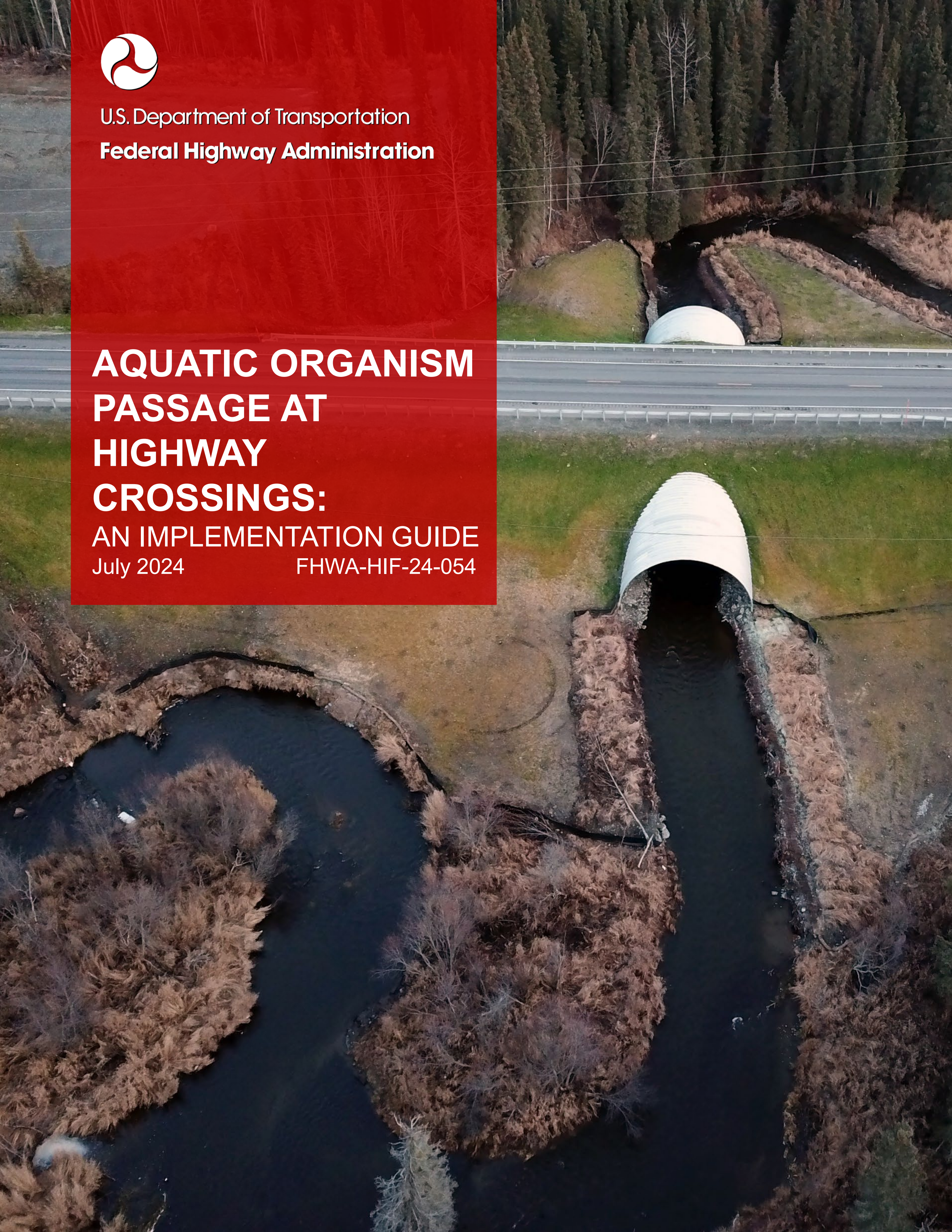

U.S. Department of Transportation
Federal Highway Administration

AQUATIC ORGANISM PASSAGE AT HIGHWAY CROSSINGS:

AN IMPLEMENTATION GUIDE

July 2024 FHWA-HIF-24-054

Front & Back Cover Photos

Crooked Creek Aquatic Organism Passage Project.
Sterling Highway, Kasilof, Alaska.
Alaska Department of Transportation & Public Facilities.
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16. Abstract
This Aquatic Organism Passage (AOP) Implementation Guide (Guide) supports transformative practices for waterway-transportation crossing design for successful removals of AOP barriers. This Guide does not present a single approach, as there are many approaches. Instead, it provides general principles for successful application allowing flexibility to meet site-specific goals, context, and constraints. This Guide is intended for non-experts, and it describes AOP goals and how they vary based on the location and needs. It provides an overall context of the magnitude of AOP barriers nationwide and explains differences between bridges and culverts. Given the vast number of AOP barriers, this Guide provides an overview of criteria that can be used to prioritize the most important projects to achieve specific goals. It also provides an overview of the AOP project delivery process, noting the key elements of planning, project delivery, monitoring, and adaptive management that make projects successful in removing AOP barriers. Finally, this Guide includes descriptions of six case studies that illustrate the material presented along with lists of other technical resources that readers may consult.

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Table of Contents

List of Figures

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Executive Summary

Where transportation systems such as roads and tracks intersect waterways, a result may create barriers that impede the passage and impair the habitat of aquatic organisms and other wildlife. The Federal Highway Administration (FHWA), an agency within the U.S. Department of Transportation (USDOT), promotes approaches to reduce or remove barriers to passage of both aquatic and wildlife species where they interact with our Nation's transportation system. The FHWA also recognizes that removing these barriers may have flood risk reduction, environmental, cultural, and societal benefits. Aquatic organism populations may be critical to local economies and Native and Tribal communities.

The FHWA is working to advance the state of water crossing design practice for aquatic organism passage (AOP). Through these advances, the FHWA seeks to encourage practices that minimize negative effects on fish and other aquatic organism populations while creating safer and more resilient structures.

The FHWA intends for this AOP Implementation Guide (Guide) to support transformative practices by providing a resource describing practices leading to successful removal of AOP barriers. This Guide does not present a single approach, as there are many approaches that can be successful. Rather it provides general principles for successful application leaving flexibility to meet site-specific goals, context, and constraints.

The FHWA intends this Guide to provide background and insights on waterway-transportation interactions and how to resolve or avoid AOP barriers created by these interactions. The primary audience is not experienced practitioners, natural resource managers, researchers, scientists, or engineers familiar with the subject matter. Rather, the FHWA hopes this Guide will serve as a resource for those interested in removing barriers, but without extensive background or expertise. It is the FHWA's hope that this Guide will enable stakeholders to be conversant when considering projects or discussing opportunities with experts.

AOP projects improve the movement of aquatic organisms within and between habitats by modifying or removing dams, culverts, and other barriers that restrict their migration. This Guide explores potential goals for AOP projects, focusing specifically on barriers related to transportation infrastructure. These goals may focus on a specific species of fish or on fish or other aquatic organisms more generally. Regardless of the specific goals, a critical component of success is a clear articulation of project goals to ensure the project design can achieve the goals. This Guide also provides brief summaries of how recent Federal programs provide direct or indirect support of AOP goals. These summaries help demonstrate the diversity of how collaborators and stakeholders may wish to approach developing such goals suited for their own AOP species, habitat, and site conditions.

This Guide also describes the potential magnitude of the waterway-transportation AOP barrier challenge. A key design feature addressed in this Guide is an overall approach to sizing AOP projects which, in turn, informs project goals.

Because the resources to address these challenges are limited, an approach to prioritizing significant needs becomes important. There is no one prioritization approach, but many will have common elements depending on the needs and goals of a program or region. A successful prioritization approach captures the anticipated and desirable outcomes of a project and provides protocols for assessing the achievement of those outcomes post-project (e.g., monitoring). These approaches often apply criteria to help characterize the prioritization. These criteria generally fall into five main categories, but can be organized in different ways:

- **Statement of clear goals and objectives**. Clear articulation is necessary to define and achieve success.
- **Ecosystem benefits**. These are benefits for fish populations, other aquatic organisms, aquatic habitat, stream stability, water quality, and terrestrial habitat.
- **Community benefits**. These are benefits for the people who live, work, or visit an area that include public safety, support for cultural practices, improvements for underserved communities, and improved recreational opportunities.
- **Sustainability and resilience**. Adherence to these concepts helps to ensure that investments continue to deliver over time.
- **Feasible project implementation**. Developing constructable designs with practicable implementation plans and stakeholder support improves the likelihood of successful AOP projects.

The delivery of AOP water crossing projects involves a variety of processes and requires a high level of coordination among interested parties. Project sponsors and asset owners play a significant role in the implementation of the project delivery process for AOP projects from inception through construction. After construction, a robust monitoring and adaptive management program can be implemented to assess whether the planned AOP benefits are being achieved and provide lessons learned for future AOP projects. As with any asset, periodic assessment, maintenance, and adjustment of an AOP project may help fully realize project goals and objectives. This Guide provides information on key aspects of project implementation including:

- **Project delivery and design methods**. The procedures and methods that have led to successful AOP projects.
- **Appropriate personnel**. AOP design is an interdisciplinary endeavor requiring numerous skills and experiences working cooperatively.
- **Stakeholder collaboration**. Multiple interested parties can help implementation of AOP projects.
- **Project monitoring and evaluation**. After construction, monitoring helps identify any needed corrective actions and provides lessons learned for future projects.

Successful AOP projects conform to the specific circumstances of a site and the goals and objectives of a project. This Guide also provides six case studies that illustrate the application of AOP project concepts and approaches to a variety of project sites and objectives. The FHWA sought a diverse mix of case studies from differing project owners and entities to provide practical illustrations of the information provided throughout this Guide. In addition, this Guide points to other reference materials for readers seeking additional insights.

Chapter 1. Introduction

Road and track crossings over waterways may create barriers that impede passage and impair the habitat of aquatic organisms and other wildlife. Aquatic organisms include a diverse group of animals growing in, living in, or frequenting water. Fish, such as salmon shown in Figure 1, have historically been a focus of aquatic organism passage.

The Federal Highway Administration (FHWA), an agency within the U.S. Department of Transportation (USDOT), promotes approaches to reduce or remove barriers to passage of both aquatic and terrestrial wildlife species where they interact with our Nation's transportation system. In addition, the FHWA recognizes that removing aquatic organism passage (AOP) barriers may also have flood risk reduction, environmental, cultural, and societal benefits.

Figure 1. Salmon in Coffman Creek, Prince of Whales Island, Alaska 2021. Photo by Casey Kramer.

Recent legislative initiatives have emphasized the importance of habitat connectivity, bolstering the need to understand and to act to improve terrestrial and aquatic organism passage. This understanding is critical as the topic of aquatic and wildlife passage is complex, involving a myriad of biologic, geomorphic, hydrologic, habitat and other elements. Further complexity occurs as these elements are influenced by planning, permitting, engineering, and construction activities associated with the crossings. This AOP Implementation Guide (Guide) provides an overview of these activities as they pertain to AOP and AOP projects. AOP projects seek to improve the movement of aquatic organisms within and between habitats by modifying or removing dams, culverts, and other barriers that restrict their migration. Where a narrowing of the scope is appropriate, this Guide specifically focuses on AOP projects associated with transportation infrastructure.

1.1 Background

Within the United States, transportation networks such as roadways and tracks traverse the landscape, providing access throughout the country. This, however, leads to interactions between these transportation systems with waterways and the environment. Transportation engineers commonly employ culverts and bridges to cross waterways. Culverts are structures comprised of one or more barrels beneath an earthen embankment that are hydraulically and structurally designed to convey water, sediment, wood, debris, and, more recently, aquatic and terrestrial organisms, which have been historically overlooked, through roadway embankments. Generally larger than culverts, bridges serve similar objectives.

In addition, other types of infrastructure such as hydroelectric projects, low head dams, and utilities interact with streams, rivers, and other waterways. Such interactions can impact aquatic organisms, including fish, by potentially causing barriers to passage, habitat fragmentation, altered streamflows, and loss of ecological connectivity (Trombulak and Frissell 2000).

Earlier design techniques emphasized “hydraulic conveyance” as the main criterion to design transportation and other infrastructure systems and generally did not consider natural stream functions and aquatic organism passage, leading to negative effects on aquatic organism passage (FHWA 2012a). Fortunately, awareness of the importance of these considerations has led to an evolution of approaches and practices for AOP and terrestrial wildlife crossings. For example, the FHWA (2023a) has described the importance and long-term benefits of the harmonious design of roadways within river corridors so that the river environment thrives while the roadway efficiently serves its function.

Culverts and other waterway crossings designed without consideration of natural processes can affect not only fish but also other aquatic organisms, such as small aquatic organisms like salamanders (USFS 2006, Schrag 2003). In general, a culvert that is impassable for fish may also pose a barrier to other aquatic organisms, including those with weaker swimming abilities (FSSWG 2008).

River and stream corridors provide vital habitat for a wide range of animal species, many of which depend on the ability to move freely throughout their ecosystem to complete their life cycles (Jackson 2003). Recognition of the need to restore habitat connectivity has added ecological considerations and other benefits to the design and retrofit of water crossings (e.g., Jackson 2003, FSSWG 2008, FHWA 2023).

The FHWA encourages consideration of AOP and provides funding opportunities for Culvert AOP projects, such as by providing discretionary grants through the Culvert AOP Program (see inset). Planners, ecologists, biologists, resource managers, and engineers understand that expanding aquatic and terrestrial wildlife connectivity can improve infrastructure resilience and

Culvert AOP Program

Section 21203 of the 2021 Bipartisan Infrastructure Law (BIL) (Pub. L. No. 117-58) created the **National Culvert Removal, Replacement, and Restoration Grant Program**, known as the Culvert AOP Program. The Culvert AOP Program provides grants for the replacement, removal, repair, and improvement of culverts or weirs that would meaningfully improve or restore fish passage for anadromous fish (49 U.S.C. 6703(b)).

reduce infrastructure repair and maintenance costs. These professionals also recognize the benefits of monitoring waterways (example shown in Figure 2) to confirm when activities are achieving their intended benefits and making adjustments when they are not.

1.2 Target Audience

The FHWA intends this Guide to provide background and insights on waterway-transportation (primarily road) interactions. The primary audience is not experienced practitioners, natural resource managers, researchers, scientists, or engineers familiar with the subject matter. Rather, the FHWA hopes this Guide will serve as an implementation resource for those interested in removing barriers and who are seeking to increase their overall understanding of passage and barriers, but without the extensive background or expertise in the subject matter.

Figure 2. Stream monitoring at Fan Creek, Nestucca, Washington 2021. Photo by Casey Kramer.

1.3 Document Organization

The organization of this Guide generally aligns with the overall concepts and process involved in implementing a successful AOP project. The FHWA recognizes that successful AOP projects:

- Apply an ecological focus.
- Use an interdisciplinary team.
- Consider streamflow, sediment, and wood transport; geomorphology; geology; and other conditions associated with the waterway, especially in the vicinity of the crossing.

- Consider affected species at all stages of their life cycle.
- May include co-benefits such as reduced structure clogging or improved terrestrial wildlife passage.

The chapters in this Guide include:

Chapter 1. Introduction. Provides background information and describes the target audience.

Chapter 2. AOP Project Goals. Describes the context and overview of AOP design.

Chapter 3. ABCs of Implementation. Introduces bridge and culvert crossings of waterways.

Chapter 4. Project Prioritization. Provides a general overview of the factors relevant for identifying AOP projects.

Chapter 5. Elements of AOP projects. Summarizes the project development process.

Chapter 6. Case Studies Overview. Introduces AOP projects described in the case studies.

In addition, the document provides references, a glossary, and abbreviations used in this Guide as a resource for readers. Several appendices provide more detailed information for the interested reader. Finally, this Guide provides six AOP project case studies to demonstrate how different practitioners applied the principles described in this Guide in the field.

Chapter 2. AOP Project Goals

This chapter explores potential goals for AOP projects. A background and context section provides a foundation that helps identify potential goals for AOP projects. The next section provides brief summaries of how current Federal programs provide direct or indirect support of AOP goals.

2.1 AOP Background and Context

Historic concerns about barriers to fish passage have broadened to include other aquatic organisms (or species) living in, or frequenting water. Humans have impaired the passage of fish and other aquatic organisms in a variety of ways to the detriment of both aquatic organisms and humans. Impairment is typically in the form of in-stream barriers to natural river functions.

Barriers can come in many forms. For example, a culvert becomes a barrier to AOP when it poses conditions that exceed the organism's physical capabilities to pass through it. Circumstances that serve as barriers are species-dependent (and even dependent on the life stage of a particular species). For fish passage, common obstructions include excessive water velocities; drops at culvert inlets or outlets; physical barriers such as weirs, baffles, or debris caught in the culvert barrel; excessive turbulence caused by inlet contraction; and low flows that provide too little depth for fish to swim.

AOP, for the purpose of this Guide, is the ability of aquatic organisms to move freely upstream and downstream to access riverine, lacustrine, estuarine, and marine habitats they require to complete their life-cycle under their own power and at multiple life stages, without delay (also known as "volitional passage"). Migratory fish can travel significant distances to reach these habitats. Aquatic organisms rely on such habitats for food, growth, reproduction, shelter, predator avoidance, and other needs.

In-Stream Barriers to Passage

A barrier to aquatic connectivity is an obstruction that prevents or alters the natural flow of water within or between waterbodies, potentially impacting water quality, sediment movement, type of habitat, and AOP. A barrier to AOP is anything that prevents or reduces the ability of fish or other aquatic species to move where needed to survive and complete their life cycle within an aquatic system.

Planners and designers seeking removal of passage barriers typically focus on physical barriers, such as culverts, weirs, and dams. However, insufficient sediment and wood can also create barriers by causing streams to erode.

In addition, river conditions, including excess sediment, poor water quality, temperature or flow variations, and other environmental conditions, may also create barriers to movement depending on the aquatic species.

Barriers may be permanent or temporary and vary based on species and or life stage of the aquatic organism.

The following terms distinguish fish species by their migration patterns, though some species can adapt their patterns for different circumstances (see the glossary for additional definitions):

- Anadromous: Fish that migrate from the sea up into fresh water to spawn.
- Catadromous: Fish that migrate from fresh water down into the sea to spawn.
- Potamodromous (resident): Fish that live and migrate wholly within fresh water. Resident fish can be subdivided:
  - Fishes residing entirely in natal (birth) streams.
  - Fishes that out-migrate from natal streams as juveniles to larger rivers (fluvial), growing to maturity before returning to spawn.
  - Fishes that out-migrate from natal streams as juveniles to lake environments (adfluvial), growing to maturity before returning to spawn.

The primary goal of AOP projects is to improve or restore impaired passage conditions by removing or mitigating in-stream barriers. For AOP projects focused on migratory aquatic organisms, the goal is to improve the movement of aquatic organisms both within and between their spawning, rearing, and other habitats by modifying, replacing, or removing dams, culverts, and other barriers that restrict their migration. AOP projects may also improve passage through the installation of nature-like fishways, bypass channels, fish ladders or through stream or streamflow restoration. Regardless of the type of AOP project, designs vary depending on the obstruction, river flow, and species of fish affected, all of which should be considered for improved AOP.

2.2 Current AOP Programs and Activities

The 2021 Bipartisan Infrastructure Law (BIL) (Pub. L. No. 117-58) includes several provisions directed towards improving AOP. The BIL includes funding for different programs that seek to improve AOP. Some of these programs focus on specific species or stocks. For example, the purpose of the FHWA Culvert AOP Program is to improve the passage of anadromous fish through existing barriers, which could be culverts or weirs (49 U.S.C. 6703(b)).

Appendix B identifies some, but not all, AOP program funding opportunities that may assist in various types of AOP program goals. Although the programs and their goals in the appendix are not exhaustive, an important takeaway is that removal or partial mitigation of an AOP barrier needs to consider and develop appropriate goals for the species, waterway, and existing and projected conditions at that location.

Chapter 3. ABCs of Implementation

Infrastructure within the United States that crosses waterways with a potential for creating barriers for AOP includes transportation systems (roads, rail, transit, airports, etc.), dams (large and low head/weirs), and water supply, irrigation, and other facilities. While such infrastructure provides important benefits to our Nation, each waterway crossing may pose detrimental local or watershed scale effects to AOP, water quality, habitat, connectivity, and watershed and floodplain values.

This chapter briefly identifies and characterizes elements of this waterway-infrastructure interaction with a focus on transportation infrastructure, specifically bridges and culverts. To begin to address the problem, this chapter introduces the implementation of **A**OP at **B**ridges and **C**ulverts (ABCs).

AOP issues with bridges and culverts are widespread. The FHWA estimates that as many as 65 million bridges and culverts cross waterways (see Appendix C). While not all are barriers, the potential scale of the AOP issues is large.

The Southeast Aquatic Resources Partnership (SARP) estimates there are more than 5 million potential roadway barriers to AOP. Of the approximately 120,000 road-related barriers assessed for AOP impacts, nearly 57,000 have AOP impacts (SARP 2023). These estimates are likely underestimates, however, as many crossings have not been included in the estimates and most potential barriers have not been assessed.

Floodplain Values

Values articulate the importance humans place on something for a variety of purposes. For floodplains, the FHWA's policy is to "restore and preserve the natural and beneficial floodplain values that are adversely impacted by highway agency actions" (23 CFR 650.103(e)) and that FHWA defines "natural and beneficial flood-plain values" to include, but not be limited to fish, wildlife, plants, open space, natural beauty, scientific study, outdoor recreation, agriculture, aquaculture, forestry, natural moderation of floods, water quality maintenance, and groundwater recharge" (23 CFR 650.105(i)).

3.1 Waterway-Transportation Crossing Types

While this Guide concentrates on the roles of bridges and culverts as potential barriers for aquatic organism and wildlife passage, other transportation crossing types may represent barriers for passage, including low water crossings, weirs, and pipelines. Likewise, roadways that are parallel to waterways may also result in encroachments of the natural riparian and floodplain system. The FHWA manual "Highways in the River Environment: Roads, Rivers, and Floodplains" provides a comprehensive discussion of these broader topics (FHWA 2023).

While transportation practice designs both bridges and culverts to allow some conveyance or passage of a feature (e.g., waterway, road, gulch, canyon, trail, etc.) underneath, practitioners usually consider bridges and culverts as separate types of structures. Bridges are typically larger structures with longer spans and culverts are simpler structures having shorter spans integrated into a roadway embankment. The glossary provides detailed definitions of bridges and culverts often used by transportation practitioners.

Appendix D of this Guide and the FHWA manuals "Hydraulic Design of Highway Culverts" (FHWA 2012a) and "Design of Safe Bridges" (FHWA 2024) provide additional background on culverts and bridges.

3.2 Alignments of Waterways and Crossings

A waterway exhibits various geomorphic characteristics, such as width, depth, slope, and sinuosity, which are the cumulative effects over time of flow, geology, land use, land cover, vegetation, transport (sediment, wood, etc.), topography, bathymetry, and other elements. Figure 3 represents a waterway flowing through a landscape and illustrates that these characteristics can change as the waterway flows downstream and they can change over time in response to changes in the watershed. Human or natural changes to the waterway tend to result in other changes in the waterway. Road crossings are fixed in their dimensions and locations so considering possible changes in the waterway over time when constructing a roadway crossing better ensures that it is in harmony with the waterway.

Geomorphology

Geomorphology is the science of the form of the Earth, the general configuration of its surface, and the changes that take place due to erosion and deposition. River geomorphology focuses on the dynamic process of the river or stream shaping the channel in which it flows. It seeks to understand and predict how human changes or constraints placed on a river channel will change width, depth, slope, shape, and even location of the river through a process of sediment erosion and deposition.

Figure 3. Schematic of a waterway (flow moving south).

When roads and other transportation systems cross waterways, historic design and engineering practice sought to minimize the length of the structure span across the waterway to minimize the materials and construction costs of the structure. As shown in Figure 4, some designs resulted in a realignment of the waterway to be perpendicular to the road, neglecting the historical forces that resulted in the original waterway alignment. The waterway realignment may have resulted in changes of the waterway slope beneath the crossing structure.

