrier locations. Permeabilities were set to 0.5 for all barriers in this example. Numbers adjacent to stream segments represent relative segment length on a scale of 1 to 8. Scenario I shows a fully connected watershed with no barriers to connectivity. Scenario II shows the same watershed with the addition of a single barrier (the barrier, with permeability 0.5, is indicated by an X over the letter "B"). Scenario III shows the same watershed, but this time highly fragmented with three barriers (with permeabilities 0.5, indicated by X's over the letters "A," "B," and "E").

Appendix 3. "dci" R Package Sample Script

This section includes an R script that will walk the user through a basic analysis of connectivity using the "dci" R package (Arkilanian, 2023). Annotations are included throughout to guide the user through each step. This is a demonstration of the use of the "dci" package meant to expedite a basic analysis but does not use all features included in the "dci" package. Please consult the package documentation for more information.

```
### LOAD REQUIRED PACKAGES ###
# You may need to install these packages before running by clicking Tools -> install packages on the tool bar or by running install.
    packages("package_name")
library(devtools)
library(tidyverse)
library(sf)
library(dci)
library(foreign)
library(ggplot2)

# Load package documentation for reference:
??dci

# Better documentation for functions:
https://rdrr.io/github/aarkilanian/dci/man/

### DATA PREP ###
# Prior to running this, you must create 3 shapefiles in ArcMap or ArcGIS Pro:
# - shapefile of your river network
# - shapefile of all culverts
# - shapefile of the outlet location of your river network
# Ideally, snap all the above points to the river network line using the Snap tool.
# Export the above features using Feature Class to Shapefile tool in ArcGIS Pro.
# Several files will be generated-- R will use the shapefile (.shp)

### LOAD SHAPEFILES ###
# Define file paths to the shapefiles, making sure to use forward slashes
# Change the names of the three files-- rivers, outlet, and culverts -- to match the names of the files in your filepath.
shapefile_dir <- "C:/YOUR/FILEPATH/HERE/"
rivers_file <- paste0(shapefile_dir, "rivers.shp")
outlet_file <- paste0(shapefile_dir, "outlet.shp")
culverts_file <- paste0(shapefile_dir, "culverts.shp")

# Read the shapefiles as sf objects
rivers_st <- st_read(rivers_file)
outlet_st <- st_read(outlet_file)
culverts_st <- st_read(culverts_file)

# Import the sf files created
# When using import_rivers() here, it will output a line plot.
# Red lines represent disconnected stream segments- this can be corrected in ArcMap by snapping the lines and re-exporting the shapefile.
rivers <- import_rivers(rivers_st)
outlet <- import_points(outlet_st, type = "outlet")
culverts <- import_points(culverts_st, type = "barriers")

### SET COORDINATE REFERENCE SYSTEM ###
# Set the projected coordinate reference system (crs) by entering its 'WKID' below- if a geographic reference system is chosen, then R
    may crash.
# It is important, if you're going to export data and open it in ArcMap, to make sure the crs matches the crs of the map it is added to.
# 3857 is Web Mercator, a common projected crs
crs <- 3857
rivers_crs <- st_set_crs(rivers, crs)
outlet_crs <- st_set_crs(outlet, crs)
culverts_crs <- st_set_crs(culverts, crs)
```

```
### CREATE A RIVER NETWORK OBJECT ###
# The tolerance argument is in distance units and will snap points to the river network file but can cause errors if set too large.
# ideally, however, points are snapped to the line before exporting from ArcMap.
river_net <- river_net(rivers_crs, culverts_crs, outlet_crs, poi = NULL, check = TRUE, tolerance = 50)

# Visualize river network with nodes colored according to their type and double check to make sure data looks right
ggplot() +
geom_sf(data = river_net %>% tidygraph::activate(edges) %>% sf::st_as_sf()) +
geom_sf(data = river_net %>% tidygraph::activate(nodes) %>% sf::st_as_sf(), aes(col = type))

### CALCULATE DCI ###
# Set the “pass” field to match the name of the permeability column in your culverts shapefile
# DCI values for the entire network and stream segment will output in the console
dci_results <- calculate_dci(river_net, form = “potamodromous,” pass = “permeability”)
dci_results

### PREP DATA FOR VISUALIZATION AND EXPORT ###
res_riv <- export_dci(river_net, dci_results)
res_riv <- res_riv %>%
select(DCI, geometry.x) %>%
rename(geometry = geometry.x)

### VISUALIZING RESULTS ###
# Basic visualization of the DCI color coded river network with barrier locations
ggplot() +
geom_sf(data = res_riv, aes(col = DCI)) +
geom_sf(data = river_net %>% tidygraph::activate(nodes) %>% sf::st_as_sf() %>% dplyr::filter(type == “barrier”))

# For more control over visual aspects, export to ArcMap or ArcGIS Pro following below directions.

### PREP DATA FOR EXPORT ###
res_riv <- res_riv %>%
select(DCI, geometry.x) %>%
rename(geometry = geometry.x)

### EXPORT DATA ###
# Ensure the above coordinate system (3857 by default) matches coordinate system of your map, or it will not display properly
# Save all 4 output files to the same folder, or there will be an error when importing to ArcGIS
st_write(res_riv, st_write(res_riv, “C:/DESIRED/FILEPATH/HERE/results.shp”))
```

Reference Cited

Arkilanian, A., 2023, dci—Calculate the Dendritic Connectivity in river networks, R package version 0.0.0.9000: GitHub software release, accessed June 1, 2023, at https://github.com/aarkilanian/dci.

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