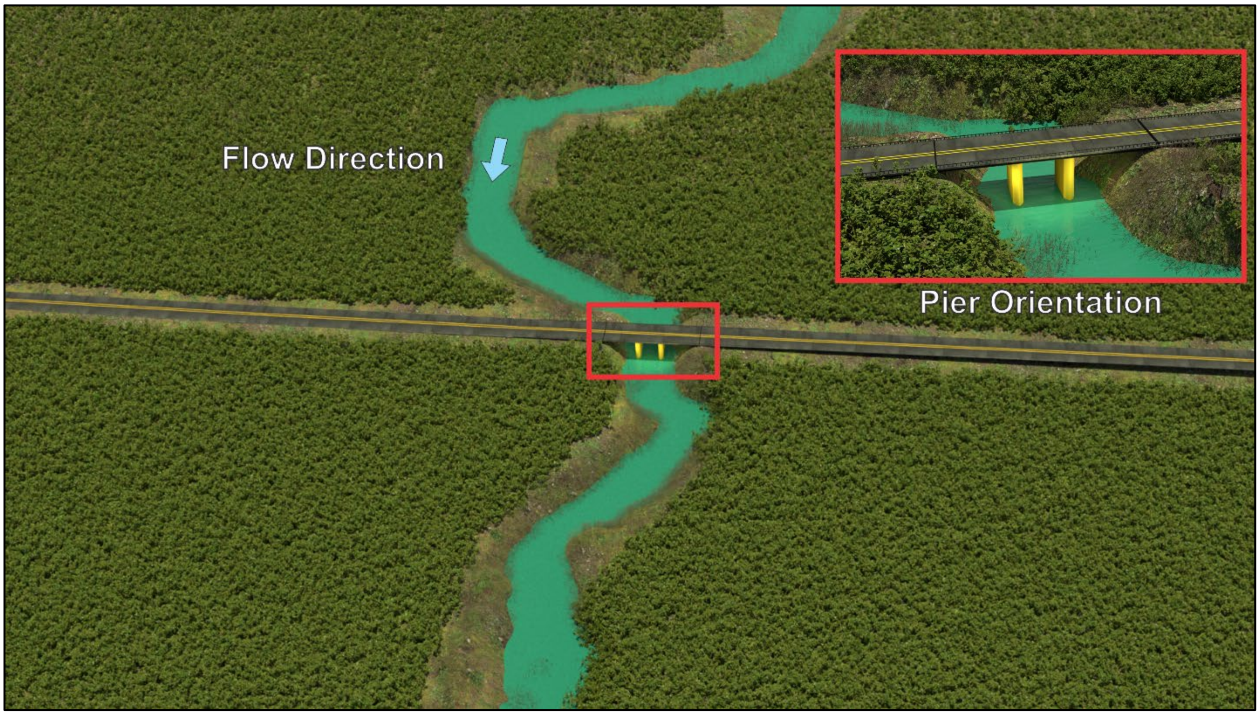

Figure 4. Waterway realigned at structure to minimize structure length.

For example, “straightening” the channel shortens the travel path of the stream resulting in a steeper slope, which in turn can result in higher velocities and forces exerted upon the stream bed, leading to erosion and scour. Narrowing natural channel widths to minimize bridge or culvert span can also create long-term problems for the bridge or culvert and for the waterway. Narrower channels confine the flow, thus increasing the velocity in the channel and, therefore, increasing the erosive power of the stream flow. Increased velocities and erosion can create potential passage barriers for fish and other aquatic organisms.

Such practices often introduce instabilities to the waterway that can move both upstream and downstream of the crossing. Undersized culverts can also create pinch points in the riparian zone (the streambank area) and adjacent floodplains. These constraints lead to a loss of floodplain and riparian connectivity. Undersized structures may reduce sediment transport through the crossing, which has the potential to degrade channels over time. Undersized structures can also lead to scour pools, velocity barriers, and flooding.

At some locations, the resulting instabilities have caused loss of habitat, introduced AOP barriers, and increased the risk of failure of the culvert or bridge. Since streams are dynamic in nature, and bridges and culverts are static, any lateral migration (movement) in the stream could result in a misaligned crossing over time. A misaligned crossing not only deters aquatic organism passage, but also reduces the intended capacity of the structure for passing flow under the road.

Better alignment practice seeks to preserve the waterway alignment by both increasing the span and skewing the structure to align with the waterway, as shown in Figure 5. While a longer span has higher capital cost, it may experience lower operations and maintenance costs and lower repair costs if the waterway shifts and damages the roadway embankment or crossing structure. A longer span may also offer additional benefits such as reducing AOP barriers.

Other design features in bridges and culverts can improve road crossing resilience to river or stream evolution while providing improved AOP. For example, the oblong piers shown in Figure 5 are aligned to minimize blockage of the flow. However, if the river shifts to a different orientation, the piers will block a larger portion of the opening. One approach to address this is to use circular piers which have less sensitivity to alignment.

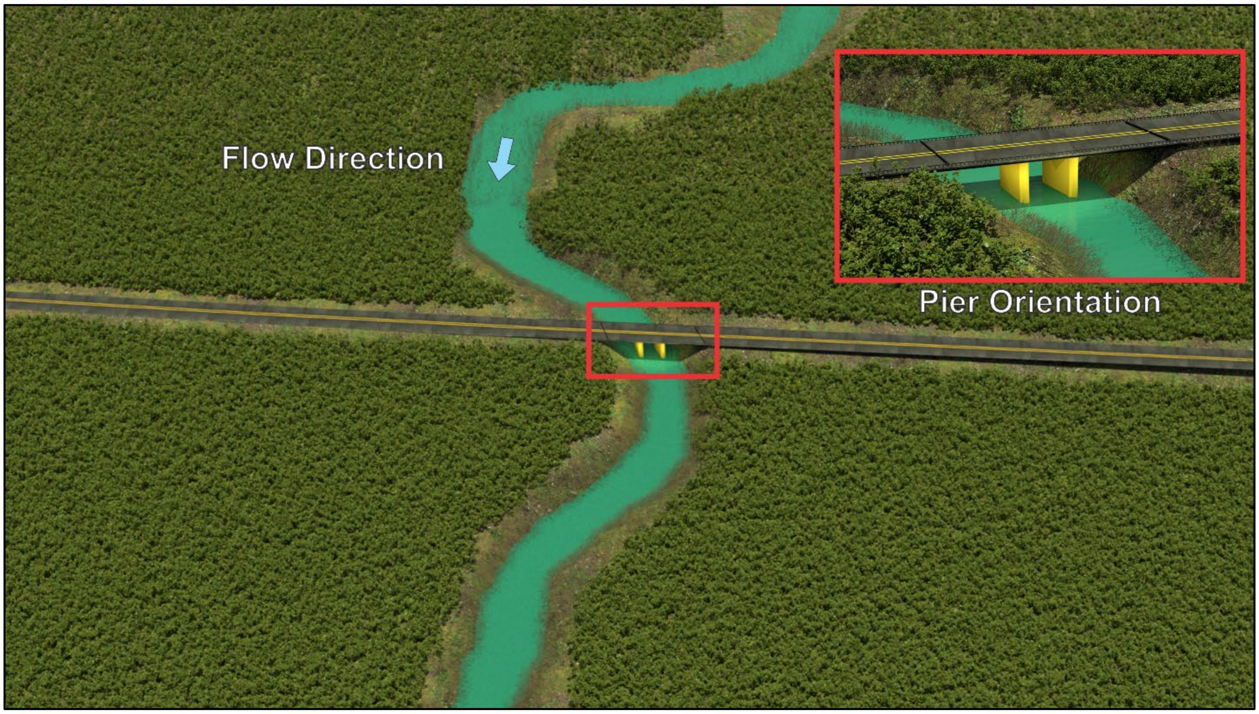

Figure 5. Extended roadway crossing structure at waterway.

Design teams should balance species and ecological needs, waterway geomorphology, projected hydrologic conditions, structure type, span length, transportation needs, and available funding. The FHWA has provided resources to inform this balancing process including "Highways in the River Environment: Roads, Rivers, and Floodplains" (FHWA 2023) and "Stream Stability at Highway Structures" (FHWA 2012c).

3.3 *Profile of Waterways and Crossings*

In addition to the horizontal alignment of waterways and crossings, the vertical alignment of the waterway (waterway profile) is an important aspect of AOP projects. If designing too steep a waterway profile, at and near the crossing, velocity in the stream or river can increase, causing erosion and potentially creating an AOP barrier. Conversely, designing too flat a waterway profile may result in sediment accumulation, with the effect of spreading out the streamflow so that it becomes too shallow for AOP, thus creating a different type of AOP barrier. Designers should determine the appropriate vertical profile at the crossing by identifying desirable conditions upstream or downstream of the crossing or in other streams with desirable conditions and mimicking those conditions at the crossing. The FHWA has provided resources on waterway profiles in "Highways in the River Environment: Roads, Rivers, and Floodplains" (FHWA 2023). The USFS stream simulation design manual, Section 5.1.3, also provides information on vertical stream profiles (FSSWG 2008).

3.4 Sizing of AOP Projects

Achieving the goals of AOP through a roadway crossing of a waterway requires the designer to properly size the culvert, bridge, or other structure. Part of the challenge in doing this is that sites vary throughout the country, from watershed to watershed, and even within a particular stream system. The planning and design team should understand natural processes (geomorphology, hydrology, hydraulics, ecology, biology) and balance restoring natural processes with cost and risk. The AOP planning and design team should include interdisciplinary participation so that important aspects of the site, aquatic organisms, and design goals are not overlooked or inappropriately treated. Chapter 5 provides a description of disciplines often needed for successful AOP projects.

Given the diverse behavior and capabilities of fish and other aquatic organisms, design procedures will generally rely on surrogate parameters and indicators as measures for successful passage design rather than attempting to assess the passage of individual species. Many of the existing AOP design procedures rely on dimensional characteristics of the stream such as bankfull width. Bankfull width is the width of flowing water in a stream when the water surface is flowing within the banks just before it spills out into the floodplain.

Many procedures use bankfull width to drive AOP crossing width because the bankfull channel geometry for dynamically stable streams and rivers is a result of natural geologic and hydrologic conditions at a project site. Spanning at least the bankfull width for an AOP project helps establish a channel geometry in harmony with the natural physical forces that shape streams.

The U.S. Forest Service (USFS) and others have promoted “stream simulation” approaches (FSSWG 2008). The USFS stream simulation design method is to construct a channel through a bridge or culvert that mimics the structure and function of the stable natural channel outside of the influence of the road. A guiding principle is that creating conditions within the crossing similar to those identified in reference channels where passage occurs will promote favorable AOP conditions through the crossing. The approach applies criteria based upon the natural geomorphic characteristics (e.g., bankfull channel geometry) of streams supporting the aquatic ecosystems of interest. Limitations of this approach exist for streams with channel geometry that are evolving and not dynamically stable. More information on the USFS stream simulation approach is found in the USFS design manual (FSSWG 2008).

A challenge with bankfull width and other dimensional stream characterization approaches (frequently referred to as “geomorphic” approaches) is that the dimensional characteristic can be difficult to identify in the field and can be variable within a stream reach. In streams that are not in dynamic equilibrium (i.e., the stream has consistent geometry over time with erosion and deposition approximately in balance), the bankfull concept may not apply because the stream is evolving its geometry. The FHWA provides additional information on the significance of - and methods for - identifying bankfull characteristics (FHWA 2023).

Other design methods attempt to improve ecosystem connectivity of a reach by spanning the entire floodplain. A planning and design team may consider such an approach when one or more of the following conditions occur:

- The stream is shifting rapidly across a wide valley flat.
- There are many side channels used by juvenile fish or other aquatic species.
- The valley flat is a migration corridor for large mammals and traffic is high on the road.
- The full range of riparian habitat diversity serves as critical habitat.

In sum, the drivers for this approach are increasing ecosystem function in the stream and floodplains and improving connectivity for aquatic and terrestrial species. However, spanning the floodplain can be expensive.

3.5 AOP in New Construction versus Retrofits

The most effective solution for improving AOP is often replacement of the existing structure with a new structure designed following appropriate AOP design methods. However, the potential number of barriers at bridges and culverts in the Nation's existing transportation infrastructure is significant, as described in Appendix C. In some cases, requiring a less costly retrofit rather than a replacement may partially or fully mitigate an AOP barrier at lower cost and in less time than a replacement. However, retrofitting existing waterway crossings involves challenges associated with:

- Limits on adjusting horizontal and vertical roadway alignments at a site.
- The footprint and timing of corrective instream work
- Potential reduction of hydraulic capacity.
- Shorter design life for some retrofits.
- Meeting State and Federal fish passage criteria.
- Financial resources available for retrofit.

In addition, prioritizing crossings is a challenge that is addressed in more detail in Chapter 4. Retrofitting crossing structures often considers improvement in AOP as an acceptable interim goal when full AOP is infeasible or prohibitively expensive. Culvert retrofits could include installation of interior baffles, repair of damaged culverts, and modification of the outlet condition to better transition to the downstream channel.

Providing AOP at new crossings also has constraints and challenges, but new construction can integrate AOP into the larger roadway, culvert, or bridge project from planning through construction to manage these constraints and challenges more flexibly. New construction also allows consideration of more design options to provide for full or at least improved AOP. Transportation agencies continue to build new roads and other transportation networks. However, the numbers of new crossings are relatively small compared to the number of existing crossings that pose AOP barriers.

Chapter 4. Project Prioritization

The previous chapter described the potential magnitude of the waterway-transportation AOP barrier challenge. Because the limited resources to address these challenges, it is important for transportation agencies to prioritize potential projects to maximize AOP benefits. This chapter seeks to provide some insights and approaches to addressing project prioritization.

To maximize the benefits of investments in improving AOP, planners, designers, and others should seek to identify those projects that provide, for each dollar of investment, the greatest improvements in passage (e.g., the greatest benefits to the highest priority fisheries) along with co-benefits. AOP planners and designers typically identify high priority projects by using an appropriate prioritization approach. The prioritization approach captures the anticipated and desirable outcomes of a project and provides protocols for assessing the achievement of those outcomes post-project (e.g., monitoring).

Co-benefits

A co-benefit is a benefit derived from a given action or strategy that is in addition to the primary objectives of the action. Therefore, what is a benefit versus a co-benefit depends on the objectives of an action.

For example, the objective of an AOP project might be to increase the extent of fish habitat by enlarging a culvert. That action might also reduce culvert repairs and maintenance by reducing clogging. Maintenance personnel might consider the former a co-benefit and the latter a benefit. Conversely, a fisheries biologist might consider the former the benefit and the latter a co-benefit.

The following sections discuss examples of AOP project prioritization approaches and criteria. While prioritization approaches can vary from program to program or agency to agency, many project prioritization approaches use variations of five general criteria:

1. Clear goals.
2. Ecosystem benefits.
3. Community benefits.
4. Sustainability and resilience.
5. Feasibility of project implementation.

4.1 Clear Goals

Early consideration of an AOP project should identify clear goals, key project elements, and realistic preliminary costs. For example, AOP project goals could include reconnecting a certain number of miles of stream for a specific species of fish or maximizing the stream miles of habitat restoration for a given budget. Goal setting is likely the most important activity but may be the most difficult on which to reach consensus and clearly articulate. If insufficient attention is paid in the early phases, the project could be ill-conceived, underfunded, or both, resulting in limited or no improvements for AOP.

Establishment of project goals, identification of key project elements, and estimating preliminary development and construction costs is important to develop the project to a sufficient level of conceptual design so that these elements are in harmony and consistent with the ability of the project sponsor to carry the project through construction.

4.2 Ecosystem Benefits

The ecosystem benefits criterion focuses on wildlife passage and habitat improvements (fish species and stocks affected by barriers, other aquatic organisms, and terrestrial species). For AOP projects, this is typically the highest priority criterion. Bozek (2022) describes ecosystem benefits as the ecological importance of a project to the natural world. These benefits can include:

- Increases in aquatic species population size and health, including priority species. This may be focused on a particular target species of fish or could refer to fish or other aquatic species more generally.
- Expansion of aquatic habitat extent, diversity, connectivity, and quality.
- Improvements in water quality, sediment transport, and wood transport that contribute to a functioning river system and, in turn, influence habitat (FHWA 2023).
- Improvements in wildlife connectivity beyond AOP.

Transportation agencies should be aware that some AOP programs may have a mandated prioritization approach. For example, the FHWA's Culvert AOP Program is statutorily required to focus on anadromous fish species (49 U.S.C. 6703(b)).

4.2.1 Aquatic Species Population Size and Health

Specific species may be targeted for AOP improvement for many reasons. In some cases, they may be federally, or State protected or at-risk species, important to fisheries, or they may be an important resource (e.g., food) for other federally or State protected species. In addition, these species may be regionally, or watershed-wide targeted species identified in recovery, management, or State wildlife action plans. Species may also be culturally important to Tribes and other groups and important for sustenance.

Information about fish species in an area may be available through Federal or State fish and wildlife agencies and web resources. Quantifying existing and projected species populations is important for building support for an AOP project. Such data can also inform measures for prioritizing projects or assessing the success of a project.

4.2.2 Aquatic Habitat Extent, Connectivity, and Quality

Although habitat and fish populations are linked, habitat can be separately considered and quantified. Restoring habitat or expanding habitat access can benefit multiple aquatic organisms regardless of whether an AOP project has a focus on a particular species. Restoring access to habitat via barrier removal is a benefit to migratory fish because it can increase the accessible length of spawning, rearing, and migratory habitats and improve the quality of accessible habitat. Restoring access is also beneficial to non-migratory fish, allowing populations to expand into currently unoccupied areas and improving gene flow.

Removal of limiting factors for watershed productivity, such as access to overwintering areas (where organisms wait out the winter season) or spawning gravels (coarse sediments where salmonids lay their eggs) is also a benefit. Local and regional watershed and recovery plans, where they exist, often identify limiting factors.

As with species populations, quantifying existing and projected habitat, such as in stream miles, may build support for an AOP project and informs measures for assessing positive effects of a project. Quantification might be through direct field measurements, estimates from maps or lidar, suitability indices, or intrinsic potential models. Keys for evaluating habitat include ecological connectivity and biodiversity.

4.2.3 Water Quality, Sediment Transport and Wood Transport

In addition to transporting water, streams and rivers transport sediment and wood through a watershed. Sediment and large wood create complex stream channels and micro-habitats on which many species and life-stages rely for survival and support physical, chemical, and biological processes that sustain river and floodplain ecosystems. If sediment or wood transport get out of balance they can create passage barriers, jeopardize crossing structures, deteriorate habitat, cause channel erosion, or disrupt riparian vegetation.

Active sediment transport creates features such as pools, bars, riffles, and steps; provides a substrate for aquatic invertebrates, biofilm and plants; and provides a spawning medium for many fish species. Sediment often builds up or aggrades upstream of undersized crossings and dams and leaves the downstream area sediment starved, which causes the channel to erode into the surrounding landscape, leading to bank instability.

Large wood provides additional channel complexity by both helping retain sediment in channels and by creating complex three-dimensional structures that provide habitat for fish and invertebrates. Though not present in all rivers and streams, large wood is critical to habitat in areas where it exists.

Imbalances in sediment and wood transport can, in turn, also affect plant growth and successional processes, movement of nutrients, and water temperature. Higher water temperatures and lower dissolved oxygen can occur in scour pools. Scour and erosion of wetlands or riparian vegetation can reduce the ability to process nutrients. Impaired water quality may not support the most sensitive aquatic organisms that are part of the aquatic food web, endangering other species.

4.2.4 Terrestrial Wildlife Connectivity

Another aspect of ecosystem benefits that may be considered are those regarding terrestrial species. Many wildlife species utilize stream and river corridors for movement, shelter, food, and other needs. Some considerations for improving wildlife connectivity include:

- The species utilizing the area.
- The number, location, and configuration of crossing structures in the floodplain.
- Openness and light penetration.
- Dry shelves within culverts.
- Flat pathways free of rock for animal movement.
- Wildlife fencing to direct animals to crossings.

Considering wildlife needs can improve safety at crossings for both wildlife and the traveling public.

4.2.5 Watershed Approach

Ecosystem benefits cannot be effectively evaluated solely at a project site. Since issues of connectivity are intrinsic to the number, health, and habitat of aquatic species, an AOP project and its ecosystem benefits should be considered within a regional or watershed context. Some project locations may fall within the scope of a regional or watershed plan or prioritization established by a Federal, State, local, or Tribal fish and wildlife agency or a non-governmental organization. The role of an AOP project in achieving the goals of such plans can inform the benefits of the project.

If there is no applicable plan or prioritization, considering the project within a larger watershed context can still inform the benefits of that project. If feasible, it will be advantageous to develop an overall regional or watershed prioritization for AOP barrier mitigation. Limitations in achieving benefits of improved passage at one location can sometimes be attributed to the lack of improvement at other locations. For example, a downstream barrier may stymie the success of an upstream AOP project. Conversely, coordinated AOP improvements at other locations within the watershed can amplify the benefits at a specific project location.

Regional and Watershed Plans

Many locations, especially in the Pacific Northwest, have "recovery plans" that focus on improving AOP on a wider geographical scale and on a coordinated basis.

Other watersheds or regions may have other types of watershed plans with a focus or component based on AOP. These can be useful for identifying priority projects.

Plans may not exist in all watersheds, especially those in rural or underserved communities.

Such a watershed scale analysis can also reveal the effects that barrier modification or removal, such as channel adjustment, can have on the stream and other crossings upstream and downstream of a given crossing. A watershed approach may also provide a forum for multiple stakeholders to coordinate. For these reasons, the watershed approach provides opportunities to combine multiple AOP projects where there are many barriers. This may offer economies of scale that may help reduce traffic delays, road closures, impacts to the public, and construction costs while opening more habitat in a watershed. A watershed approach can also be integrated into an overall water crossing asset management strategy, such as prioritizing work at water crossings that are failing structurally. Some prioritization tools are available at https://streamcontinuity.org/.

4.3 Community Benefits

Community importance addresses the value of an AOP project to the people that live in the watershed or pass through it. At the nexus of the AOP project, the community uses the transportation network, benefits from a healthy, functioning river ecosystem, and usually does both.

4.3.1 Public Safety Improvements

Public safety is of primary importance in the design, operation, and maintenance of the transportation infrastructure. AOP projects should preserve or improve public safety by maintaining emergency access during floods, reducing potential damages from flood events, reducing vehicle collisions with wildlife, and removing hazardous crossing designs.

4.3.2 Infrastructure Improvements

Improvements for AOP may also result in improvements to roadways, culverts, and bridges. Increasing opening dimensions, for example, can reduce clogging and erosive conditions that require maintenance and repair of the structure. AOP projects can also address longstanding maintenance needs. For example, a culvert may be on a list for future maintenance for repair or replacement because of hydraulic or structural deficiencies. A comprehensive review of hydraulic, structural, AOP, water quality, terrestrial passage, and other potential infrastructure deficiencies can inform prioritization of AOP projects and may provide efficiencies for addressing other infrastructure needs.

4.3.3 Restoration or Improvement of Cultural Practices

Native American communities are often directly affected by AOP barriers and the projects that remove them. Terrestrial and aquatic wildlife, as well as the land upon which people and wildlife live, may have religious and cultural significance for Tribes. Additionally, the Federal government may have trust and treaty responsibilities to Tribes concerning AOP projects.

This criterion considers the extent to which a project restores or improves cultural practices:

- Benefits to aquatic species that are culturally important to Tribes.
- Enhancements to the physical sustenance of, or economic benefits to Tribes.

Indian Tribes and other Native American communities may choose to lead, co-manage, or otherwise participate in AOP projects. In all cases, successful engagement should be respectful of Tribal sovereignty and seek full understanding of the religious and cultural significance of places and lands affected by AOP projects. Tribal engagement can also result in the watershed wide identification and improvement of AOP barriers, whether on Tribal lands or affecting Tribal interests.

4.3.4 Enhanced Recreational and Health Benefits

AOP project prioritization can also emphasize recreational and health benefits. When successful, AOP barrier removal can result in many community benefits such as improved water quality for water supply or expanded habitat for recreational or subsistence fishing.

4.3.5 Support of Underserved Communities/Equity

Equity can be considered as a component of the importance of a project to the community. Underserved and economically disadvantaged communities can be overlooked with respect to the community benefits mentioned previously: public safety improvements, infrastructure improvements, restoration or improvement of cultural practices, and enhanced recreational and health benefits. This criterion also considers the extent to which a project supports underserved or economically disadvantaged communities:

- Benefits to aquatic species that are important to underserved communities.
- Enhancements to the physical sustenance of, or economic benefits to, underserved communities.
- Employment opportunities for underserved communities.

4.4 Sustainability and Resilience

Sustainability represents the ability of a project to continue providing the benefits for which it was designed throughout its service life or, in some cases, indefinitely. Resilience expresses the ability of a project to resist or recover from damages caused by stressors such as extreme weather events or climate change. Sustainability and resilience are linked together and a prioritization criterion that expresses these concepts may include a project’s ability to:

- Adapt to changes over time resulting from natural variability in hydrologic and watershed processes, potential changes in the watershed, and potential changes in climate.
- Be resilient when it experiences extreme weather events such that it maintains its function or can be expeditiously restored to its function.
- Support ecological resilience for species and ecosystems that may be vulnerable to climate change or extreme weather events.

Sustainability and resilience capture the quality of the project and its ability to continue to deliver the transportation, ecological, and community benefits over the anticipated project lifetime. Sustainability also means being resilient if circumstances change, e.g., climate conditions or changes in the watershed. Use of design standards and guidelines that effectively address AOP, natural river functions, transportation, and public safety contribute to a sustainable project.

Sustainability is also affected by the water crossing condition. If a water crossing deteriorates, it may cease to serve numerous functions including facilitation of AOP.

4.5 Feasibility of Project Implementation

The final category of project prioritization criteria relates to the planning, design, construction, and post-construction aspects of a project. Regardless of the goals, projected ecosystem benefits, project community benefits, and sustainability, if the project cannot be successfully implemented, the other criteria remain theoretical. The following elements are important for identifying feasible AOP projects.

4.5.1 Project Design and Delivery Methods

This criterion assesses whether a project is sufficiently developed to increase its likelihood of success. Relevant factors include:

- Clearly describing the AOP barrier and the condition of the habitat upstream and downstream of the barrier.
- Applying appropriate and technically sound biological, geomorphic, and engineering methodologies, including design standards applicable to fish passage, consistent with applicable fish passage guidance. (See Appendix A for resources.)
- Identifying maintenance responsibilities and demonstrating that the project will perform satisfactorily over its anticipated service-life, while accounting for unique exposures to future climate conditions such as those identified in NMFS Risk Pathway Tables for culverts (NMFS 2023e).
- Obtaining right-of-way or easement approvals.
- Obtaining permitting approvals by regulatory agencies
- Leveraging early coordination and existing procedures, where applicable.

These factors capture project feasibility and proponent capacity to successfully implement the AOP project. Most directly, feasibility addresses whether the project proponent possesses the logistical capability and readiness to identify, evaluate, design, permit, acquire right-of-way, and construct an AOP project (see Chapter 5 for more detail on the project delivery steps). These activities do not need to be undertaken in-house, but the proponent needs to acquire, coordinate, and manage the needed resources and skills.

Feasibility also captures landowner willingness to participate in the AOP project (if the landowner and project proponent are different entities). Project proponents do not have to own the land or possess the right-of-way needed to implement the project at project conception but should provide a plan for how they propose to address these critical elements because access through ownership or easements is important for implementation and maintenance of successful AOP projects.

4.5.2 Including Appropriate Personnel

Every project is different and may require knowledge and experience from an interdisciplinary team to anticipate the needs of each project. Lessons learned from successful AOP projects can inform the types of knowledge and expertise needed at a specific project or location. The type of knowledge and expertise also depends on the simplicity or complexity of the site as well as the goals for the project. Interdisciplinary teams may include, but are not restricted to, the following areas of expertise:

- Aquatic wildlife biology (e.g., fisheries biology) and ecology to identify aquatic wildlife passage needs.
- Terrestrial wildlife biology and ecology to identify terrestrial wildlife connectivity needs.
- Fluvial geomorphology to understand the watershed processes that the design must accommodate and the fluvial processes, anticipated future adjustments in the channel, and channel features upstream, downstream, and at the project site.
- Engineering (hydrology, hydraulics, structural, and geotechnical) to apply design criteria and standards for safety, scour, etc., to design fixed structures and other physical elements such as rock and wood, that will be constructible and withstand the anticipated environment to ensure a sustainable project.
- Environmental and permitting to identify agencies involved and navigate the regulatory paths for regulatory approvals and consultation.
- Tribal interests to seek Tribal involvement, particularly for incorporating traditional ecological knowledge, and considering religious and cultural importance of aquatic and terrestrial wildlife passage.

Individual professionals may have expertise in one or more of these disciplines. The size of an interdisciplinary team depends on individual skills, the characteristics and complexity of the project site, and objectives of the AOP project. Chapter 5 provides more information on interdisciplinary teams.

4.5.3 Stakeholder Collaboration

Federal agencies, Tribes, State governments, local governments, nonprofits, and private landowners often have a stake in the permitting, configuration, or funding (in-kind or monetary) of AOP projects. Early planning informs potential stakeholders regarding the nature of the AOP project including identification of potential funding sources and co-benefits. The needed level of detail also depends on whether the project is similar to others or is unique in important ways. Stakeholders can also assist in identifying and coordinating the improvement of nearby barriers owned by public and private entities to partner on correcting multiple barriers at the same time.

4.5.4 Project Monitoring and Evaluation

This criterion evaluates the plan to assess effectiveness of the implemented project including:

- Clear goals and objectives for monitoring and evaluation.
- Identification of data collection and monitoring needs or requirements for pre-project or post-project implementation (or both).

Storing and maintenance of data and sharing of results are important for the sustainability of a project and for incorporation of lessons learned in new projects. This information may be included within asset management systems or regional AOP databases. Chapter 5 provides more information on AOP monitoring protocols and data.

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Chapter 5. Elements of AOP Projects

The delivery of AOP projects involves a variety of processes and requires a high level of coordination among all interested parties. Project sponsors and asset owners play a significant role in the implementation of the project delivery process for AOP projects from inception through monitoring. Responsibilities of the owner include but are not limited to asset management; prioritization; scoping, including estimating costs; ensuring the fulfillment of environmental and Federal requirements; obtaining adequate financing; design; construction; and the overall management of the various disciplines and parties involved in bringing the project to a successful completion. After construction, a robust monitoring and adaptive management program should be administered to assess the AOP effectiveness and make any necessary corrections over time. As with any asset, operations, and maintenance over the design life of the AOP project may ensure project goals and objectives are met.

Figure 6 provides an example of the different elements needed for a successful AOP program, which includes planning, project delivery, and monitoring and adaptive management. Elements may have various activities as sub elements.

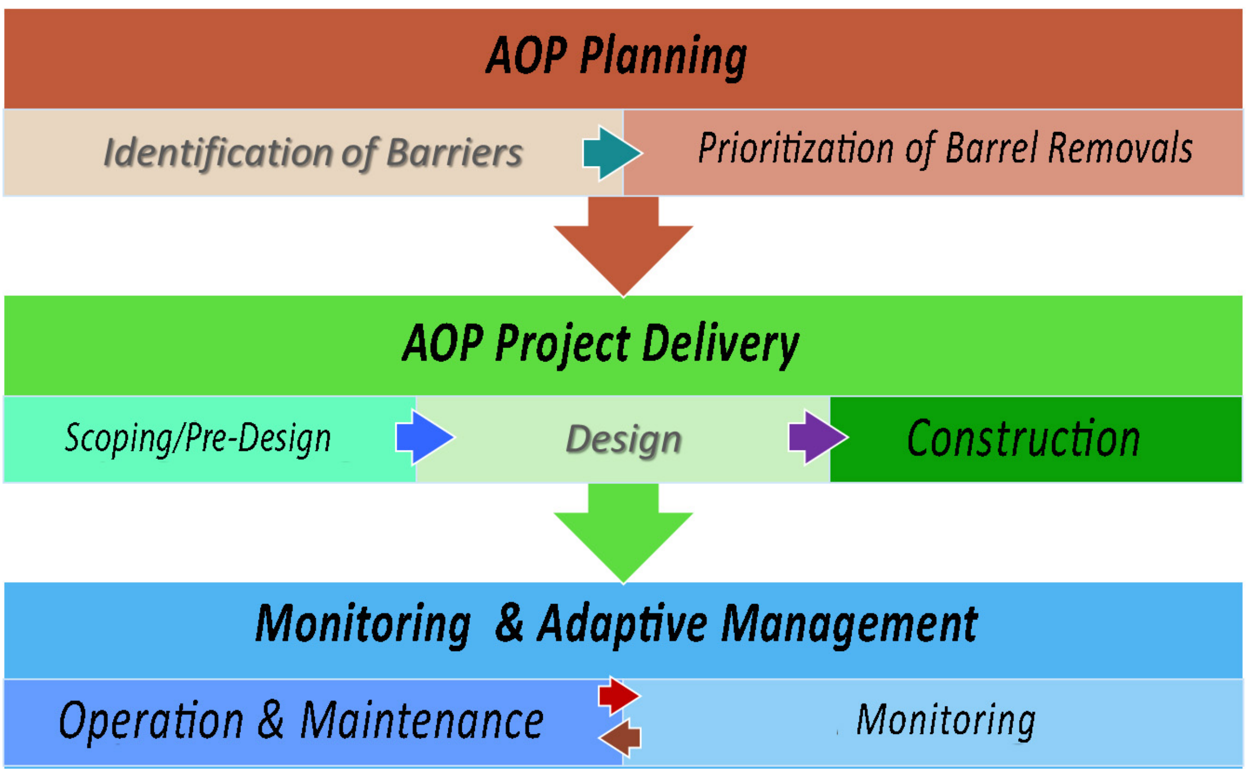

Figure 6. Example AOP program elements.

As described throughout this Guide, different entities and agencies may use different nomenclature or groupings of these elements (or sub elements). Additionally, some entities or agencies may seek to focus on just one element (or sub element). For example, one entity or agency may focus on AOP planning where another may focus on AOP project delivery or applying AOP monitoring.

This chapter discusses each of the AOP program elements in Figure 6. After describing these program elements, this chapter also provides informational materials on the important roles that an interdisciplinary team serves on AOP projects and programs.

5.1 AOP Planning

Planning is a critical first step in development of an AOP program (Figure 6) for identifying barriers to AOP and prioritizing projects for barrier removal in a strategic manner. In addition to AOP, a comprehensive review of hydraulic, structural, water quality, terrestrial passage, and other potential infrastructure deficiencies can inform prioritization of AOP projects and may provide efficiencies for addressing other infrastructure needs.

5.1.1 Identification of Barriers to AOP

Planning efforts should identify and assess AOP barriers to ensure aquatic organisms are able to benefit from accessing habitat and that replacement of a barrier will not create new barriers upstream or downstream. Another important planning consideration is that not all streams are fish bearing; however, such streams may still provide habitat for other aquatic species (e.g., salamanders and freshwater invertebrates such as insects, crustaceans, mollusks, mites, nematodes, and rotifers). While many barrier assessments focus on identification of barrier for a specific species or genera of fish, they may not capture all aquatic organisms present in that habitat. For example, some barrier assessments may be focused on salmonids which may not be useful for other species such as lamprey. There are also various types of barrier assessments, including visual, modeled, and rapid assessments. The type of assessment and species of interest should be reviewed in collaboration with resource agencies during planning to ensure they align with AOP goals.

To assist in prioritizing fish passage barrier removals, the first step should be to determine all barriers within the watershed or at a minimum, a reach scale. There are various examples around the United States for AOP barrier databases; the focus of many being barriers to fish passage. For example, the Stream Continuity Portal which is maintained by the North Atlantic Aquatic Connectivity Collaborative (NAACC), provides a location for various tools and regional collaboratives focused on aquatic organism passage and fragmentation of river and stream ecosystems. One of the regional collaboratives, the Southeast Aquatic Resources Partnership (SARP) is a collaboration of natural resource and science agencies, conservation organizations, and private interests developed to strengthen the management and conservation of aquatic resources in the southeastern United States. The SARP operates the National Aquatic Barrier Inventory and Prioritization Tool. SARP's inventory is available for multiple regions throughout the United States. The SARP intends to expand the inventory to a national scope by 2026. Several States have fish passage barrier databases to identify and document various attributes of fish passage barriers. Notable agencies include, but are not limited to: the Alaska Department of Fish and Game, the California Department of Fish and Wildlife, the Maine Department of Inland Fisheries and Wildlife, the Massachusetts Division of Marine Fisheries MassMapper, the Washington State Department of Fish and Wildlife, the Oregon Department of Fish and Wildlife, and the State of Utah Department of Natural Resources. A useful approach for a potential AOP project would be to review existing inventories and coordinate with local resource agencies during planning to obtain the best available data on potential barriers to AOP.

Key attributes that may be part of a AOP barrier assessment include, but are not limited to:

- Various types of species to which the barrier assessment is applicable.
- Barrier geographic coordinates.
- Road name and milepost.
- Stream or river on which a barrier is located.
- Tidal or non-tidal system.
- Owner.
- Assessment date.
- Who conducted the assessment.
- Type of barrier (e.g., culvert, fishway, weir, diversion, natural barrier, etc.).
- Type of assessment (e.g., visual, modeled rapid, etc.).
- Reason for barrier (e.g., slope, velocity, drop height, etc.).
- Passability compared with upstream and downstream reaches.
- Structure condition.
- Potential habitat gain (e.g., length or area of habitat gain).
- Quality of habitat gain.

In addition, these AOP barrier assessments can be combined with other types of assessments (e.g., terrestrial passage, structure condition, etc.) to develop more comprehensive scopes.

5.1.2 Prioritization of AOP Barrier Removals

Prioritization of fish passage barrier removals is important to achieve effective AOP crossings and maximize benefits of restoring natural processes and AOP. After AOP barriers have been determined, prioritization of replacements can be performed in a strategic manner. Chapter 4 describes a prioritization process to assist in project prioritization. In addition to barrier assessments, other types of assessments (e.g., terrestrial passage, structure condition, etc.) may be beneficial for determining a project scope.

5.2 AOP Project Delivery

Project delivery for AOP projects should involve an interdisciplinary team from scoping through construction. Early and regular coordination with resource agencies and other interested parties can assist in providing efficiencies during the delivery of an AOP project.

5.2.1 Scoping and Pre-Design

After AOP planning, successful implementation of a selected AOP project starts at scoping and involves an interdisciplinary team (Section 5.4). Having all key disciplines and interested parties (e.g., resource agencies) involved at the scoping level is critical to environmental and fiscal stewardship. Scoping also informs potential interested parties regarding the nature of the AOP project including identification of potential funding sources and project bundling opportunities. In addition, the scoping or pre-design phase should investigate right-of-way and any need for easements (Section 5.4.11). For Federally funded projects, project sponsors need to comply with the National Environmental Policy Act (NEPA) (42 U.S.C. 4321 *et seq.*) before beginning construction.

Scoping identifies the goals and objectives; key elements; preliminary engineering; and construction costs for an AOP project. The scoping process generally includes pre-design activities and attention by an interdisciplinary team. Pre-design typically requires making more funds available at the beginning stages of the project. However, such an approach often can save costs over the entire project delivery process by identifying, early in the process, critical elements that may drive costs and impact the project schedule.

Scoping and pre-design should involve attaining pertinent information from an interdisciplinary team (Section 5.4), which sets the stage for designing and constructing a sustainable AOP project. Scoping and pre-design is not intended to fully design AOP projects, but rather to set the stage for success as a project moves through design and construction. The FHWA Central Federal Lands Highway Division's (CFLHD) website has an example of a scoping report template. Within that template, as part of scoping and pre-design, CFLHD requires (1) development of a hydraulics pre-design memo and (2) providing this memo to interested parties to show how the proposed project will meet project goals. These goals are often project specific given the differences in watershed characteristics, site geometrics, species of interest, and potential risks to property and the traveling public. Other agencies and organizations have similar templates and checklists. As an example, the Massachusetts Department of Fish and Wildlife, Division of Ecological Restoration website has a sample scope of work for site assessment for culvert replacement projects. Appendix E provides an example pre-design checklist that includes deliverables and documents for various disciplines that may be part of pre-design activities.

5.2.2 Design

The design of an AOP project should start with the documentation and assessments performed during scoping and pre-design. The design team should assess the validity of the assessments performed during scoping and pre-design and determine what additional information is needed to support the basis of design. As with scoping, the design team should be interdisciplinary, ideally consisting of a team comprised of the disciplines referenced in section 5.4. Early coordination with resource agencies is an important step in the design process.

The project delivery process should include milestones that may vary with the type of project. They could, at a minimum, include conceptual, intermediate, and final milestones. At each of the identified project design milestones, key deliverables and disciplines should be defined with roles, responsibilities, and relationships between the interdisciplinary team. For example, a structure span needs deliverables from roadway, survey, geotechnical, hydraulics, environmental, utilities, etc. However, since each project may have unique characteristics, the needed disciplines, milestones, and deliverables should vary to suit the needs of a successful project.

Given the diverse range of aquatic organisms and hydrologic and geomorphic conditions that exist nationwide, it is not feasible to recommend any one method or procedure for AOP design. Appendix A provides several available technical resources from around the United States. Likewise, the case studies in this Guide offer other information that demonstrates the various design standards being used across the country.

As with most hydraulic and river engineering applications, each site is different and requires a holistic understanding of the system to design sustainable and resilient infrastructure. For these reasons, following one standard approach for all projects typically leads to maintenance issues over the design life of the water crossing. Successful AOP design should accommodate anticipated natural and human-induced channel adjustments. Ultimately, what will define successful AOP design practices will involve many factors, including geographic location, local hydrologic, geomorphic, and hydraulic conditions, species of interest, adjacent infrastructure, and regulatory guidelines. Any project needs to balance all such factors with costs and level of risk the owner is willing to accept.

5.2.3 Construction

Construction should start with a comprehensive set of design plans, specifications, and estimates (PS&E). Constructability reviews should be held at critical milestones with the interdisciplinary design team throughout the project delivery process (e.g., conceptual, intermediate, and final design) with individuals familiar with construction management and inspecting AOP project elements. When awarding a construction contract, there should be a meeting with the interdisciplinary design team to answer any questions pertaining to the design from the contractor and construction inspectors. A preferred practice makes staff from the design team available for inspection of AOP-specific project design elements during construction (e.g., stream bypass design, streambed material gradation, large woody material, and other habitat elements).

An example of a common problem during and after construction consists of streamflow going subsurface into the streambed fill which results in potential fish stranding in the channel. A solution for reducing this situation involves using the correct streambed gradations and ensuring fine sediment fills the voids of the placed material. A common technique to assist ensuring fine sediment fills the voids is by constructing the streambed in lifts and watering in the fines (i.e., applying water and fine sediment on top of the streambed to facilitate filling the interstitial voids of the placed streambed fill) while constructing the streambed (Figure 7). However, as each project site differs, these types of situations are where the interdisciplinary team (that includes geotechnical engineers and geomorphologists) can aid in providing an appropriate resolution.

Figure 7. Construction of streambed and watering in fine sediments (SR 202 Tokul Creek, Washington). Photo by Casey Kramer.

5.3 AOP Monitoring and Adaptive Management

After project delivery, a robust monitoring and adaptive management program can be implemented to assess whether the project has achieved planned AOP benefits and provide lessons learned for future AOP projects. A project can use the findings from monitoring protocols described in Section 5.3.1 to identify and prioritize where adaptive management may require a project owner to perform repairs. The evolution of AOP project delivery processes increasingly seek to capture these advantages. Additionally, after storm events, it may be beneficial to assess the condition of AOP projects to assess erosion and scour and to gauge whether AOP-specific features require maintenance. Monitoring and adaptive management not only can facilitate identification of these project specific maintenance needs, but also can enable potential improvements to the project delivery process.

5.3.1 Monitoring

An often-overlooked activity, monitoring is an important component for AOP water crossings to function in a successful manner not just immediately after construction, but over their service life. Monitoring not only provides the owner and other interested parties an understanding of the effectiveness of the AOP water crossings over time, but also provides a key feedback loop into the design and construction process to potentially improve the entire process based on lessons learned from projects over time.

5.3.1.1 Monitoring Timing and Scope

Historically, monitoring begins after the construction of the AOP project. However, the practice of monitoring is evolving and expanding to cover other periods. Many recent, successful AOP projects have begun to implement monitoring, or collection of similar data, as part of the project scoping/pre-design activity. For several Federal agencies, such pre- and post-monitoring is becoming a consensus approach for implementation of AOP projects.

Another manifestation of evolving monitoring practices involves what information monitoring personnel collect. Historical monitoring practice saves construction infrastructure “as-builts” (see glossary) or collects infrastructure condition information during bridge inspections. This practice may address the structural and roadway asset components of a project. However, such practice typically does not address the primary objectives and components of an AOP project. This can make it difficult to know whether changes have occurred as a result of activities encountered during construction (e.g., different soil conditions than represented in the plans) or resulting from the channel adjusting from natural processes (or both). In addition to traditional as-built practices, monitoring for AOP projects could include additional supplemental information, such as collecting geomorphic and habitat conditions, other pertinent field data or conducting biological assessments over time. When finding a deficiency in AOP during the monitoring, the project owner or regulatory agency can implement an adaptive management plan which may require maintenance activities to mitigate the identified deficiency.

5.3.1.2 Monitoring Example: aopMAP

There are various monitoring protocols available around the United States. As an example of an agency approach to facilitate success in their AOP projects for various Tribal and land management agencies, the FHWA has developed a standardized AOP monitoring protocol and an accompanying mobile application called “aopMAP.” The aopMAP application allows the user to collect data with a mobile device (e.g., tablet or mobile phone). The FHWA monitoring protocol can work on all the common AOP design methods across all geomorphic channel types ranging from high mountain streams to low-lying wetland areas. As with AOP design, the protocol recommends use by an interdisciplinary team consisting of a geomorphologist, hydraulic engineer, and a biologist. However, the protocol and associated training (FHWA 2022b) has been developed such that it can be used by other disciplines (e.g., maintenance personnel, bridge inspectors, etc.). The monitoring protocol and aopMAP currently consists of two stages. Stage 1 documents pertinent as-built information and Stage 2 collects pertinent field data.

Stage 1. Stage 1 of the FHWA AOP monitoring protocol starts immediately after construction to obtain as-built conditions which provides a baseline for future monitoring, not only for the infrastructure, but more importantly the as-built conditions for features to satisfy AOP requirements. As-built information facilitates evaluation of whether the project was constructed as designed. If alterations to the design were made during construction, the as-built documents should include the nature and rationale for any modifications. Confirmation that the project was built as designed is important for understanding project effectiveness over time.

Stage 2. Stage 2 of the FHWA AOP monitoring protocol evaluates geomorphic and habitat related attributes in upstream and downstream reaches and compares them with those within the AOP water crossing. This allows a direct comparison to show how there is (or is not) continuity of geomorphic characteristics and habitat related attributes on a reach scale. This is different than many other monitoring protocols available that focus on hydraulic design criteria (e.g., swimming capabilities of a given species, drop heights and flow depths) at a given flow.

In 2022, FHWA developed and recorded a training workshop that provided an overview of various types of AOP water crossings, methods, and recommended equipment for collection of field data, definitions for key geomorphic terms, and detailed instruction on the monitoring protocol and aopMAP.

5.3.2 Operations and Maintenance

Operations and maintenance of water crossings can be a significant cost over the service life of the AOP water crossing. High levels of maintenance are generally not programmatically and environmentally sustainable. Many successful AOP projects require little maintenance over their service life. Maintenance personnel typically have the most experience with a given site and thus can provide critical information to assist in minimizing the need for maintenance at a proposed AOP water crossing. For these reasons, evolved practices include maintenance personnel in scoping through the construction of AOP water crossings.

5.4 Roles of Interdisciplinary Teams

The roles of an interdisciplinary team are worth noting as they play important parts of the AOP project and program delivery process. AOP water crossings can vary depending on the complexity of the project and thus disciplines involved may vary. Some disciplines may apply to the entirety, or only a portion, of the delivery process, based on needed specialized skill and expertise for the specific project. This section describes many (but not all) potential disciplines needed for an AOP project.

As all watersheds and water crossing sites are different, key metrics and roles of a given discipline are important to design an AOP water crossing to fit within the context of the watershed and site. While not all encompassing, the listing below provides some key attributes each discipline could consider for an AOP water crossing.

5.4.1 Project Management

- Oversight of all elements identified in project goals and objectives, which may include scoping, design, construction, and monitoring.
- Coordination of various disciplines at key milestones throughout the project.
- Adherence to schedule and budget constraints.

5.4.2 Fisheries and Habitat Biology

- Identification of affected aquatic organisms (e.g., fish).
- Identification of State and Federal AOP criteria (required water depths, water velocity, etc.) and habitat conditions required by identified aquatic organisms.
- Expertise on fish and other aquatic organism swimming, leaping, and movement capabilities.
- Expertise on habitat restoration including channel and bank construction.
- Assessment of Channel Characteristics (see Section 5.4.4).

5.4.3 Environmental and Permitting

- Identification of consultations, authorizations, and permits required (NEPA/SEPA process completed as required for project type).
- Identification of environmental studies required.
- Identification of cultural resources and archaeology.
- Identification of wetlands and other waters.
- Identification of fish and wildlife.
- Identification of possible site contamination.
- Stormwater and water quality.

5.4.4 Geomorphology, Hydrology and Hydraulics

- Assessment of Channel Characteristics
    - Watershed-scale long profile (sufficient length upstream of project to capture potential for future profile adjustment and downstream of project to identify base level controls (e.g., bedrock outcropping)).
    - Active channel and bankfull widths and depths.
    - Floodplain widths.
    - Geomorphic classification.
    - Stream Stability.
    - Natural & human-constructed grade controls.
    - Knickpoints and knickpoint-zones.
    - Wood transport potential.
    - Streambed and bank material characterization.
    - Sediment transport.
    - Constructed channel modifications.
- Assessment of available aerial imagery.
- Capturing site photos and videos.
    - 360 photos and videos.
- Assessment of various waterway flows.
- Identification of FEMA Special Flood Hazard Area (SFHA).

- Stream design
    - Channel geometry
    - Channel profile
    - Extents of design
    - Habitat features
    - Grade control (if needed).
- Expertise on AOP design at new and existing road crossings.
- Hydrologic and hydraulic modeling.
- Scour analyses.

5.4.5 Geotechnical

- Identification of geologic and geohazard maps.
- Identification of available or collection of subsurface information, including information on bedrock location.
- Identify potential for scour or other geohazards (e.g., slope stability).
- Identification of foundation options and design:
    - Deep foundation.
    - Shallow foundation.

5.4.6 Bridges, Culverts, and Structures

- Identification of type, size, and location of the proposed structure
    - Structure span.
    - Structure type.
    - Foundation type and depth.
    - Necessity for walls to minimize fill in critical areas.

5.4.7 Roadway Design

- Identification of functional classification of roadway.
- Identification of available as-builts (e.g., number and width of lanes/shoulders, profile, clearance to streambed, etc.).
- Identification of current ADT.
- Identification of posted speed.

5.4.8 Traffic and Safety

- Identification of existing and projected roadway flooding.
- Identification of emergency vehicle access.
- Identification of wildlife and vehicle collision risk.

5.4.9 Survey

- Identify available sources of existing terrain (e.g., LiDAR).
- Survey collection.
  - Sufficient length upstream and downstream of project to capture potential for future profile adjustment.
  - Sufficient lateral extents to capture inundation during large flood events.

5.4.10 Utilities

- Identification of utilities that may conflict with the waterway crossing.

5.4.11 Right-of-Way

- Identification of parcel owners.
- Coordination with parcel owners.
- Identification of any need for acquiring parcels.
- Identification of any need for temporary construction easements.

5.4.12 Construction

- Traffic bypass and traffic bypass restoration.
- Traffic control.
- Temporary stream diversion/dewatering.
- Temporary structure assessment.
- Administration of construction contract.

5.4.13 Maintenance

- History of crossing and project reach.
- Post-construction maintenance.

Chapter 6. Case Studies Overview

Successful AOP promotion efforts conform to the specific circumstances of a site and the goals and objectives of a project. Following the Appendices of this Guide are six cases studies that illustrate application of a variety of objectives and approaches over different project sites. The FHWA sought a diverse mix of case studies from differing project owners and entities.

Each of the six case studies follows a similar format. They begin by identifying the project owner and any collaborators. This reflects the importance of a project having an interdisciplinary and collaborative element. The case study then provides the project location, including a map insert of the United States. As AOP is the driving rationale for each project, the case study provides the aquatic species of concern. As AOP projects may have co-benefits to other areas, the case studies provide a brief listing of these areas (e.g., resilient infrastructure, flood risk reduction, etc.).

The “heart” of each case study provides some background and then sections with a narrative of conditions and insights from that particular project. As monitoring has become an increasingly important aspect of a successful AOP project, the case study notes and describes that element.

Finally, each case study summarizes any key takeaways or outcomes associated with each project.

The six case studies found in this Guide are:

1. Crooked Creek (Kasilof, AK)
2. Almasie Creek (Greenleaf, OR)
3. Red Sandstone Creek (Vail, CO)
4. Perkins Meadow Brook (Walden, VT)
5. Logger Brook (Essex County, VT)
6. Half Mile Pond Brook (Amherst, ME)

These case studies do not all represent preferred methods but instead serve to provide some indication of the complexity and diversity of AOP projects around the United States. Some case studies provide lessons-learned pointing to processes or considerations that would have improved AOP outcomes. Others are examples of highly successful projects.

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Glossary

Anadromous	Fish that spend portions of their life cycle in both fresh and salt waters and migrate from the ocean to spawn in fresh waters.
Appurtenance	Some form of transportation system or structure that spans or otherwise crosses a waterway. Examples include culverts, bridges, and low water crossings.
Aquatic Organism	Animal growing in, living in, or frequenting water.
Aquatic Organism Passage (AOP)	(See Fish Passage) Aquatic organism passage is the ability for fish and other aquatic organisms to move freely between habitats that they rely on for food, growth, reproduction, and other needs.
AOP Project	(See Fish Passage Project) AOP projects improve the movement of fish and other aquatic organisms within and between habitats by modifying or removing dams, culverts, and other barriers that restrict their migration. AOP projects include dam modification, removal or both modification; culvert removal or replacement; nature-like fishways or bypass channels; and technical fish ladders.
As-built	Design plans that have been modified during construction to account, for example, actual site conditions encountered during that construction. This assists in reflecting the project's condition for future maintenance, asset management, and rehabilitation activities.
Bankfull	Water level in a stream corresponding to where water is flowing within the banks just before it spills out into the floodplain.
Bankfull Width	Width of flowing water when the water level is at the bankfull depth/elevation (see bankfull).
Bridge	A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening. [Source: 23 CFR § 650.305.]
Catadromous	Fish that spawn at sea and move to and spend most of their lives in fresh water.
Co-benefit	Benefit derived from a given action or strategy that is in addition to the primary objectives of the action.
Connectivity	In a river or stream context, describes the ease with which water, solids, and organisms can move through a river system.

Culvert	A structure comprised of one or more barrels, beneath an embankment and designed structurally to account for soil-structure interaction. These structures are hydraulically and structurally designed to convey water, sediment, debris, and, in many cases, aquatic and terrestrial organisms through roadway embankments. Culvert barrels have many sizes and shapes and have inverts that are either integral or open, i.e., supported by spread or pile-supported footings (FHWA 2023).
Endangered Species	As defined on section 3(6) of the Endangered Species Act, 16 U.S.C. § 1532(6), the term “endangered species” means any species which is in danger of extinction throughout all or a significant portion of its range.
Estuarine	Relating to bodies of water found where rivers meet the sea (or larger lakes). The Chesapeake Bay on the U.S. East Coast is an example of an estuarine habitat.
Fish Passage	Fish passage is the ability of fish to move freely between habitats that they rely on for food, growth, reproduction, and other needs. (See Aquatic Organism Passage).
Fish Passage Project	Fish passage projects improve the movement of fish within and between habitats by modifying or removing dams, culverts, and other barriers that restrict their migration. Fish passage projects include dam removal or modification; culvert removal or replacement; nature-like fishways or bypass channels; and technical fish ladders.
Fragmentation	Describes the situation where roadway crossings have the effect of breaking up the habitat or natural and beneficial processes associated with a waterway. Broadly, a goal of AOP projects seeks to restore waterway and habitat connectivity. (Antonym; see Connectivity).
Geomorphology	The science of the form of the Earth, the general configuration of its surface, and the changes that take place due to erosion and deposition.
Headcutting	Channel degradation associated with abrupt changes in the bed elevation (headcut) that generally migrates in an upstream direction.
In-Stream Barrier	In-stream barriers include several potential elements. A barrier to aquatic connectivity is an obstruction that prevents or alters the natural flow of water within or between waterbodies, potentially impacting water quality, sediment movement, type of habitat, and fish passage. A barrier to fish passage is anything that prevents or reduces the ability of fish or other aquatic species to move where needed to survive and complete their life cycle within an aquatic system. The extent to which a barrier may reduce or prohibit the movement of fish or other aquatic species may vary by species and life stage.

Barriers may be the result of structural impediments, such as a dam, levee, undersized culvert, or other human structures, or result from environmental conditions, such as, waterfalls, bedrock, sediment, water quality, temperature, or flow.

A partial barrier to fish passage reduces movement of some individuals of one or more fish or other aquatic species some or all the time.

A complete barrier to fish passage prohibits movement of all individuals of one or more fish or other aquatic species all the time.

Knickpoint — Location along the profile of a stream at which a sudden gradient change occurs, often associated with a headcut.

Lacustrine — Relating to habitats, species, formations, or other features found in (usually) freshwater lakes. The Great Lakes would be examples of lacustrine systems.

Marine — Relating to habitats, species, formations, or other features (such as coasts) of oceans, saltwater seas, and gulfs connected to oceans. The Gulf of Mexico is an example of a marine system.

Potamodromous (resident) — Fish that live and migrate wholly within fresh water.

Reach — For purposes of study, a segment of stream length that is arbitrarily bounded or characterized by a consistent attribute.

Riparian — Pertaining to anything connected with or adjacent to the banks of a stream (e.g., corridor, vegetation, zone).

Riverine — Relating to habitats, species, formations, or other features found in (usually) freshwater streams and rivers. The Missouri River is a riverine system.

Thalweg — The line following the lowest elevation of the riverbed.

Threatened Species — As defined in Section 3(20) of the Endangered Species Act, 16 U.S.C. § 1532(20), the term threatened species means any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.

Underserved Community — As stated in Section 2(b) of Executive Order 13985, “Advancing Racial Equity and Support for Underserved Communities Through the Federal Government,” (86 FR 7009), populations sharing a particular characteristic, as well as geographic communities, that have been systematically denied a full opportunity to participate in aspects of economic, social, and civic life, as exemplified by the list in the definition of “equity” in Section 2(a).

Waterway — A body of water providing transport or storage of water, including streams, rivers, lakes, estuaries, bays, and wetlands.

Weir — A constructed barrier on a stream channel designed to provide hydraulic control without completely stopping flow or creating a large storage impoundment.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
AEP	Annual exceedance probability
AOP	Aquatic Organism Passage
BIL	Bipartisan Infrastructure Law
BFE	Base Flood Elevation (FEMA)
BPR	Bureau of Public Roads
CEQ	Council on Environmental Quality (White House)
CFR	Code of Federal Regulation
DOI	Department of Interior
DOT	Department of Transportation
EPA	U.S. Environmental Protection Agency
FHWA	Federal Highway Administration (USDOT)
FIS	Flood Insurance Study (FEMA)
FLH	FHWA Office of Federal Lands Highways Division
FSSWG	Forest Service Stream Simulation Working Group
GIS	Geographical information system
GPS	Global positioning system
HDS	Hydraulic Design Series (FHWA manual)
HEC	Hydraulic Engineering Circular (FHWA manual)
HUC	Hydrologic Unit Code
LiDAR	Light Detection and Ranging
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standard
NEPA	National Environmental Policy Act
NFHL	National Flood Hazard Layer (FEMA resource)
NGS	National Geodetic Survey
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
PS&E	Plans, Specifications, and Estimate
RC	Resource Center
SARP	Southeast Aquatic Resource Partnership

SEPA	State Environmental Policy Act
SNBI	Specifications of the National Bridge Inventory
TFHRC	Turner-Fairbank Highway Research Center (FHWA)
USACE	U.S. Army Corps of Engineers
U.S.C.	United States Code
USDOT	U.S. Department of Transportation
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service (USDA)
USFWS	U.S. Fish and Wildlife Service (DOI)
USGS	U.S. Geological Survey (DOI)
2D	Two-dimensional
3D	Three-dimensional

Appendix A. Resources

The variation in migratory behaviors and capabilities of fish and other aquatic species over various life-stages makes designing water crossings with satisfactory AOP characteristics a challenging endeavor. Over the years, resource agencies and others have assembled significant empirical data and field experience to guide the design of water crossings, particularly culverts, for successful passage.

Recall that an overall goal of a successful AOP project is to optimize the ability of species to travel and reside within the waterway and associated stream flows of their habitat over their life cycle and life span.

This appendix contains examples of resources useful in the development and monitoring of AOP crossings. This listing is not all encompassing; there may be many other such resources potentially available to interested parties. Additionally, as the descriptions indicate, the listing includes resources limited in their applicability by region and others that may focus on a single or subset of aquatic species. These resources supplement sound engineering and design practices and must be applied in accordance with all applicable State and Federal laws and regulations.

A.1 Federal Agencies

Federal Interagency Fish Passage Task Force

- Fish Passage Portal (Task Force, 2023). This website provides information, funding, and resources to improve fish passage and aquatic connectivity projects. A dashboard for BIL fish passage projects is provided which shows an interactive map of fish passage projects across the United States. The website also provides links to the National Aquatic Barrier Inventory and Prioritization Tool created by the Southeast Aquatic Resource Partnership and a Fish Passage Training Portal with various resources, including checklists for fish passage projects.

Federal Highway Administration

- Monitoring Protocols for Assessing Aquatic Organism Passage at Water Crossings (FHWA 2022b). FHWA has developed a standardized AOP monitoring protocol and an accompanying mobile application called "aopMAP." The aopMAP application allows the user to collect data with a mobile device (e.g., tablet or mobile phone). See Section 5.3.1.2 for more information on aopMAP.

NOAA Fisheries

- NOAA Fisheries Guidelines for Salmonid Stream Crossings in WA, OR and ID (NMFS 2023c). The intent of this document is to assist with improving conditions for salmonids that must migrate past barriers to complete their life cycle. It seeks to maintain ecological function of the streams and pass flood flows, sediment, and wood. It describes stream simulation and hydraulic design methodologies.
- NOAA Fisheries WCR Anadromous Salmonid Design Manual (NMFS 2023d). This document assists with improving conditions for salmonids that must migrate past barriers to complete their life cycle. It does not address water crossing culverts but focuses on hydroelectric project barriers and fishways. It provides information on project development and informational needs as well as technical guidelines.

- NOAA Fisheries WCR Guidance to Improve the Resilience of Fish Passage Facilities to Climate Change (NMFS, 2023e). This document provides methods for incorporating future climate change into engineering designs of fish passage facilities and stream crossings. One of the goals of the document is to assist parties in satisfying NMFS regulatory authorities and NMFS' policy on the treatment of climate change in Endangered Species Act decisions. The document is part of a series of documents that NMFS recommends using when designing a fish passage project in the West Coast Region, which encompasses California, Oregon, Washington, and Idaho.
- NOAA Fisheries Guidelines for Salmonid Passage at Stream Crossings in California (NMFS, 2023f). This document provides guidelines for design of stream crossings to aid upstream and downstream passage of migrating salmonids. The intent is to facilitate the design of a new generation of stream crossings and assist the recovery of threatened and endangered salmon species. The document provides criteria, rationale, guidelines, and definitions for designing proper fish passage facilities in California.
- NOAA Fisheries Pre-Design Guidelines for California Fish Passage Facilities (NMFS, 2023g). This document provides a framework to assist in the development of facilities, fishways, and fish passage appurtenances, as well as operational, monitoring, and maintenance plans necessary for the successful operation of such facilities. Within this framework approach, design factors are discussed, but specific engineering criteria for various fishways and fish passage appurtenances are generally not provided. For engineering criteria on facility fishways and fish passage appurtenances, see NOAA Fisheries WCR Anadromous Salmonid Design Manual (NMFS 2023d).

U.S. Forest Service

- Stream Simulation: An Ecological Approach to Road-Stream Crossings (FSSWG 2008). This document developed by the U.S. Forest Service has been an important reference or fish passage design. Much of the criteria are based upon the natural geomorphic characteristics of streams supporting the aquatic ecosystems of interest, and many of the procedures implementing those criteria seek to replicate the stream and floodplain characteristics and geometries within the water crossing.

U.S. Fish and Wildlife Service

- Culvert Design Guidelines for Ecological Function (USFWS, 2022). This document provides information on the basic culvert design guidelines preferred by the U.S. Fish and Wildlife Service (USFWS) Alaska Fish Passage Program. These technical guidelines are intended to be used when selecting a culvert as the stream-crossing structure in a fish-bearing stream. Whenever possible, the USFWS supports minimizing the degradation of the ecological continuity of stream corridors and wetlands by choosing transportation routes that avoid the stream crossing altogether or by using bridges that span across the floodplain.

A.2 State and Other Organizations

Many States have developed their own regulations and guidelines that reflect their unique environments and AOP needs. The following reference documents reflect requirements and preferred approaches in various States. This list is not all encompassing and work in other States should begin with identification of State-specific regulations and guidelines.

California

- Salmonid Stream Habitat Restoration Manual, Part XII, Fish Passage Design and Implementation (CDFG 2009). This document provides technical information for the design of fish passage projects at stream crossings, small dams, and water diversion structures using geomorphic and hydraulic approaches. Options, in order of preference, range from having no structure to constructing fishways.
- Fish Passage Design for Road Crossings Guidance (Caltrans 2014). This document provides detailed instructions to assist designers in generating projects that will achieve resource agency goals for fish passage within a California highway project context. Developed in conformance with the California Department of Fish and Game (CDFG) and the National Marine Fisheries Service (NMFS), Southwest Region criteria, it provides worksheets, flow charts, design examples and other design aids to assist the designer.

Georgia

- Stream Crossings in Georgia. A Handbook for Connectivity and Resilience (Georgia Aquatic Connectivity Team 2021). This handbook is intended to encourage the proper design and implementation of all new stream crossings in Georgia to maintain stream connectivity, improve stream health, provide for public safety, improve water quality, and make communities more resilient.

Maine

- Stream Smart (Maine Audubon 2023). Stream Smart works with contractors, landowners, and other professionals responsible for road-stream crossings to construct culverts that maintain fish and wildlife habitat while protecting roads and public safety. The website provides resources for project planning and support, Stream Smart workshops, and a resource library.

Maryland

- Recommendations for Aquatic Organism Passage at Maryland Road-Stream Crossings (Chesapeake Bay Program 2021). This document provides recommendations for crossing structures to improve or maintain aquatic organism passage along non-tidal waterways. The document is not a technical handbook or design manual and should not be used as a standalone reference to successfully replace or install a culvert.

Massachusetts

- Massachusetts Stream Crossings Handbook (MA Fish and Game, 2018). The suggested guidelines described in this handbook are minimum goals for fish and wildlife passage; additional design considerations are needed to ensure structural stability and effective passage of flood waters.

New Hampshire

- New Hampshire Stream Crossing Initiative (New Hampshire 2023). The New Hampshire Stream Crossing Initiative is a multi-agency group that collaboratively works to align resources and improve management of stream crossing infrastructure across the State. The Initiative provides the tools needed for stakeholders to make data-driven decisions for targeting investments in projects that support transportation, stream connectivity, fish and wildlife habitat, and flood resilience.

Rhode Island

- Rhode Island DOT Road-Stream Crossing Assessment Handbook (RIDOT 2019). This handbook is intended to serve as an informational document and decision-making tool to identify road-stream crossings in Rhode Island that should be prioritized for replacement or upgrades.

Vermont

- Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont (Bates and Kirn 2009). This document provides technical information in the design and construction of stream and road crossings where the need for passage of aquatic organism passage has been identified. It presents several approaches including Vermont low-slope, stream simulation, hydraulic, and alternative.
- VTrans Hydraulics Manual (VTrans 2015). This document provides information on the importance of considering AOP in culvert design and points interested readers to other references.

Washington

- WSDOT Hydraulics Manual (WSDOT 2023). This document provides context for AOP within the project development process and technical guidance. In addition, references to other documents for detailed technical guidance are provided.
- WSDOT Hydraulics and Hydrology Training (WSDOT 2023). This website provides various resources and training through presentations and videos. Training topics include fish passage and stream restoration design, scour, the WSDOT Hydraulics Manual, and the WSDOT Highway Runoff Manual.
- WDFW Water Crossing Design Guidelines (Barnard et al. 2013). This document provides detailed information on multiple design methods and describes the advantages and limits of each when implementing an AOP project in Washington. The document also covers project management, construction, and monitoring.

Appendix B. Current AOP Programs and Activities

This appendix lists current AOP programs and activities, the Federal agency involved, and, where possible, web links to the program site. More information on AOP programs and activities can be found in the Interagency Fish Passage Portal (USFWS 2023).

Aquatic Ecosystem Restoration

The U.S. Army Corps of Engineers (USACE) plans, designs, and builds projects to restore aquatic ecosystems through various authorities under its Aquatic Ecosystem Restoration program, to which the BIL provides $1.9 billion. The emphasis of this program is restoring nationally or regionally significant ecosystems where the solution primarily involves modifying hydrology or geomorphology. The BIL provides an additional $115 million to restore fish and wildlife passage through in-stream barrier removal under Section 206 of the Water Resources and Development Act of 1996.

Bridge Investment Program

The Bridge Investment Program (BIP) is an annual competitive, discretionary grant program established by the BIL and administered by FHWA. The BIP focuses on existing bridges and culverts, having a span greater than 20-feet, with a goal to reduce the overall number of bridges in or at risk of falling into poor condition. The BIP allows up to 5% of BIP funding, or $125 million per year, to be used for eligible projects that consist solely of culvert replacement or rehabilitation of bridge-sized culverts for the purpose of improving flood control and improved habitat connectivity for aquatic species.

Collaborative-based Aquatic-focused Landscape Scale Restoration

The U.S. Forest Service (USFS) Collaborative Landscape Restoration Program aims to fund and complete high priority projects on Federal and non-Federal land to improve water quality or restore passage for fish and other aquatic organisms. The BIL provided $80 million over 5 years to the USFS for this program.

High Hazard Dam Decommissioning

The BIL provided $10 million over 5 years for the decommissioning and removal of USFS owned, non-hydropower, high hazard dams. Removal of these dams will restore watershed health and aquatic connectivity while improving public safety.

Hydropower Incentives Program

The BIL provided the Department of Energy (DOE) $753 million for the Hydropower Incentives Program. The program will incentivize Federal Energy Regulatory Commission licensed hydropower facilities to improve efficiency, maintain dam safety, reduce environmental impacts, and ensure generators continue to provide emission-free electricity. Reduction of environmental impacts may include projects aimed at improving fish passage at hydropower facilities.

Legacy Roads and Trails Remediation

The USFS's Legacy Roads and Trails Remediation Program supports restoration, protection, and maintenance of crucial watersheds in national forests and grasslands. This is accomplished by restoring fish and aquatic organism passage, improving road and trail resiliency, preserving access, and decommissioning unneeded or unauthorized roads. The BIL provided $250 million over 5 years to this program.

National Culvert Removal, Replacement and Restoration Grant Program

The National Culvert Removal, Replacement, and Restoration Grant Program (Culvert AOP Program) is an annual competitive grant program established by the BIL and administered by FHWA. Grants are awarded to eligible entities for projects that replace, remove, and repair culverts or weirs that meaningfully improve or restore fish passage for anadromous fish. The BIL appropriated $1 billion to the program over five years.

National Fish Passage Program

The U.S. Fish and Wildlife Services' (USFWS) National Fish Passage Program works with local communities on a voluntary basis to restore rivers and conserve our Nation's aquatic resources by removing or bypassing barriers. The BIL provided $200 million to the program over five years to restore fish and wildlife passage by removing in-stream barriers and providing technical assistance to partners.

Pacific Coastal Salmon Recovery Fund

The National Oceanic and Atmospheric Administration's (NOAA's) National Marine Fisheries Service (NMFS) administers the Pacific Coastal Salmon Recovery Fund to that seeks reverse the declines of West Coast salmon and steelhead populations This competitive grant program funds eligible projects that provide measurable benefits to Pacific anadromous salmonids and their habitat and can include projects to restore fish passage and habitat connectivity. Eligibility in the program also provides an opportunity to fund non-passage projects that benefit Pacific Salmon. The eligible entities for applying to this program are the States of Alaska, Washington, Idaho, Oregon, California, Nevada, and Federally recognized tribes of the Columbia River and Pacific Coast (including Alaska) or their representative tribal commissions and consortia. The BIL provided an additional $172 million in funding over 5 years to support the program.

Rehabilitation of High Hazard Potential Dams Grant Program

The Federal Emergency Management Administration's (FEMA's) Rehabilitation of High Hazard Potential Dams grant program provides technical, planning, design, and construction assistance for eligible rehabilitation activities that reduce dam risk and increase community preparedness. The purpose of this program is improving dam safety through rehabilitation or removal which can also provide benefits for fish passage and aquatic habitat connectivity. The BIL provided additional funding to this program to support State programs to improve safety at high hazard potential dams, with no less than $75 million for the removal of dams.

Restoring Fish Passage through Barrier Removal

NMFS's Office of Habitat Conservation's Restoration Center will implement the fish passage provision with the goal to fund projects that eliminate in-stream barriers to restore fish passage while applying a watershed level approach to address fish passage barriers. These projects will assist in the recovery of endangered migratory fish and our Nation's fisheries, while providing additional benefits such as jobs and increased climate resilience, by removing or improving outdated infrastructure. The BIL provided NOAA $400 million over 5 years for fish passage projects that will remove in-stream barriers.

Restoring Tribal Priority Fish Passage through Barrier Removal Grants

Up to 15% of the $400 million that the BIL provided NOAA will be directed to Indian Tribes through a focused grant competition. NMFS's Office of Habitat Conservation's Restoration Center will implement the tribal fish passage grants with the goal to provide financial and technical assistance to tribes and tribal commissions or consortia to address tribal priority restoration needs, including building capacity for planning and implementation. Project funding through these grants will assist in the recovery of tribally important species, endangered migratory fish, and our Nation's fisheries, while also providing additional benefits, such as jobs and increased climate resilience, by removing or improving outdated infrastructure.

WaterSMART Aquatic Ecosystem Restoration Projects

BIL allocated $250 million to the Bureau of Reclamation (BOR) for Aquatic Ecosystem Restoration Projects (AERP). Through AERP, Reclamation provides funding for the study, design, and construction of projects that are collaboratively developed, have widespread regional benefits, and result in the improvement of the health of fisheries, wildlife, and aquatic habitat through restoration and improved fish passage. Funding may be provided for the removal or modification of dams or diversion structures under AERP.

WaterSMART Environmental Water Resources Projects

BIL allocated to BOR over $100 million in project funding, including funding for multi-benefit projects to improve watershed health, under Section 40907 of the BIL. Eligible project types include water conservation and efficiency projects that result in quantifiable and sustained water savings and benefit ecological values or watershed health; water management or infrastructure improvements to benefit ecological values or watershed health; and watershed restoration projects benefitting ecological values or watershed health that have a nexus to water resources or water resources management.

Water Infrastructure Investments

The BIL provided the U.S. Environmental Protection Agency (EPA) over $50 billion to improve our Nation's drinking water, wastewater, and stormwater infrastructure. While the primary goal of much of this funding is to improve water quality and delivery, projects may have secondary benefits that include fish passage and habitat restoration.

Wildlife Crossing Pilot Program

The Wildlife Crossings Pilot Program (WCPP) is a BIL enacted competitive grant program with the goal of reducing Wildlife Vehicle Collisions (WVCs) while improving habitat connectivity for terrestrial and aquatic species.

Appendix C. Waterway-Transportation Overlap

This appendix characterizes the approximate extent of waterway crossings within the United States. The FHWA acknowledges that the discussion herein does not represent exact numbers and locations of these crossings nor whether the crossings are barriers. However, by focusing on available information, broad potential estimates of the magnitude of the waterway-transportation system interactions are possible.

C.1 Extent of Streams, Rivers, and Waterways

NOAA Fisheries estimates that the United States has 3.5 million miles of rivers and their tributaries. The 25 longest rivers in the country (including the Missouri (2,504 miles) and Mississippi (23,40 miles)), total approximately 31,000 of those miles and represent less than one percent of the total stream and river miles nationwide (Kammerer 1990). While there are large bridges spanning these rivers, the vast majority of waterway crossings occur on smaller rivers and streams.

To aid in classifying these waterways, hydrologists developed several categorization approaches that can be helpful to think about waterway-transportation crossings and potential AOP barriers. The appendix discusses three approaches: hydrologic units, stream levels, and stream order.

C.1.1 Hydrologic Units

A commonly applied characterization approach to look at the extent of waterbodies employs the concept known as “hydrologic units” based on topography, hydrology, and other landscape characteristics. Nomenclature for hydrologic units comprise a series of nested, two-digit codes that denote, from largest to smallest waterway extents:

- Regions (first two digits).
- Subregions (second two digits).
- Accounting units (third nested two digits).
- Cataloging units (fourth nested two digits in the sequence).

Figure 8 illustrates 21 regions that characterize the U.S. And U.S. Territories, as well as portions of Canada and Mexico. Across the U.S., there are a total of 221 subregions, 378 accounting units, and 2,264 cataloging units (USGS 2023).

Hydrologists identify each hydrologic unit by a unique “hydrologic unit code” (HUC) that consists of two to twelve digits. The first four HUCs (i.e., HUC2, HUC4, HUC6, and HUC8) correspond to the four levels of classification in the hydrologic unit system (USGS 2023). More recent HUC designations expand the HUC levels down to 12 digits (HUC12). Figure 9 depicts the nesting of HUCs moving from a region to the HUC12 level of the watershed.

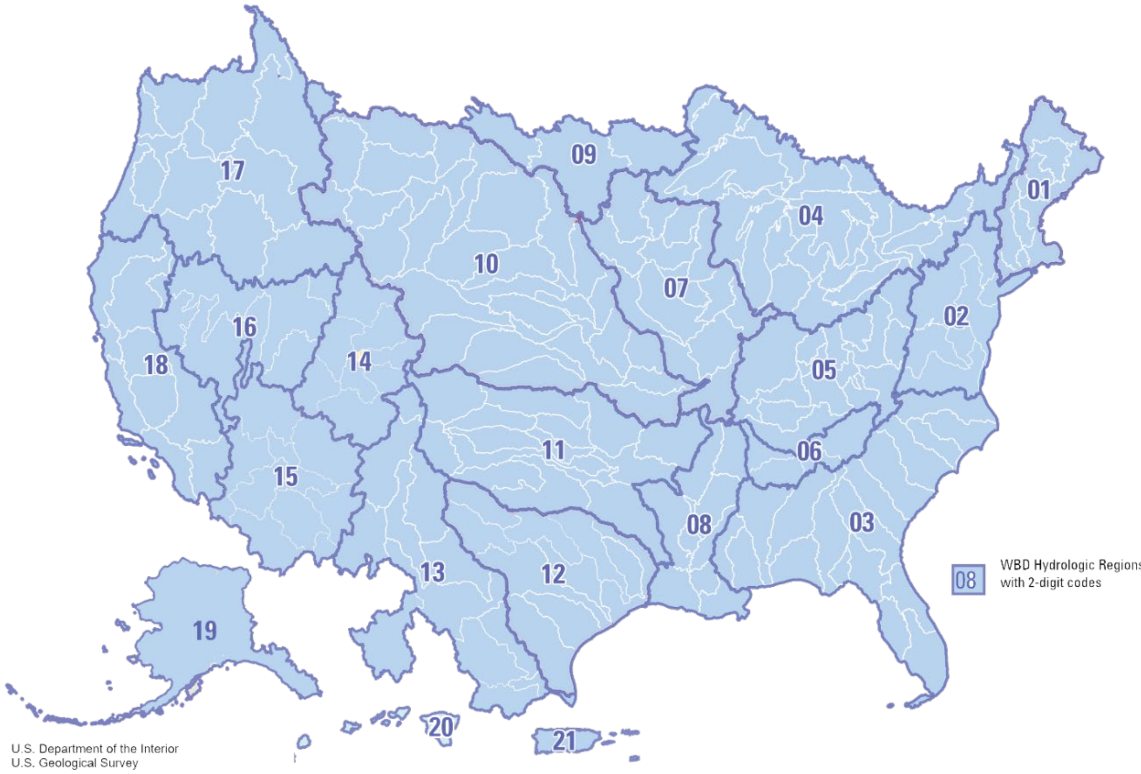

Figure 8. Hydrologic regions of the United States. (Source: USGS).

Figure 9. Sequencing of HUC levels from HUC2 to HUC12 (Source: USGS).

C.1.2 Stream Levels

To aid in understanding the connectivity of waterways, hydrologic and fluvial scientists developed a categorization approach referred to as “stream levels.” In this approach, the waterways range from level 1 (i.e., a river or stream with a terminus in the ocean) with reach “branches” proceeding up to the final or “terminal” level. For example, the Mississippi River would be a level 1 waterway (since its terminus is the Gulf of Mexico), the Missouri River a level 2 (as it enters the Mississippi River at Saint Louis), Big Sioux River (in South Dakota) a level 3 (and so on). Multiple higher-level waterways (e.g., tributaries) can enter a lower-level reach (for example the Missouri and Ohio Rivers both are level 2 tributaries to the level 1 Mississippi River). Figure 10 illustrates the extent of the first three levels of waterways within the U.S. reaching the Atlantic Ocean, Pacific Ocean, and Gulf of Mexico (this excludes the Colorado River and others that exit the U.S. Through a land border with Mexico or Canada).

One advantage of the stream level approach is understanding stream network connectivity and associated pathways that aquatic species may use for habitat or length of migration. The approach also lends itself to capturing how aquatic barriers may impede or close connectivity, and the location(s) of those barriers.

Figure 10. Map of some level 1-2-3 waterways within the United States (Source: USGS).

C.1.3 Stream Order

Strahler (1952) developed the concept of stream order to characterize the relationship between waterways. In contrast to the stream level described above, stream order begins at the upstream most portion of a waterway ("headwater" stream) and proceeds downstream, with each downstream waterway segment increasing in stream order. The first and second order streams comprise a majority of these waterways. Figure 11 illustrates stream order with the Potomac River watershed. In this case, first order streams comprise 57 percent of the stream network with the Potomac River as it flows to the Chesapeake Bay, which is an eighth order waterway. The advantage of the stream order approach is that it allows a focus on the upstream portions of a habitat, which may be locations where fish species spawn or juveniles reside.

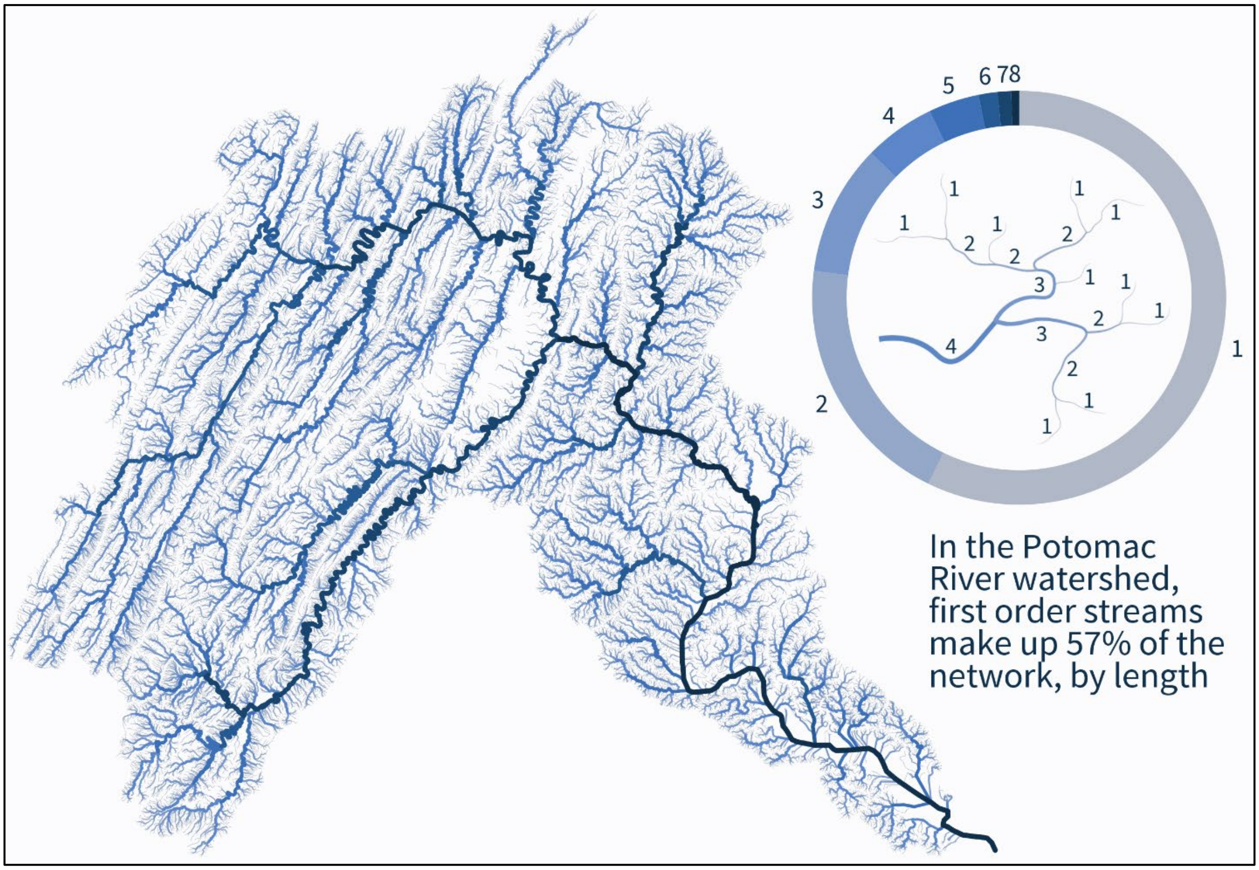

Figure 11. Example of stream order on Potomac River (Source: USGS).

C.2 Potential Waterway-Transportation Crossings

The U.S. Transportation system is a network of roads, railroads, and other infrastructure linking our Nation. As of 2020 the USDOT Bureau of Transportation Statistics estimated there are approximately 4.2 million miles of paved (68 percent) and unpaved (32 percent) public roads (BTS 2023). Likewise, railroad networks and corridors have over 140,000 route miles of track (FRA 2023). In spanning the Nation, these transportation networks cross waterways, including streams, rivers, and other waterbodies potentially creating AOP barriers.

Tidal Restrictions

In addition to transportation crossings of rivers and streams, transportation facilities cross tidal waterways. These can constrict tidal flows affecting habitat and aquatic organisms (USEPA 2020).

The FHWA's National Bridge Inventory (NBI) includes information about 621,581 public road bridges within the United States, with 514,621 of those highway bridges spanning waterways (NBI 2022, NBI 2023). The NBI contains 146,597 structures listed as culverts (NBI 2023). However, the NBI is not a comprehensive database of all bridges because the NBI only captures those bridges (and culverts) that have a span greater than 20 feet. Likewise, there are 69,510 railroad bridges with 51,412 spanning waterways (BTS 2010). Some airports have additional bridges or culverts that allow runways and airport roads to cross both roads and streams.

Determining the frequency of waterway-transportation crossings requires a way to identify the number of bridges and culverts with spans 20 feet or less crossing waterways. Using GIS tools, the FHWA investigated the number of NBI bridges that intersect with level 1 through 4 waterways. As depicted in Figure 12, these account for 18,420 bridges nationally. This represents approximately only 3.6 percent of the total number of NBI bridges spanning waterways.

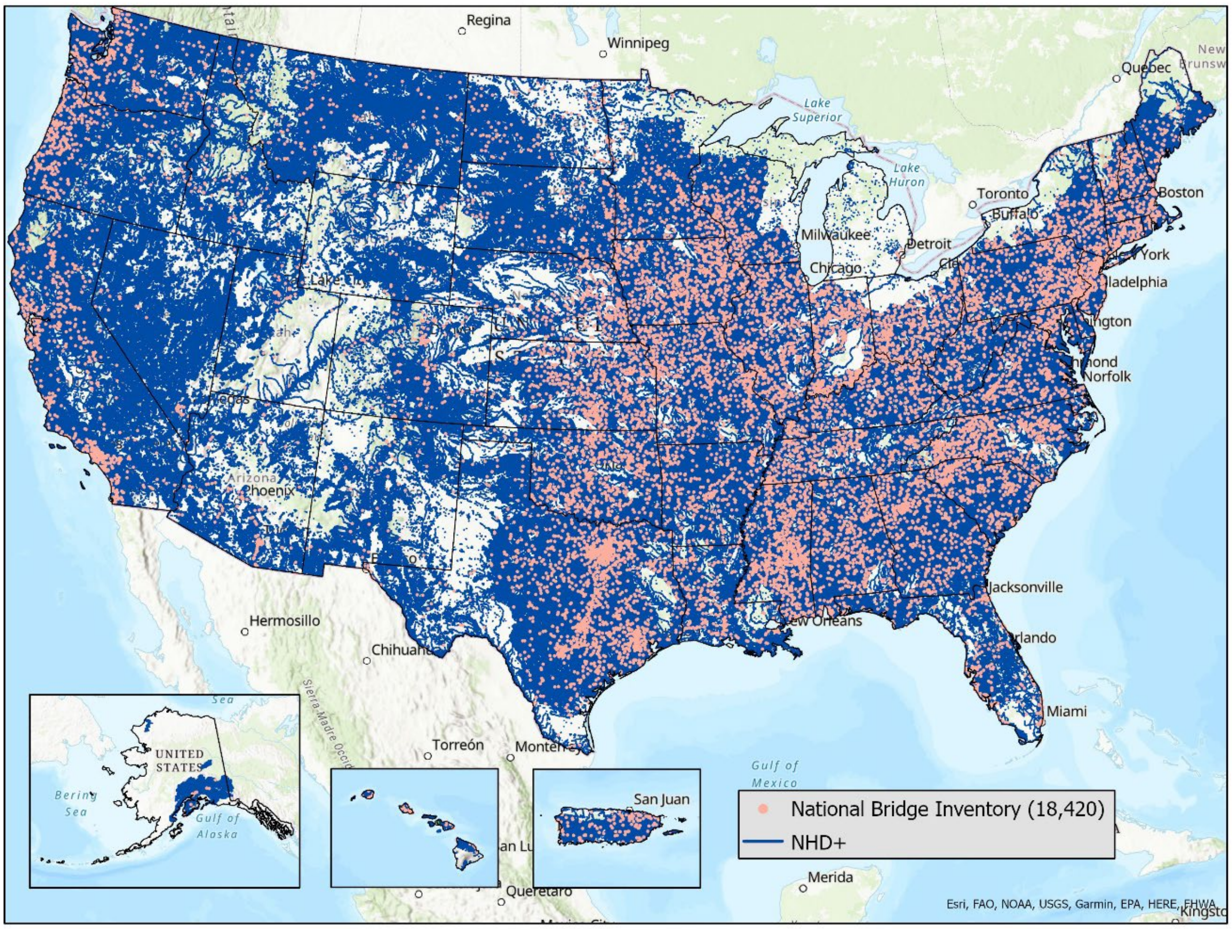

Figure 12. Possible NBI bridges crossing level 1 through 4 waterways (NBI 2022).

Performing a similar GIS analysis to identify road crossings over level 1 through 4 waterways not identified as being within the NBI yields 2,300,829 crossings shown in Figure 13. These include bridges 20 feet or less in length and culverts with a span of 20 feet or less.

Assuming that the percentage of these smaller crossings on level 1 through 4 waterways to the total number of smaller crossings is the same as for the crossings in the NBI yields an estimate of 63.9 million waterway crossings (2,300,829 divided by 3.6 percent). The FHWA anticipates that most crossings not included in the NBI are culverts (although bridges 20 feet and less are captured in this estimate).

Adding the NBI crossings and railroad crossings brings the total road/rail bridge and culvert crossings of waterways to 64.5 million. Adding crossings contributed by other infrastructure would result in a higher number. These numbers are approximate but illustrate the magnitude of the challenge in determining which crossings present barriers to AOP and which of those should be prioritized for mitigation.

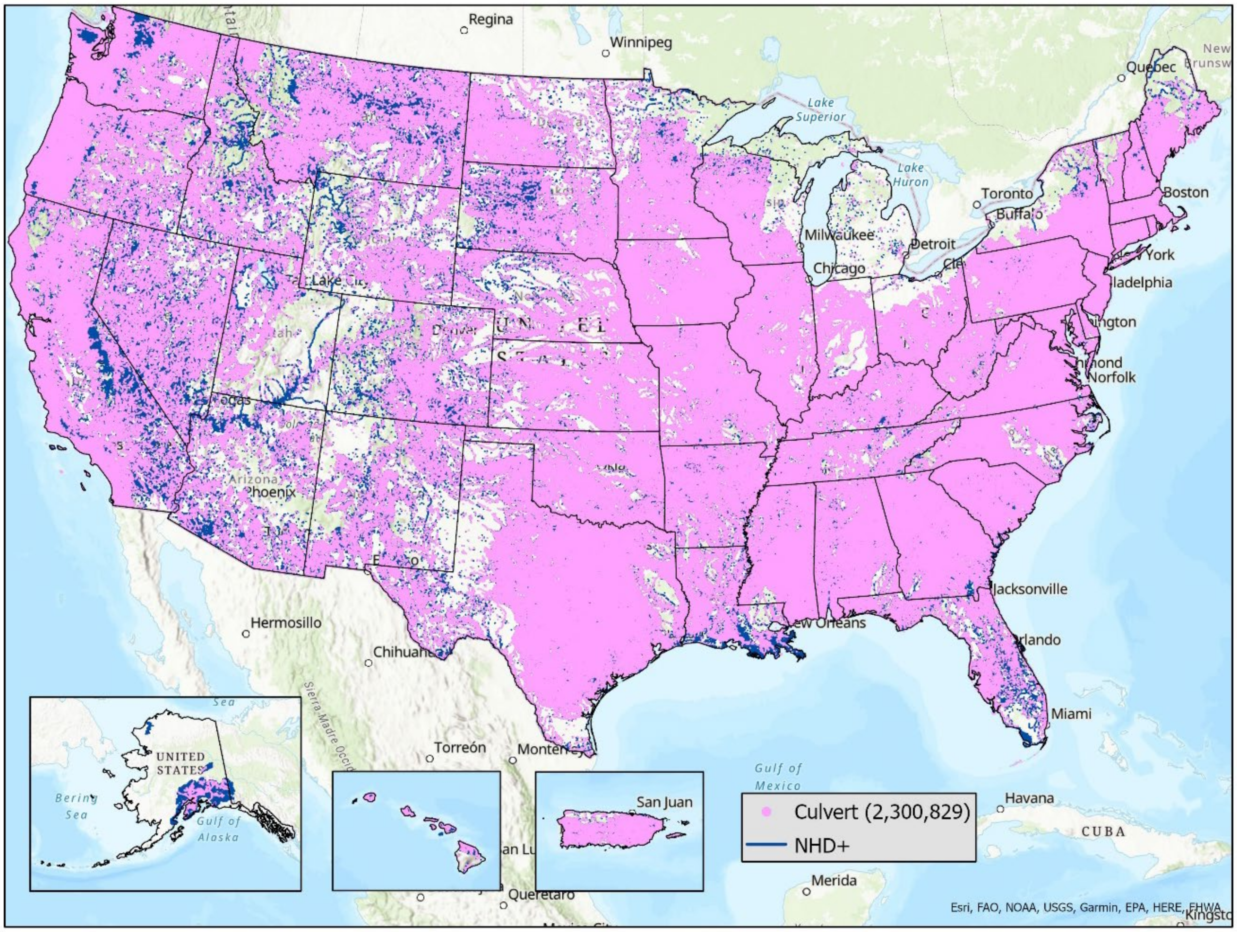

Figure 13. Possible culverts crossing four stream levels (NBI 2022).

Appendix D. Culvert and Bridge Design

This appendix describes important differences between culverts and bridges and discusses the evolution of hydrologic and hydraulic approaches used in their design.

D.1 Structural Differences

While there are certainly natural objects that allow egress across some feature or waterway, this Guide considers those facilities associated with the human-built environment. As this section describes, the structural characteristics of culverts and bridges have important similarities and distinctions.

D.1.1 Bridge Structures

Generally, a highway (or roadway) bridge consists of a structural deck (or superstructure) that conveys traffic. Supporting the deck and the traffic loads are foundations (or substructures), consisting of abutments (the portion of the bridge supporting the superstructure) and perhaps piers (see Figure 14). Figure 14 depicts two common types of foundations: (A) deep foundations, such as the drilled shafts or piles shown on the left side of the bridge and center pier; and (B) shallow foundations, such as a spread footing depicted on the right side of the bridge. When selecting the type of foundation, the owner should consider potential hazards such as total scour (FHWA 2012b). Bridge designs have some distance between the design water surface elevation and the bottom of the superstructure (known as freeboard), as depicted in Figure 14.

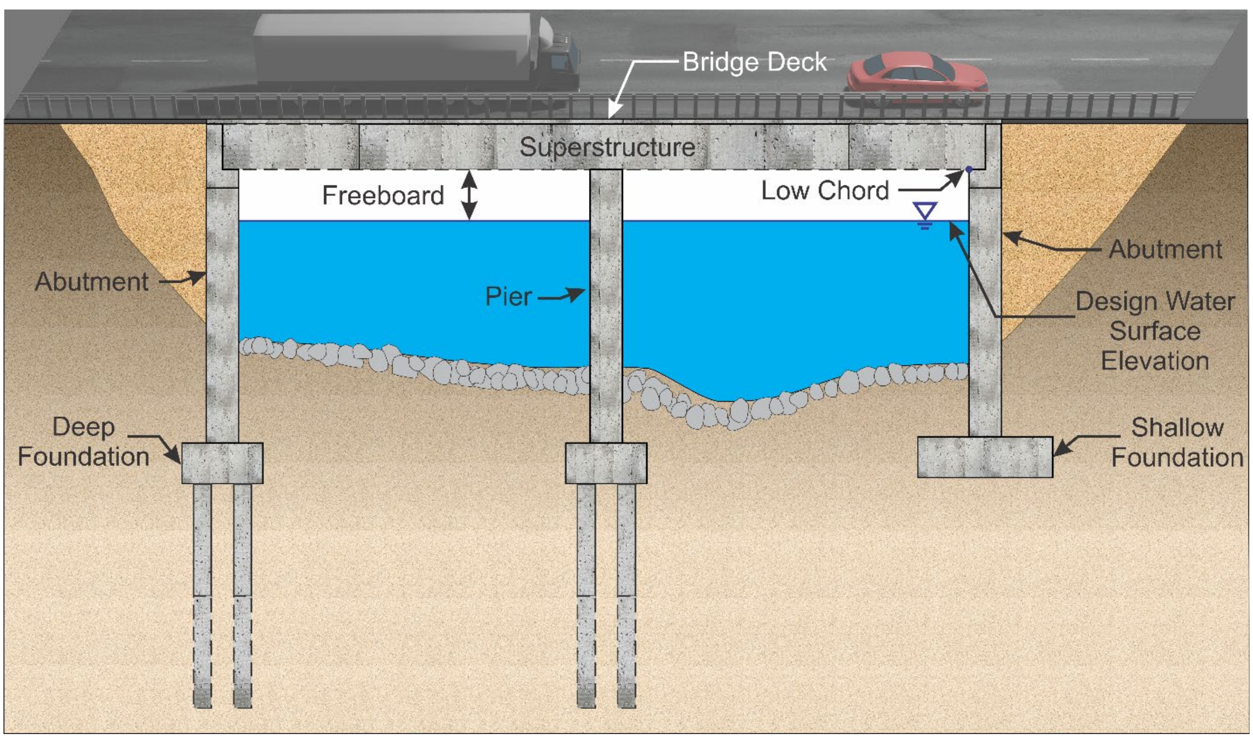

Figure 14. Schematic of a bridge (not to scale).

Bridge materials typically consist of concrete and steel, but timber bridges are common for certain locations and instances. Some bridges may be subject to the National Bridge Inspection Standard (NBIS) under 23 CFR Part 650, subpart C. Specifically, as defined under 23 CFR § 650.305 of the NBIS, a bridge is *"… a structure including supports erected over a depression or an* *obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes, including multiple pipes, where the clear distance between openings is less than half of the smaller continuous opening."*

A structure may not fit this definition of a bridge, and therefore not be subject to the NBIS. However, they can still be subject to applicable design standards that seek to ensure the safety of the travelling public under 23 CFR Part 625.

Bridges may also have these structural components (i.e., deck, abutments, foundations) but have soil and natural elements added on top to facilitate passage of terrestrial species, e.g., wildlife crossings. Bridge engineering practice refers to these types as "buried bridges" (and does not consider them to be culverts or tunnels). Additionally, there are numerous wooden covered bridges (often historic) that have "roofs" that protect the superstructure (typically wood) from exposure from the elements.

Railroad and other non-roadway bridges (e.g., pedestrian, trails, etc.) have similar descriptions and associated standards.

D.1.2 Culvert Structures

The primary intent of most roadway culverts is to convey water, sediment, wood, and aquatic or terrestrial organisms beneath the roadway. Typically, a culvert location has soil materials (i.e., backfill) between the roadway and the culvert structure (see Figure 15 through Figure 18). The culvert structure (that may consist of multiple barrels, cells, or elements), backfill, and soil bedding underneath the culvert provide the support of the various loads.

AOP culvert designs typically have streambed material and features within the culvert that are designed to mimic the streambed from the adjacent channel reaches. Traditional culverts do not have a foundation separate from this structure/soil support (see Figure 15) and may present challenges in placement of streambed material during construction due to limited clearance for construction equipment.

However, for certain structures, there may be advantages in placing the culvert on some type of foundation element (see Figure 16 through Figure 18).

Figure 17 and Figure 18 depict a common type of culvert utilized for an AOP structure, where there is a joint on the structure wall, shown as a dark black horizontal line. This joint allows the bottom of the structure to be constructed, followed by placement of streambed materials and features prior to placing the top portion of the structure.

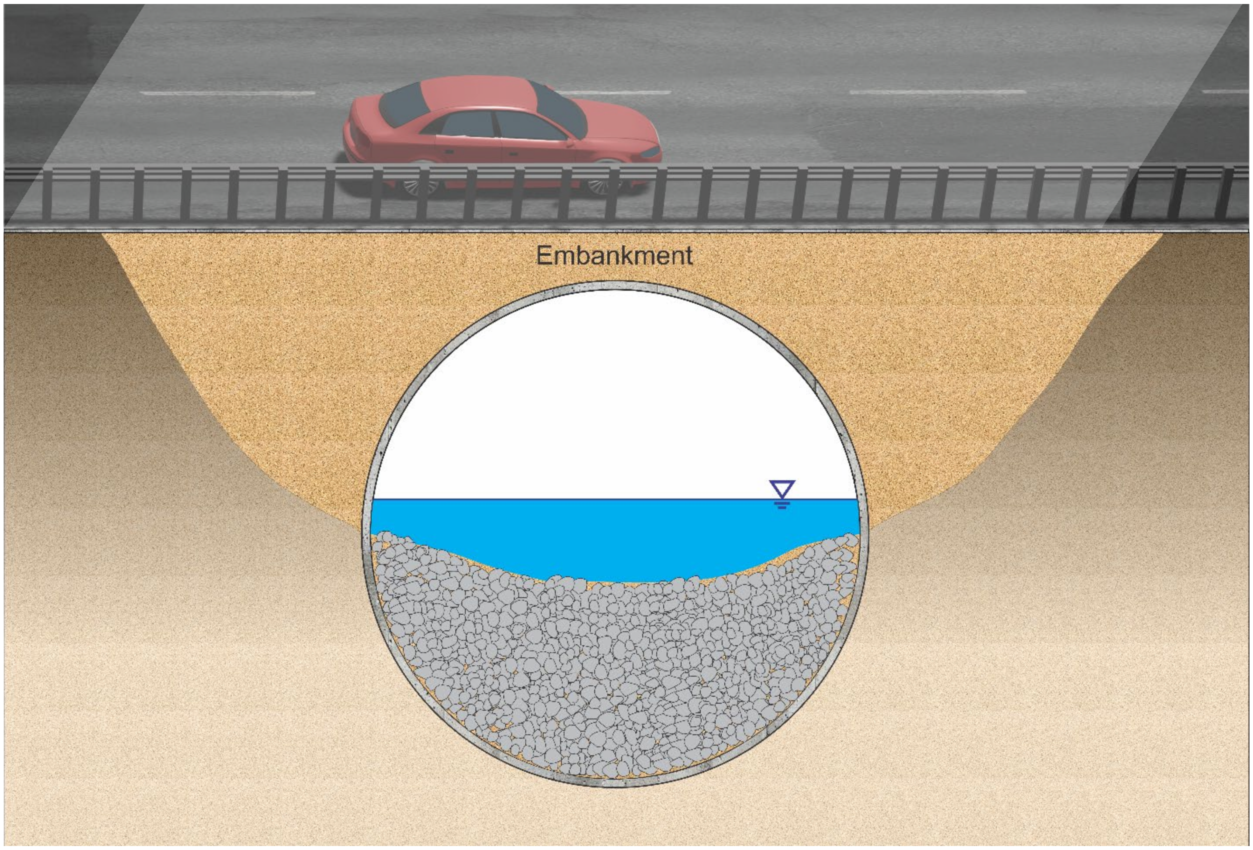

Figure 15. Schematic of a culvert (not to scale).

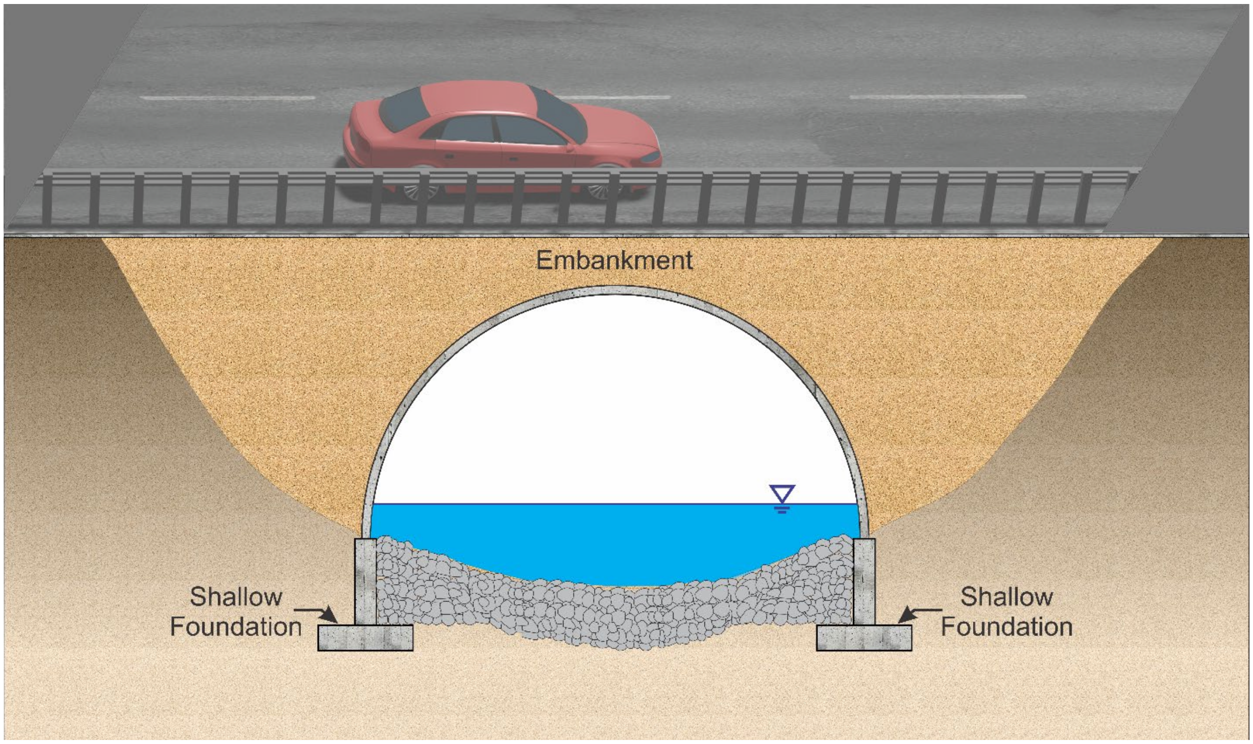

Figure 16. Culvert placed on a foundation system (not to scale).

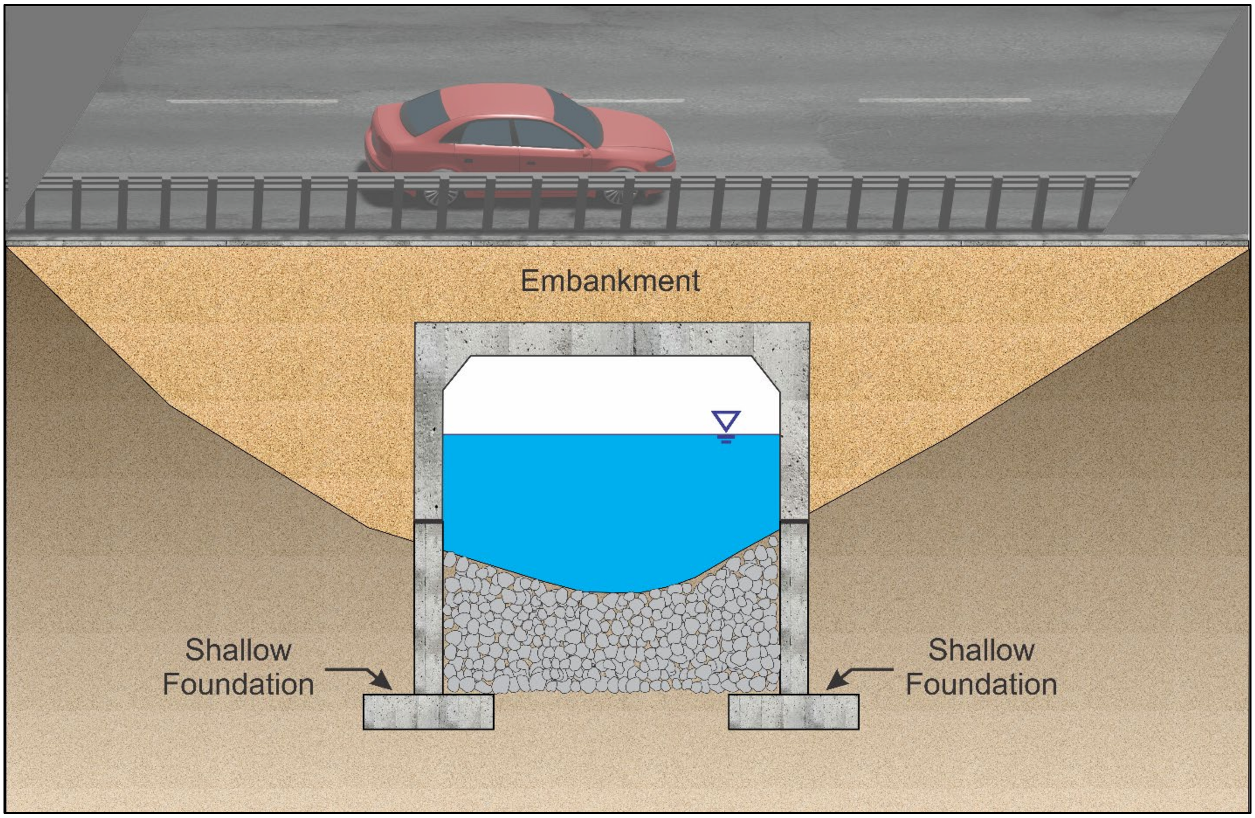

Figure 17. Three-sided open bottom structure (not to scale).

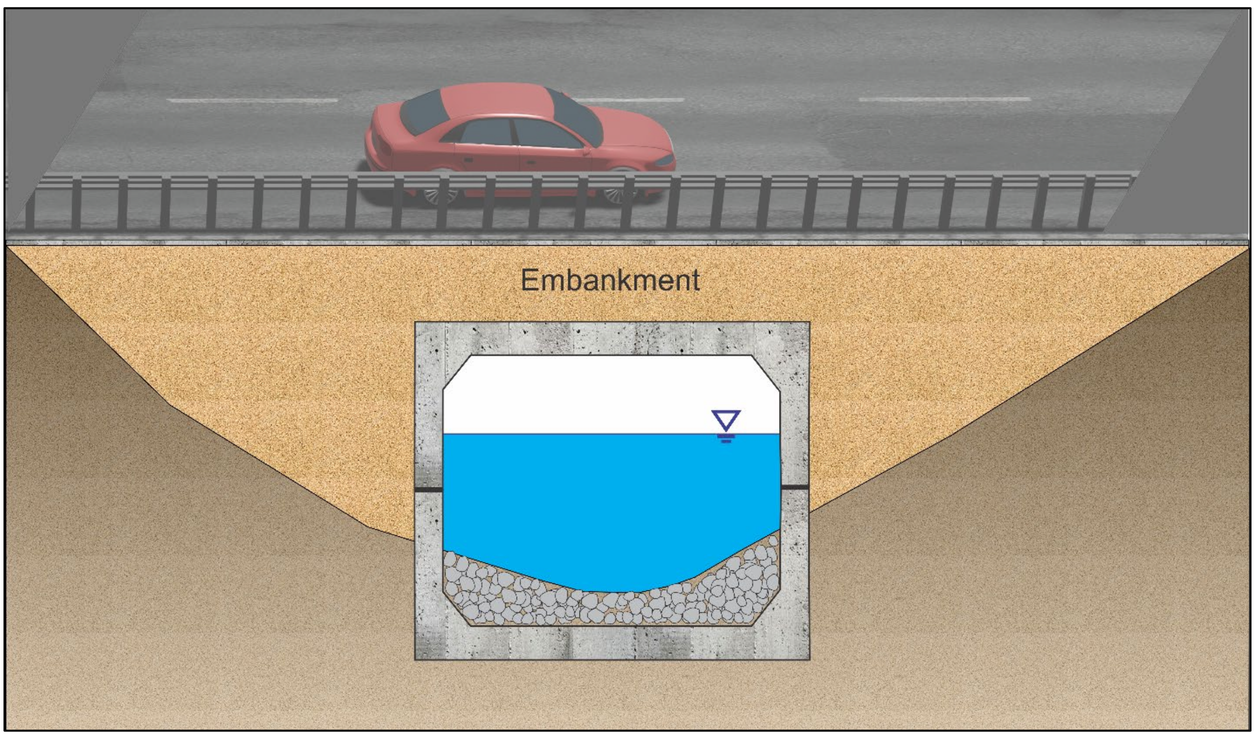

Figure 18. Split-box culvert (not to scale).

Regardless of the layout, culverts that fall under the definition of a bridge in 23 CFR § 650.305 are subject to the NBIS. The Specifications of the National Bridge Inventory (SNBI) describe the characteristics of the NBIS (FHWA 2022a). The SNBI defines a culvert as:

Culvert. A structure comprised of one or more barrels, beneath an embankment and designed structurally to account for soil-structure interaction. These structures are hydraulically and structurally designed to convey water, sediment, debris, and, in many cases, aquatic and terrestrial organisms through roadway embankments. Culvert barrels have many sizes and shapes and have inverts that are either integral or open, i.e., supported by spread or pile-supported footings. Many culverts take advantage of headwater submergence of the inlet to increase hydraulic efficiency and economy.

D.2 Hydrology and Hydraulics

The second important distinction between culverts and bridges is the means to describe the hydraulics (i.e., the study of the behavior of flowing water) of the waterway passing under the structure. Exploring these distinctions necessitates a brief overview of not just hydraulics, but the hydrology that allows those hydraulic behaviors to exist and function. The following sections provide some background, history, and discussions of the hydrologic and hydraulic distinctions related to bridges and culverts.

D.2.1 Hydrology

Hydrology is the science that *"… addresses the physical properties, occurrence, and movement of water in the atmosphere, on the surface of, and in the outer crust of the earth …"* (FHWA 2024b). Roadway practice narrows this broad concept to focus on *"… water that moves on the earth's surface and in particular that part that ultimately crosses transportation arterials."* (FHWA 2024b).

For both bridges and culverts, typical practice used in hydraulic design determines a waterway discharge (flow) associated with a probability that the flow will be equaled or exceeded in any year. Highway practice refers to this flow condition as the "hydraulic design flood" (AASHTO 2020). The use of probability seeks to allow consideration of risk to the transportation system in a consistent manner. This risk varies on factors such as the type of roadway classification (e.g., Interstate Highway versus unpaved road), the type of crossing (e.g., bridge, culvert, low water, etc.) and other social, environmental, engineering, and economic concerns.

D.2.1.1 History and Evolution of State of Practice

Historically, approaches to sizing waterway openings for bridges and culverts were generally ad hoc. One practice was looking for local heights of floods and (perhaps) adding some additional height (i.e., "freeboard"). As a result, the same waterway might have multiple crossings along its reach, each bigger or smaller as dictated by the flood recollections of local residents or practice. Varied (and inconsistently occurring) damages and failures of these crossings was one common outcome.

During the period from 1850 to the early twentieth century, such approaches began to evolve within U.S. engineering practice. The evolution reflected an on-going development of hydrologic and hydraulic methods that attempted a scientific and engineering assessment of flood events (BPR 1916, King 1918). Practitioners applied these approaches to bridge and culvert design. One widely used approach, Talbot (1887), used the contributing watershed area to calculate the waterway area for design of a bridge or culvert (BPR 1919). The concept behind the Talbot method was that the watershed area reflected the potential hydrology and, thus, a means to estimate the crossing opening area (King 1918).

However, practice also used other methods. To illustrate, by 1918, those interested in estimating flow in a channel could choose between (at least) four different approaches (Chezy, Kutter, Bazin, and Manning's equations or methods), each of which might provide a different value (King, 1918).

Regardless of the approach, important takeaways were that (1) the methods focused on a larger, peak flow (see Figure 19), and (2) that this focus did not necessarily capture a wider spectrum of flows, both larger and smaller, that could occur at the crossing.

From the 1910's through 1930's, a variety of Congressional and Federal actions began to advance hydrologic practice, mostly in a flood control context (White 1945). Still, Federal approaches and standards still retained a corresponding diversity of flow and flood related engineering approaches. For example, in 1942, Dr. Gilbert White (White 1945) describes that *"… each district engineer [of the United States Army Corps of Engineers] was free to attack the flood problem as he saw fit, and the result was a series of reports displaying a considerable variety in methods."*

Differing Federal agencies attempted to develop and apply some standards related to their authorized missions. The Army Corps of Engineers developed standards for its navigation and flood control missions. The Bureau of Public Roads (BPR), precursor to the FHWA, developed "standards" applicable to hydraulic appurtenances, such as culverts (BPR 1919).

By the 1940's and 1950's, determining hydraulic behaviors for bridges and culverts had begun to evolve beyond empirical approaches. Statisticians sought to improve hydrologic and statistical flood flow estimate methods, including introducing probabilistic concepts such as the "return period" (Gumbel 1941). The concept of the return period remains the predominant flood and flow characterization method in use within the United States.

D.2.1.2 Peaks, Hydrograph and Low Flows

Natural waterways exhibit what is known as "unsteady flow." In other words, the water surface elevation, horizontal extent, and velocities of the waterway vary as a function of fluctuations in flow. These fluctuations may occur over various time frames. To illustrate, a rainfall event results in water (e.g., runoff) entering a stream. The stream does not suddenly reach some peak flow. Rather, over time, at any location on that stream, the flow increases to some peak flow and then recedes to some baseflow condition (see Figure 19). Hydrologists define this change of flow over time as a "hydrograph" (Figure 19). The term "rising limb" refers to the portion of the hydrograph where the flow increases. The term "recession limb" (or "falling limb") is that portion of the hydrograph where the flow decreases.

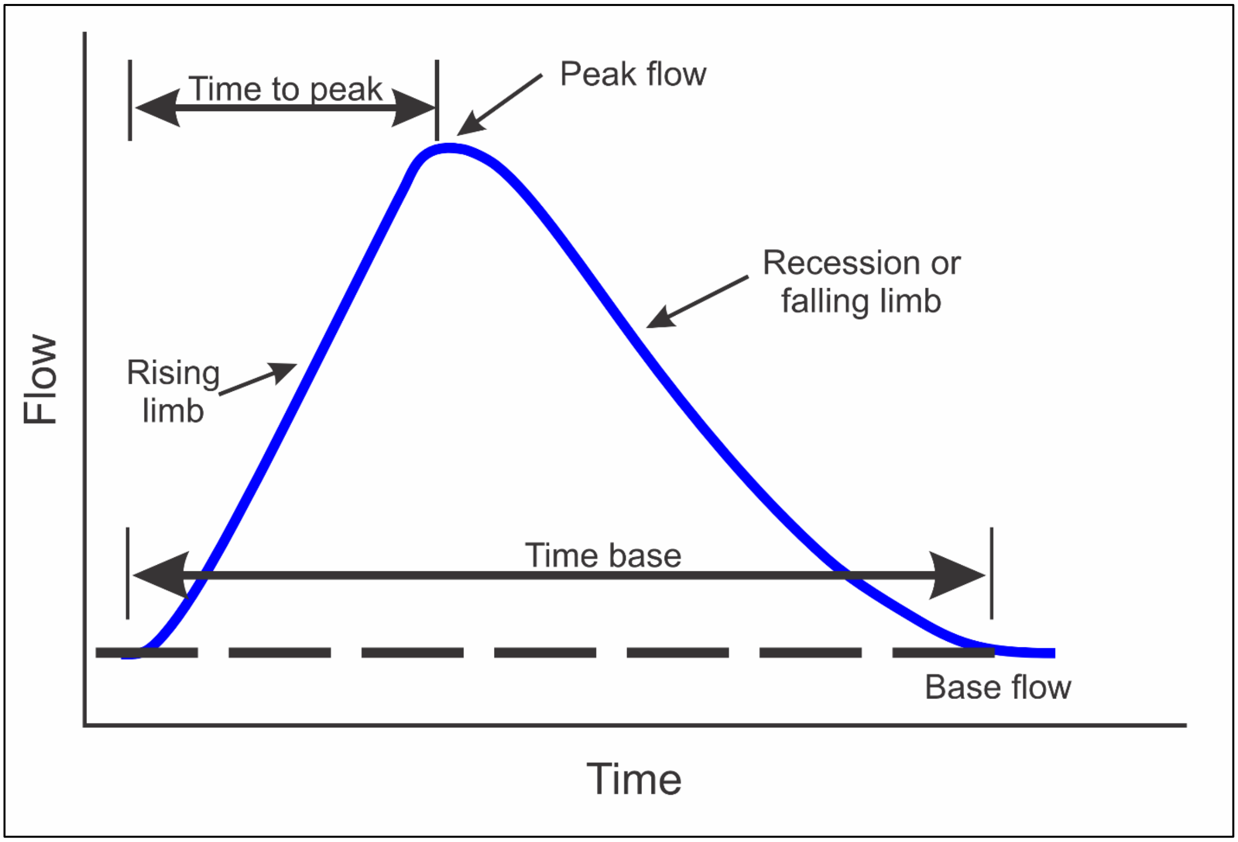

Figure 19. Conceptual representation of a hydrograph.

Additionally, whereas the duration of a rainfall event may occur over hours or days, flow may also vary on a seasonal basis (e.g., as a response to snowmelt or monsoons), an annual basis, or over even longer-term timeframes (e.g., El Niño or la Niña fluctuations). To better understand the ramifications of these longer durations, “flow duration” characteristics of a stream are of interest to hydrologists, geomorphologists, and engineers. The term flow duration refers to the *“cumulative frequency curve that shows the percent of time specified discharges were equaled or exceeded during a given period. It combines in one curve the flow characteristics of a stream throughout the range of discharge, without regard to the sequence of occurrence”* (USGS 1959). The flow duration concept becomes useful when trying to characterize what range of streamflow might allow aquatic organism or fish passage at some location.

Unfortunately, it may be difficult to measure streamflow, which normally requires some type of stream gaging station in the proximity of the site. FHWA supported research, being conducted by the USGS, seeks to provide the means to characterize flow duration and other hydrologic information for sites across the United States that do not have a stream gaging station. The research seeks to capture high flow, mean flow, and low flow situations.

How do hydrographs and flow duration concepts apply to culverts? Traditional culvert hydraulic design approaches allowed potential submergence of the upstream entrance (i.e., allowable headwater) at peak design flow. One consequence when experiencing varying flow conditions is that these culverts tend to alter (or attenuate) the hydrograph, reducing the peak and increasing the duration of flow as it continues downstream. Altering the flow duration changes the frequency in which certain important flows might occur in a stream. Changing natural systems tends to result in introductions of instabilities to that system until the system establishes some (new) equilibrium. That instability may result in impacts to passage, habitat, and connectivity of the waterway.

Assessing natural flow conditions should not just focus on the higher flow events (that occur less frequently). Natural waterways also experience periods of flow lower than average flow, resulting in “low flow” stream conditions. Examples of such conditions may be seasonal periods of lower rainfall, drought conditions, etc. These low flow periods also have some associated frequency and flow duration characteristics. Sometimes, “low flow” means no stream flow at all. Hydrologists may classify such streams as ephemeral or intermittent. Over a typical year, an ephemeral stream has flowing water only during and shortly after a precipitation event. An intermittent stream has flowing water during certain periods of the year, the water source being snow melt or groundwater. Intermittent streams may supplement their flow during precipitation events. Again, traditional culvert design approaches may not adequately consider low flow conditions necessary for habitat and other ecological purposes.

Many (if not most) aquatic species have evolved to react to both higher flow and lower flow conditions. Fish rarely move upstream or downstream during peak flows or at very low flows and will typically hold in an area of lower velocity during peak flows and seek cool water and abundant food during low flows. For example, some fish species make their migratory “runs” during periods of the rainfall induced rising limb of the hydrograph. As another example, during low flow conditions, species may use small pools within the waterway as habitat. A water crossing with an exposed bottom (base or invert) may hinder such habitat.

Bridges, as they span larger portions of the waterway (to varying degrees), do not typically face these varying flow situations and conditions to the same extent as traditional culverts. Dams and other larger structures can exacerbate these hydrologic situations.

D.2.2 Evolving Bridge Hydraulic Practices

In the 1950’s the BPR began to develop and support usage of more physics-based approaches and standards. For bridges, BPR hydraulic engineer Joseph N. Bradley (Bradley 1959) noted: *“No generally accepted method has existed for the design of bridge waterways. The determination of the length of a bridge over a stream has been left to the bridge engineer's personal observation and experience.”* Bradley’s solution was to develop techniques that calculated the bridge backwater (i.e., the amount of additional water surface elevation increase resulting from the physics associated with bridge constricting the natural channel). Being able to predict the backwater allowed the designer to evaluate different waterway opening configurations (e.g., span and elevation of the low chord) and select the size that allowed passage of some peak flow without the backwater exceeding some desired water surface elevation. The approach allowed consistent assessment of this backwater level versus the size of the span. While the approaches to make such calculations have vastly improved over the intervening decades, this backwater approach remains the typical bridge sizing practice to this day (although refinements to physics, including more complex approaches, have also occurred). The approach also lends itself to considering a variety of flow conditions at the bridge crossing as most models allow for the selection of multiple scenarios. Today, an increasingly common modeling approach is to use two-dimensional (2D) (Figure 20) and three-dimensional (3D) (Figure 21) models to represent the hydraulics through a bridge crossing.

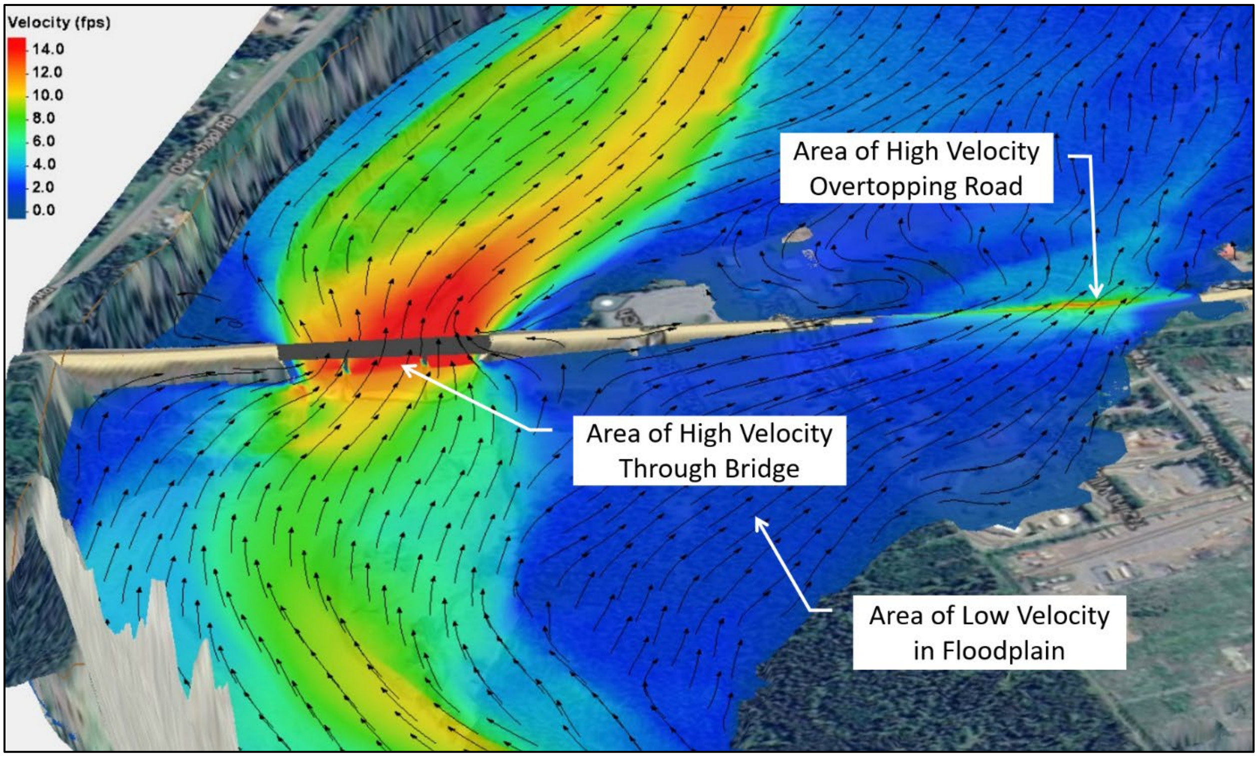

Figure 20. 2D Hydraulic model applied to a bridge crossing.

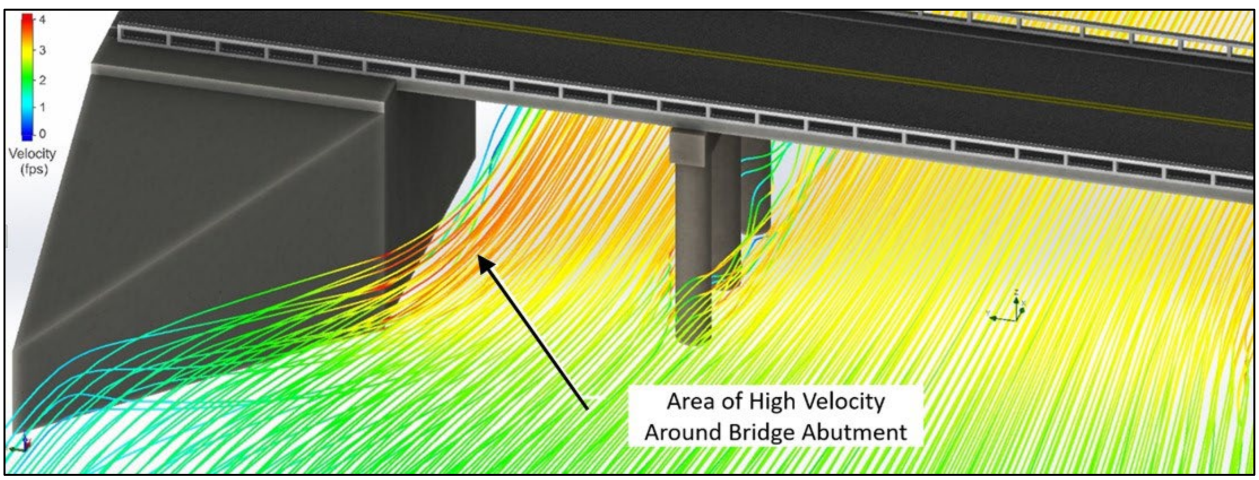

Figure 21. 3D (CFD) Hydraulic model applied to a bridge crossing.

D.2.3 Evolving Culvert Hydraulic Practices

For culverts, in 1945, BPR hydraulic engineer Carl F. Izzard noted the following: *"The most advanced design practice favors design of the culvert to carry the flood of occasional occurrence without submergence of the entrance end being capable of handling the maximum flood without excessive damage to property or significant interruption to essential traffic. The design engineer must develop his own policy fitted to the economic value of the particular class of transportation facility under consideration. Low traffic roads may be designed deliberately to be overflowed several times a year for short periods of time (a few hours) without seriously impairing their usefulness. … On the other hand, highways carrying important traffic are usually designed to be* *usable at all times regardless of flood stages to the extent that practical considerations will permit*" (Izzard 1945).

However, in the same report Izzard proposed a culvert hydraulic methodology that applied physics (i.e., energy equation), with variables related to the culvert type and conditions. The result of those computations provided some "allowable headwater" (i.e., ensuring the upstream water surface elevation remains below the roadway surface elevation) as meeting the needs for "important traffic" described earlier.

Over the following decades, Izzard and others refined the physics-based approach to estimating culvert hydraulics conditions. These included refinements to the various culvert hydraulic equation variables and coefficients. However, what remained was the concept of designing culvert sizes for some allowable headwater associated with some peak flow.

In contrast to bridge hydraulics design criteria, historical culvert hydraulic design criteria may allow the complete submergence of the culvert opening and partial inundation of the upstream roadway embankment. The resulting hydraulic conveyance may induce greater velocities within and downstream of the culvert barrel and expose erosive forces to portions of the downstream waterway (Figure 22). These hydraulic conditions often serve as primary barriers to passage of aquatic species and disruption of movement of sediment, wood, and other stream transport mechanisms.

Also, unlike bridges, the resulting (and current) culvert hydraulic methods and models typically still represent the same approaches that Izzard advocated in 1945, although FHWA and others are conducting research on culvert hydraulics to better characterize flow behavior in culverts. This methodology often causes conflicts with the required hydrology and hydraulics most effective for AOP. Recall that Chapter 2 related how fish and other aquatic species need to move both upstream and downstream at a large range of waterway flow conditions.

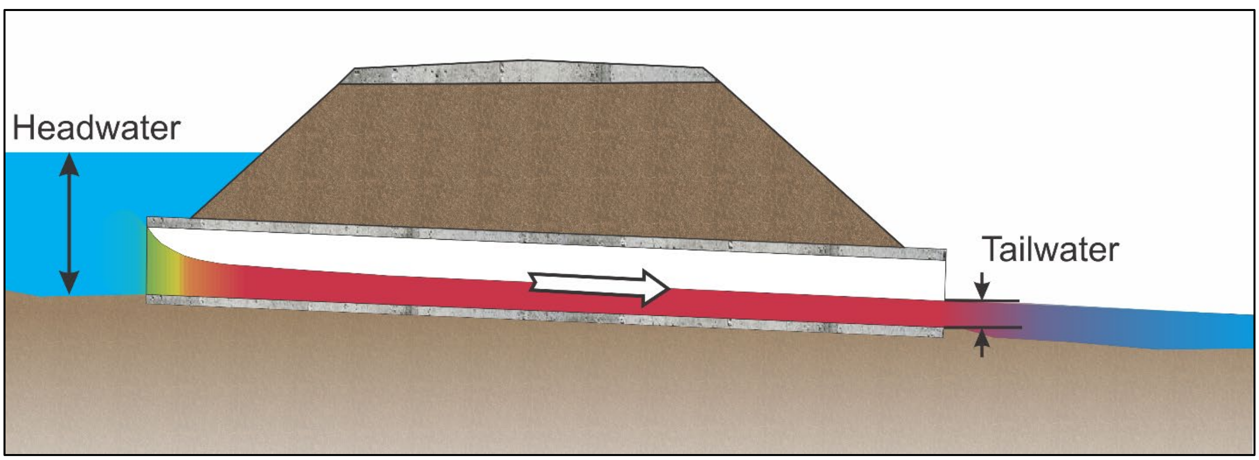

Figure 22. Example of submerged culvert.

Many AOP culvert design methods do not allow submergence of the culvert inlet, which combined with a larger opening, can better mimic hydraulic conditions within the culvert to those naturally occurring in upstream and downstream reaches (Figure 23). These hydraulic conditions within the culvert structure allow for more natural passage of flow, aquatic species, sediment, wood, and other stream transport mechanisms.

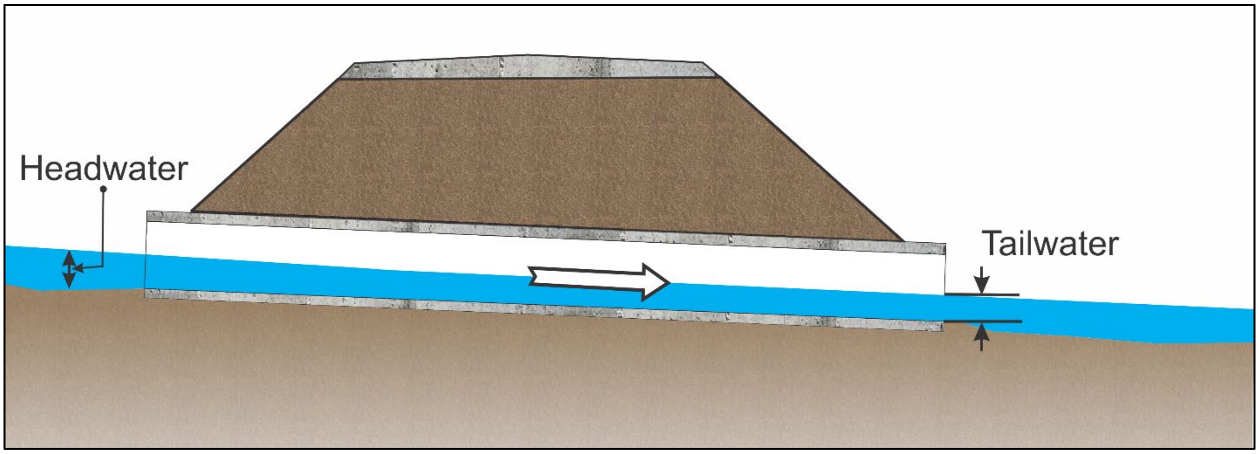

Figure 23. Example of unsubmerged culvert.

D.2.4 Takeaways

It is important to understand the evolution of the above-mentioned historical methods for sizing culverts and bridges. Below is a summary of a few of those:

- The use of a single "peak flow" for AOP design approaches may not characterize the broader range of flows experienced within a stream that are important for aquatic species and AOP.
- While bridge hydraulics seeks to prevent water surface elevations from contacting the low chord of the bridge superstructure (Figure 14), traditional culvert hydraulics can allow such upstream submergence, which often serve as primary barriers to passage of aquatic species.
- The historical culvert related concept of "allowable headwater" (sometimes described as "hydraulic conveyance") can impede the natural transport of sediment and wood and can result in an AOP barrier.
- Bridge hydraulics (having larger spans) may have robustness for a larger range of waterway flows. However, bridges are generally more expensive than culverts and may require inspections over their service life.

Just as bridge hydraulics have taken advantage of improved methods, the FHWA anticipates that design methods for AOP structures will follow a similar path as the field evolves and advances and as practitioners engage in increased dialogue and share lessons learned among the interdisciplinary community tasked with improving habitat connectivity.

Appendix E. Example Pre-Design Checklist

Potential entities considering an AOP project (or other types of projects) may find the following pre-design checklist, adapted from a Washington DOT checklist, useful in developing an AOP project baseline scope and cost estimate. Alternatively, they can further customize this checklist to specifically address AOP design for their particular situation.

Hydraulics

- ☐ Hydraulics Pre-Design Memo
- ☐ Site visit summaries or field notes

Environmental

- ☐ Wildlife Habitat Connectivity Memo
- ☐ Preliminary wetland and sensitive area information
- ☐ Preliminary threatened and endangered species, critical habitat, and essential fish habitat information

Geotechnical

- ☐ Geotechnical Scoping Memo

Bridge and Structures

- ☐ Type, size, and location proposal

Maintenance

- ☐ Documentation from area maintenance regarding any issues they are dealing with at the site.

Survey

- ☐ Survey data including field books, surfaces, and base map files.
- ☐ Horizontal and Vertical Datum information.
- ☐ Survey Control Data.

Traffic

- ☐ Crash Data (last 5 years).
- ☐ Traffic Volumes (ADT).
- ☐ Basic Traffic Control Strategy for Construction. Usually a narrative of expected staging/closures.

Utilities

- ☐ Utility Franchise and Permit report
- ☐ As-Built data from utilities in the vicinity

Right of Way

- ☐ Parcel and Ownership data for adjacent properties
- ☐ Current Right of Way plans in electronic form

Documentation

- ☐ Basis of Design
- ☐ Project Profile
- ☐ Basis of Estimate
- ☐ Risk Register
- ☐ Value Engineering Study (if applicable)

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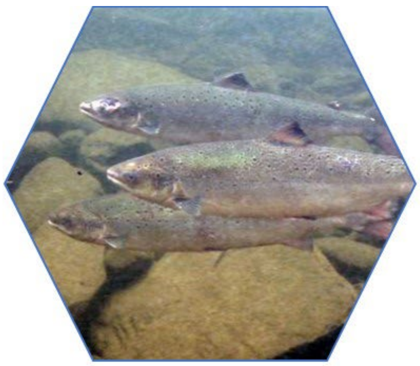
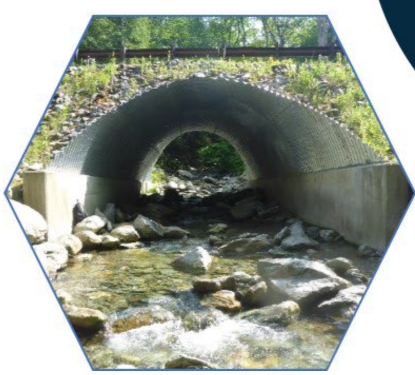
Crooked Creek (Kasilof, AK)

Case Study 1.



Culvert AOP Program



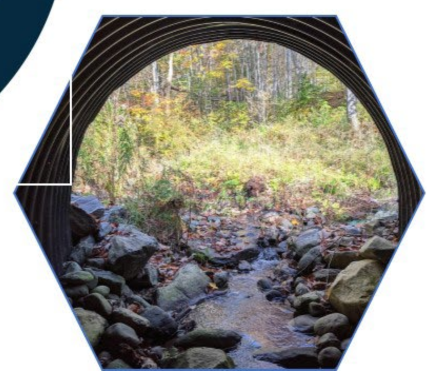


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Table of Contents

List of Figures

Acknowledgements

Figures 1, 6 through 15 courtesy of Alaska Department of Fish and Game (used with permission). Figures 5, 4, 5, 16, and 17 courtesy of Alaska Department of Transportation and Public Facilities (used with permission). All remaining photos and imagery by FHWA.

Project Owner and Collaborators

Project Owner: Alaska Department of Transportation and Public Facilities

Project Collaborators:

- Alaska Department of Fish and Game
- United States Fish and Wildlife Service
- NOAA Restoration Center
- Kenai Watershed Forum

Project Location

Stream Name: Crooked Creek

City, State: Kasilof, Alaska

Latitude-Longitude: 60°18'07.5"N 151°16'17.2"W

Road: State Route 1 (Sterling Highway)

Structure Type: Structural Plate

Aquatic Species of Concern

- Chinook Salmon
- Coho Salmon
- Sockeye Salmon
- Pink Salmon
- Steelhead Trout
- Rainbow Trout
- Dolly Varden
- Pacific Lamprey
- Threespine Stickleback

Co-Benefits

- Resilient Infrastructure
- Reduction of Flood Risk
- Reduction of Maintenance Costs & Risks
- Wildlife Crossing (Small Mammals)
- Safer Roadway for Traveling Public
- Sport Fishery for the Public
- Personal Use Fishery for Alaska Residents

Pre-Construction and Post-Construction Conditions

Figure 1. Pre-construction (left) and post-construction (2021) (right).

Design and Construction Cost

No cost data available.

Pre-Construction Conditions

Background

The Alaska Department of Fish and Game (ADF&G) received funding from the Exon Valdez Oil Spill Fund (EVOS) to replace the crossing at Crooked Creek. The new structure was constructed as part of the Alaska Department of Transportation and Public Facilities (ADOT&PF) highway safety improvement program (HSIP): Sterling Highway Shoulder Widening milepost (MP) 97 – 118 project. The HSIP project widened shoulders on the Sterling Highway by adding an additional four feet to each shoulder. Crooked Creek crosses the Sterling Highway near MP 110.6. The crossing is approximately 2.5 river miles upstream of the Crooked Creek confluence with Kasilof River.

Species of Concern

The ADF&G fish resource monitor catalogues Crooked Creek as anadromous both upstream and downstream of the MP 110.6 water crossing. Crooked Creek has six anadromous fish species: Chinook, coho, and sockeye salmon; dolly varden; steelhead trout; and pacific lamprey, all of which benefited from the removal of the pre-construction culverts. In addition, Crooked Creek supports a broodstock collection program used to stock many sport fisheries on the Kenai Peninsula. The collection site is approximately 0.7 stream miles upstream of the crossing location.

Co-Benefits

In addition to the immediate improvements to fish passage, this project offered both social-economical and infrastructure resilience co-benefits.

Crooked Creek is a tributary of the Kasilof River, which is a large glacial system draining out of Tustumena Lake and emptying into Upper Cook Inlet. The confluence of Crooked Creek with the Kasilof River is approximately 6.8 miles upstream from the mouth of the Kasilof River. The Kasilof River is the second largest personal use fishery on the Kenai Peninsula. In 2021, a total of 101,159 salmon were harvested by dipnet, with an additional 18,497 being harvested by gillnets. The majority of these were Sockeye salmon returning to spawn in Tustumena Lake. This personal use fishery allows Alaskan residents with permits the opportunity to either dipnet or gillnet for salmon at the mouth of the Kasilof River.

With two historically disadvantaged communities and several small communities considered to be areas of persistent poverty on the Kenai Peninsula, these personal use fisheries are critically important in providing food resources. Although many of the fish caught at the mouth of the Kasilof River utilize habitat within the mainstem itself, research has shown that when a single watershed has a large variety of healthy habitat drainage wide, fish populations within those systems are healthier.

This project also improved infrastructure resilience. The original pipes were inadequate to convey high flows. Concerns for a potential road failure at this location arose when a similarly sized upstream crossing failed during a storm event in 2007, leading to concern regarding the safety of the road during future storms.

Pre-Construction Structure

Crooked Creek previously crossed Sterling Highway through a dual 8-foot span by 9-foot rise structural steel plate pipes (Figure 2). A 2001 culvert survey by ADF&G identified the overall fish passage rating to be “red”, meaning the pipes likely impacted fish passage. The site posed several challenges to fish attempting to migrate upstream to access spawning and rearing habitats. At low water conditions, flow inside the pipes was observed to be extremely low, being less than 6 inches on several occasions. At the outlet, the pre-construction culverts had a 6-to-8-inch drop from the culvert invert to a large scour pool, approximately 8 feet deep (Figure 3). The scour pool had been created due to high velocities exiting the pre-construction culverts.

The pre-construction culverts did not meet ADOT&PF criteria during the design discharge and limited the passage of ice and debris based on observations during routine inspections (Figure 4). This was due to the headwater divided by diameter (HW/D) being over 1.5 and the minimum clearance to pass ice and debris not being provided between the approach water surface elevation and the top of the culverts during the 2% annual exceedance probability (AEP) discharge (Q_{50}).

Figure 2. Outlet during 2017 inspection.

Figure 3. Scour hole during 2017 inspection.

Figure 4. Observed debris at inlets during 2013 inspection.

Utilities

No utilities were impacted as part of the project.

Right of Way

The water crossing and design elements of the project are fully within ADOT&PF right of way.

Water Crossing Design

Roadway Geometric Alignment

The Sterling Highway was the primary limiting geometric factor for the Crooked Creek water crossing. In the vicinity of the Crooked Creek crossing, the Sterling Highway profile gradually slopes to the south at approximately 1.3 percent. Under pre-construction conditions, during the 1% AEP event, model results showed water overtopping the road approximately 280-feet south (measured along the road centerline) from the center of the pre-construction culverts. At this location, the road centerline elevation was 90.2 feet, and the water surface elevation was 94.2 feet during the 1% AEP event. Therefore, the water depth over the road centerline was 4 feet. This was caused from backwater due to the pre-construction culverts. Under pre-construction conditions, the water surface elevation for a HW/D equal to 1.5 was 82.3 feet and 82.9 feet for the north and south culverts, respectively. Under post-construction conditions, the Sterling Highway profile will stay the same with the shoulder widening. However, the new structure capacity is increased to prevent the road from overtopping during the 1% AEP event. At the location stated above, the road is overtopped during the upper 90% confidence limit of the 0.2% AEP event for post-construction conditions.

Reach Geomorphology

Crooked Creek is a highly sinuous meandering stream. Typical of meandering streams is lateral channel migration caused by natural erosional and depositional processes. Typically, erosion occurs on the outside of meander bends and material is deposited on the inside of downstream meander bends. Erosion is typically greatest beyond the apex of the bend. This causes the meander to migrate downstream over time. Figure 5 illustrates the upstream and downstream meander bends upstream and downstream of the crossing (top of figure is north).

Figure 5. Crooked Creek aerial view. Google Earth imagery dated 4/17/2011.

Meander U2 was considered a threat to the pre-construction unprotected Sterling Highway embankment. The shoulder widening would only worsen the erosion potential. With time, U2 was expected to naturally migrate in the NW direction. Therefore, the potential for erosion on the embankment could increase with time if left unprotected. Survey data used for the lateral migration analysis showed meander U3 had been cut off due to natural processes. This likely had increased the velocity and increased the rate at which meander U2 migrated. Meander D1 was not considered an immediate threat to the Sterling Highway, though it is expected to flow adjacent to the Sterling Highway embankment during the design life of the post-construction structure.

In addition to lateral migration, degradation of the streambed occurred at the outlet of the pre-construction culverts due to the culverts being undersized compared to the natural channel width. The constriction increased outlet velocities that created a large scour pool that was approximately 110' wide and 8' deep at the outlet. Local aggradation was also observed upstream of the pre-constructed water crossing, likely due to the culvert inlet elevations being too high and backwater during various flow events.

Bankfull width (BFW) was measured approximately 400-feet upstream (measured along the stream centerline) of the water crossing. Stream bank slopes varied but were measured as approximately 0.75:1 (H:V). Therefore, the bed width was only slightly less than the BFW at 24-feet. Outside the influence of the pre-construction culverts, the natural streambed slope upstream and downstream of the Sterling Highway was approximately 0.70 percent. The slope of the pre-construction north and south culverts were 1.48% and 1.73%, respectively.

A volumetric sample of bed material was taken with a shovel at a riffle about 375-feet upstream of the pre-construction culvert inlets. Results of a sieve analysis showed the D_{50}, D_{84}, and D_{100} was 15 mm (0.6 inch), 29 mm (1.1 inches), and 50 mm (2 inches), respectively. This correlates to approximately 75% gravel, 24% sand, and 1% silt/clay.

Project Hydrology

Crooked Creek generally flows north from the Caribou Hills to the Kasilof River, approximately 1.5 miles NW of the Sterling Highway crossing. The upstream drainage basin for Crooked Creek, southeast of the Sterling Highway, is approximately 54.4 square miles. The drainage area was delineated using USGS StreamStats version 3 and verified in ArcMap version 10.2 with 4-foot contours from the Kenai Peninsula Borough. The drainage area is primarily undeveloped and consists of brush alders and spruce forest.

Crooked Creek has not been gaged and its drainage basin is primarily undeveloped. Therefore, discharges were estimated using the linear-regression method described in the USGS Scientific Investigation Report 2016-5024, "Estimating Flood Magnitude and Frequency at Gaged and Ungaged Sites on Streams in Alaska and Conterminous Basins in Canada, Based on Data through Water Year 2012.". The upper limits of the 38%, 68%, and 90% confidence intervals were also calculated for each AEP event.

Water Crossing Design

The Crooked Creek water crossing was designed following design standards and guidelines developed by several agencies, including ADOT&PF, ADF&G, USFWS, FHWA, AASHTO, USGS, and FEMA. The ADOT&PF requires structures over 20' to be hydraulically designed for the 2% AEP event for all highways, except when located in a designated flood hazard area, where a 1% AEP event is required. The Crooked Creek water crossing is not located in a FEMA floodplain or floodway and therefore the 2% AEP event was used as the design discharge.

FHWA Hydraulic Engineering Circular (HEC) No. 17 (HEC 17) provides a hierarchy that has 5 levels of analysis. The levels focus on quantifying exposure to extreme flood events considering climate change and other sources of nonstationarity (i.e., changes in watershed land use/cover). Level 1 and 2 analyses were performed for this project, which uses confidence intervals of historical data. The project did not perform a Level 3 analysis, which uses projected precipitation data, due to appropriate precipitation projections for the project region not being available at the time of design.

In addition to ADOT&PF and FHWA standards and guidelines, the water crossing was designed to allow for fish passage following stream simulation criteria and other recommendations by ADF&G and the USFWS. The water crossing design simulated the natural stream characteristics (e.g., slope, width, sinuosity, substrate, etc.) as much as practicable. The channel design was based on surveyed cross sections and a BFW measurement of 27 feet, which was measured during a site visit with ADOT&PF, ADF&G, USFWS, and NOAA on May 30, 2017.

In addition to spanning the measured BFW, the following stream simulation design criteria were used for the water crossing:

- The structure was to be embedded at 40% of the rise.
- A low flow channel and overbank areas were constructed in the structure.
- The structure profile was similar to the stream slope of a reference reach chosen outside the influence of the pre-construction culverts.
- The structure accommodates 100-year flood flows.
- The upper substrate material in the structure was similar to the natural streambed material in the reference reach, as much as practicable, and was designed to be stable up to the design discharge, Q_{50}.

Following the various criteria and guidelines, the pre-construction Crooked Creek culverts were replaced with a single 35-foot, 2-inch diameter structural plate pipe. A bottomless structure with a similar span was also considered but was not chosen due to foundation issues. The 35-foot, 2-inch diameter structure is 8 feet greater than the natural bankfull width of Crooked Creek. This allowed for a channel with stable banks to be constructed inside the structure. In addition, since the structure is classified as a bridge pursuant to the National Bridge Inspection Standards, 23 CFR Part 650, subpart C, it is required to meet the applicable bridge requirements.

As part of the channel inside the structure, a V-shaped low flow channel with a depth of 1 foot and top width of 16 feet was constructed through the entire reach. The centerline of the low flow channel follows a slight meander through the reach. The purpose of the low flow channel was to ensure adequate depth for adult fish during low flow conditions. The low flow channel banks were designed to be entirely under water at ordinary high water (OHW).

Outside of the structure, the constructed channel was stabilized with riprap and rootwads with riprap below the channel for erosion protection. Brush layering with willows was also utilized behind the rootwads. The downstream scour pool was filled in and the stream channel was reconstructed to match the channel width, depth, bed elevation, and channel slopes downstream of the pre-construction scour pool. Due to the high sinuosity of Crooked Creek upstream of the Sterling Highway and the potential for lateral channel migration over the life of the structure, a guide bank on the upstream right bank was constructed at the structure inlet. The purpose of the guide bank was to provide a smooth transition and contraction of the streamflow through the structure opening. The upstream guide bank also reduced erosion risk on the approach embankment by cutting off the flow adjacent to the embankment. Furthermore, scour risk at the structure inlet was reduced due to flow lines being more parallel to the structure rather than impinging.

Project Hydraulics

In addition to utilizing a BFW to estimate a structure span, which would allow for natural processes, a hydraulic model was developed for the reach. The hydraulic model allowed for a comparison of hydraulic conditions through the reach and provided hydraulic parameters to assure a safe water crossing for the traveling public. The hydraulic model was based on the existing topography, using ground survey and field measurements and observations to better model the reach. From the existing conditions model, two additional post-project models were developed. The first post-project conditions model was based on the proposed channel geometry to be built within a 29-foot, 3-inch span structure. The second post-project conditions model was based on the proposed channel geometry to be built within a 35-foot, 2-inch span structure.

Based on the hydraulic analysis, the 35-foot, 2-inch diameter structural plate structure was recommended for the following reasons:

- It provided better fish passage by allowing a channel with stable banks to be constructed inside the structure.
- It provided greater hydraulic capacity.
- It provided greater clearance (vertically and horizontally) for debris and ice passage.
- It provided less potential for erosion at the structure inlet and outlet due to lower water velocities.

Scour Analysis

The ADOT&PF requires structures over 20 feet to be designed for scour for the magnitude flood through the 1% AEP event, that ADOT&PF assumes generates maximum total scour. A scour check is performed using the 0.2% AEP event, which ADOT&PF assumes corresponds to 1.7 times the magnitude of the 1% AEP event, or the road overtopping flood, whichever is the least. In addition to the geomorphic assessment, a scour analysis following FHWA HEC 18 was conducted for the 35-foot, 2-inch span structure. By using a full round pipe, with the invert embedded below estimated scour, the structure is resilient to scour which provides a safer roadway for the traveling public while also providing fish passage and the natural movement of water, sediment, ice, and wood.

Water Crossing Construction

Construction Window

The permitted fish window to complete all in water work was May 1 through July 15, 2019. The project was constructed within one construction season with the channel being diverted on May 5, 2019 to allow for construction and flow being re-introduced within the new crossing on June 22, 2019.

Maintenance of Traffic

Traffic was diverted around the site using a temporary bridge located approximately 2000 feet upstream of the Sterling Highway. The temporary bridge was placed at the site of the crossing that failed during a storm event in 2007. Post-failure the crossing was not replaced but the roadbed was left in place to serve as a temporary route during the anticipated replacement of the Crooked Creek – Sterling Highway crossing. After completing construction of the new highway crossing, the project removed the temporary bridge was removed and restored the riparian area.

Temporary Stream Diversion and Construction

After both a detour of Sterling Highway as well as a temporary stream diversion was in place, the preconstruction culverts were removed, which allowed for construction of the new water crossing. The temporary stream diversion was an open channel designed to accommodate the 2-year flow event and lined with dark material such that fish and other aquatic organisms were less noticeable to reduce chances of predation. Rock and gravel substrate were also added to facilitate fish movement and provide flow diversity and cover for small fish. Large numbers of adult salmon used the diversion channel to migrate to upstream spawning areas during construction. Figure 6 through Figure 11 show the temporary stream diversion in place and the structural plate pipe being assembled.

Figure 6. Aerial view of temporary stream diversion and new structure.

Figure 7. Aerial view of temporary stream diversion.

Figure 8. Structural plate pipe being assembled.

Figure 9. Structural plate pipe being assembled.

Figure 10. Structural plate pipe being assembled.

Figure 11. Structural plate pipe being assembled.

After the structure was assembled, the channel geometry, including channel banks, was constructed within the structure using the designed streambed material (Figure 12).

Figure 12. Excavator placing the streambed inside the structure.

After constructing the new structure and channel features, Crooked Creek was reintroduced to the new water crossing (Figure 13). Adult salmon were observed moving through the new structure within hours of re-watering the new water crossing.

Figure 13. Crooked Creek reintroduced to new water crossing.

Water Crossing Monitoring

The ADOT&PF performs routine inspections of the new water crossing. In terms of structure resilience, the following are the relevant NBI codes for the Crooked Creek water crossing:

- Item 61 (Bank Protection) – 8 Protected
- Item 62 (Culvert) – 9 Excellent
- Item 71 (Waterway Adequacy) – 9 Above Desirable
- Item 113 (Scour Critical) – 8 Stable

ADF&G reviewed the designs and conducted site inspection to rate the new structure as "green," or unlikely to impede fish passage. Photo monitoring of the structure and the restored riparian areas has taken place annually (Figure 14, Figure 15, and Figure 16 depict various observed conditions). ADF&G operates a fish counting weir on Crooked Creek located approximately 0.6 miles upstream of the crossing which has been in continuous operation since 2005.

The Kenai Watershed Forum also conducted a before and after PIT-tag study to examine movement of juvenile fish into Crooked Creek from the Kasilof River and their passage through the crossing. The Forum completed fieldwork in 2022.

Figure 14. Crooked Creek water crossing 3 years after construction.

Figure 15. Crooked Creek water crossing 3 years after construction.

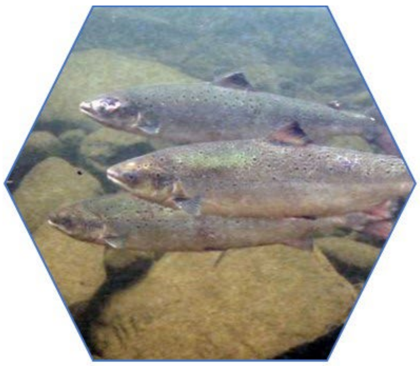
Figure 16. Stable benches in place during 2021 inspection.

With the installation of the new roadway embankment and woody material placed along the banks, anglers have used the banks to access Crooked Creek (Figure 17), which in some cases destabilized the banks from their original shape and height. The roadway slope and banks have re-stabilized over time and pose no threat to the roadway.

Figure 17. Performance of rootwads upstream during 2021 inspection.

Almasie Creek (Greenleaf, OR)

Case Study 2.



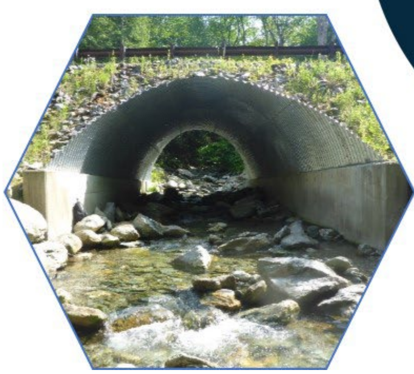
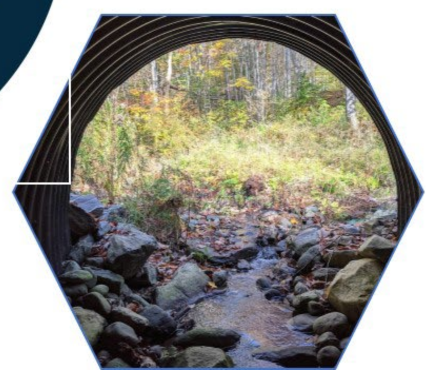



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Table of Contents

List of Figures

Acknowledgements

Left photo in Figure 1 courtesy of Oregon DOT (used with permission). Photos in Figures 3 and 7 courtesy of Casey Kramer (used with permission). Photos in Figures 4 and 5 courtesy of Oregon Department of Fish and Wildlife (used with permission). All remaining photos and imagery by FHWA.

Project Owner and Collaborators

Project Owner: Oregon Department of Transportation

Project Collaborator: Oregon Department of Fish and Wildlife

Project Location

Stream Name: Almasie Creek

City, State: Greenleaf, Oregon

Latitude-Longitude: 44°05'53.6"N 123°41'47.9"W

Road: Oregon Route 36

Structure Type: Corrugated Metal Pipes

Aquatic Species of Concern

- Coho Salmon
- Chinook Salmon
- Cutthroat Trout
- Steelhead
- Rainbow Trout
- Pacific Lamprey

Co-Benefits

- Rehabilitated structurally deficient culverts.

Pre-Construction and Post-Construction Conditions

Figure 1. Pre-construction (left) and post-construction (2022) (right).

Design and Construction Cost

- Total Cost: $88,300
  - Preliminary Engineering: $13,800
  - Construction: $72,000
  - Construction Engineering: $2,500

Pre-Construction Conditions

Background

The Oregon Department of Transportation (ODOT) and the Oregon Department of Fish and Wildlife (ODFW) are implementing a five-year Culvert Repair Programmatic Agreement (CRPA) project that allows ODOT to make specific short-term repairs to culverts without having to meet full fish passage criteria at the repair location. This enables ODOT to make critical repairs of aging culverts in a cost-effective manner, while providing a benefit to Native Migratory Fish (NMF) over the status quo by improving fish passage at each site repaired. In addition, ODOT paid $2.5 million into an ODFW-managed account that will fund the highest priority fish passage restoration projects off the State highway system.

This case study focuses on a culvert repair under the CRPA on Almasie Creek, which crosses Oregon Route (OR) 36 at milepost (MP) 16.41, approximately 16.4 miles northeast of Mapleton in Lane County, Oregon. Almasie Creek is a tributary to Lake Creek in the Siuslaw River Basin.

Species of Concern

Almasie Creek supports several species, including cutthroat trout, federally listed coho salmon, steelhead, rainbow trout, Chinook salmon, and Pacific Lamprey.

Co-Benefits

In addition to the immediate improvements to fish passage, the project rehabilitated the structurally deficient culverts, providing a safer roadway for the travelling public.

Pre-Construction Structure

The OR 36 MP 16.41 crossing of Almasie Creek consists of two 60-foot long, 72-inch diameter culverts. The pre-construction culverts were in critical condition due to voids, channel scour, and damage to the inverts from bedload abrasion and corrosion over time. In addition to being structurally deficient, the culverts were velocity barriers to aquatic organisms at high flows.

Utilities

There were no utilities at the water crossing.

Right of Way

The water crossing and design elements of the project are fully within ODOT right of way.

Water Crossing Design

Roadway Geometric Alignment

The roadway geometry was not changed as part of the project.

Reach Geomorphology

Almasie Creek is between a riffle-pool and plane bed channel morphology at the location of the water crossing. The reach has slopes ranging from 2%-3% and consists of sediment ranging from sands up to small cobbles. Localized outcrops of bedrock upstream of the crossing were observed to have drops in the water surface (Figure 2). Active channel widths were measured through the reach and ranged between 17 feet to 25 feet.

Figure 2. Bedrock outcrop upstream of culvert inlets.

Project Hydrology

Peak flows were determined with USGS StreamStats and adjusted based on conditions measured on site. The project hydrology analysis evaluated flows with the following annual exceedance probabilities (AEP) 0.5% (2-year), 2% (50-year) and 1% (100-year).

Water Crossing Design

The culverts were rehabilitated by placing a 4-inch-thick layer of concrete with welded wire fabric over the culvert corrugation crests. Fish rocks (small boulders) were embedded into the concrete to provide additional roughness to aid in reducing velocities inside the culverts (Figure 3).

Figure 3. Fish rocks embedded in concrete.

Project Hydraulics

The hydraulic analysis was performed utilizing both HY-8 and HEC-RAS, which demonstrated that the retrofit did not increase the headwater divided by diameter (HW/D) greater than existing conditions. The placement of the fish rocks decreased velocities and increased depths within the culverts. This improved access to approximately 2 miles of habitat for fish and other aquatic species.

Scour Analysis

The project did not perform a scour analysis as part of the effort.

Water Crossing Construction

Construction Window

The retrofit project was constructed within the in-water work period (between July 1 and September 15).

Maintenance of Traffic

The construction of the project did not affect the traveling public.

Temporary Stream Diversion

A temporary stream diversion was constructed to keep water and aquatic organisms out of the construction work area. The diversion consisted of a sandbag berm and visqueen to limit seepage into the work area (Figure 4, left). A block net was also installed to keep aquatic organisms from entering the work area (Figure 4, right).

Figure 3. Upstream berm and diversion pipe (left) and downstream diversion pipe and block net (right).

A diversion pipe was properly sized based on the estimated anticipated flows during the construction and fish windows. The diversion pipe was placed through one of the two culverts while the other was being repaired and then switched to the other culvert (Figure 5, right).

Figure 4. Downstream diversion pipe (left) and diversion pipe in culvert (right).

Water Crossing Monitoring

The OR 36 MP 16.41 crossing of Almasie Creek was assessed with the FHWA Western Federal Lands AOP monitoring protocol at a site reconnaissance in April 2022. During the site reconnaissance, the downstream portion of the culverts were observed to be partially inundated due to a downstream riffle, which created backwater (Figure 6, left). Some woody material was observed in the culverts which assisted in retaining streambed material in the culvert (Figure 6, right).

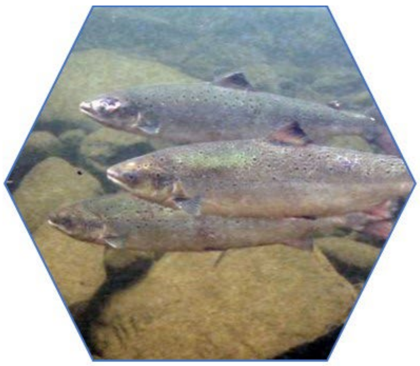

Figure 5. Looking upstream at culvert outlet (left) and looking downstream in right culvert (right).

In the right culvert (Figure 6, right), streambed material was observed on the invert of the culvert due to the placement of the fish rocks (Figure 7, left). The streambed material mainly consisted of gravels and small cobbles, with finer sediment deposited within the hydraulic shadow of the fish rocks (Figure 7, right). Small juvenile fish were also observed on the downstream side of the fish rocks and just upstream of the culverts.

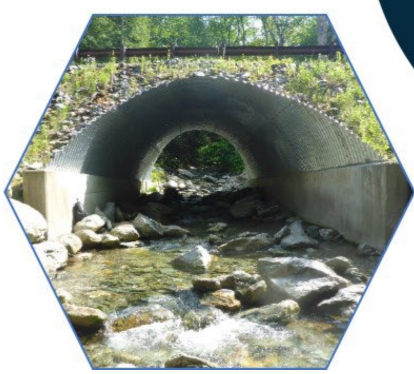

Figure 6. Fish rock with streambed material (left) and downstream side of fish rock with deposition (right).

Red Sandstone Creek (Vail, CO)

Case Study 3.



Culvert AOP Program



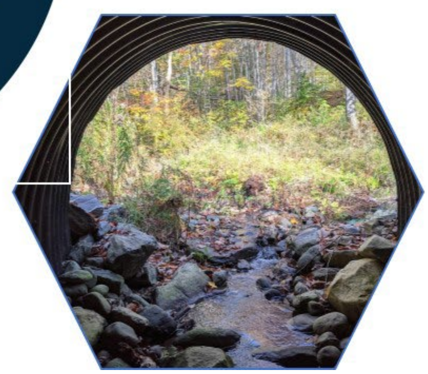


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Table of Contents

List of Figures

Acknowledgements

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Project Owner

Project Owner: USDA Forest Service

Project Location

Stream Name: Red Sandstone Creek
City, State: Vail, Colorado
Latitude-Longitude: 39°40'56.6"N 106°24'05.2"W
Road: Red Sandstone-Muddy Pass Road NFSR 700.1
Structure Type: Aluminum Box Culvert

Aquatic Species of Concern

- Colorado Cutthroat

Co-Benefits

- Flood Resilience
- Reduction of Maintenance Costs & Risks
- Terrestrial Wildlife Connectivity

Pre-Construction and Post-Construction Conditions

Figure 1. Pre-construction (left) and post-construction (2022) (right).

Design and Construction Cost

- Total Cost: $345,453
  - Design: $58,953
  - Construction: $286,500

Pre-Construction Conditions

Background

Red Sandstone Creek crosses Red Sandstone-Muddy Pass Road (NFSR 700.1) at milepost (MP) 3.6, approximately 4 miles north of Vail, Colorado. The water crossing is located within the White River National Forest.

Species of Concern

The main species of concern are Colorado Cutthroat; however, the crossing was designed to allow passage for other aquatic and terrestrial species.

Co-Benefits

In addition to the immediate improvements to fish passage, this project provided flood resilience, improved terrestrial and aquatic connectivity, and reduced maintenance costs.

Pre-Construction Structure

Red Sandstone Creek previously crossed NFSR 700.1 through a 95-inch span by 78-inch rise, 60.5-foot-long corrugated metal pipe (CMP). The CMP had a slope of 3.97% and was considered a velocity barrier to Colorado Cutthroat, among other aquatic organisms.

Figure 2. Pre-construction culvert inlet (left) and pre-construction culvert flow conditions (right).

Utilities

There were no utilities at the water crossing.

Right of Way

The water crossing is fully within the White River National Forest.

Water Crossing Design

Roadway Geometric Alignment

The Red Sandstone Muddy Pass Road (NFSR 700.1) geometry consists of a 20-foot wide aggregate surface. No changes to the horizontal or vertical alignment were made as part of the new water crossing; the skew of the structure to the road is 43 degrees.

Reach Geomorphology

Red Sandstone Creek is a step-pool channel morphology at the location of the water crossing (Figure 27). The reach has slopes ranging from 3%-5% and consists of sediment ranging from sands up to large boulders. There are localized outcrops of bedrock and generally limited cover of streambed material over the underlying bedrock (Figure 27). Bankfull widths (BFW) were measured approximately 200 feet downstream of the water crossing and ranged between 13 feet and 16 feet. Pebble counts of bed material were taken in the reference reach approximately 200 feet downstream of the crossing. Results of the analysis showed the D_{16}, D_{50}, D_{84}, and D_{95} were 48 mm (1.9 inches), 146 mm (5.7 inches), 310 mm (12 inches), and 439 mm (17 inches), respectively.

Project Hydrology

The drainage area of Red Sandstone Creek is within the White River National Forest and has an upstream drainage basin at the crossing of approximately 7.4 square miles. The USGS operates a stream gage 120 feet upstream from the inlet of the water crossing. This stream gage had over 40 years of continuous flow data and was thus utilized to develop a range of peak flow statistics to support the design of the water crossing.

Water Crossing Design

The Red Sandstone Creek water crossing was designed following the 2008 Forest Service "Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings" design guidelines. The water crossing (19-feet, 5-inch span by 4-foot, 11-inch rise (rise measured above top of precast footing/stemwall) by a 62-foot-long barrel length) was sized to accommodate the measured bankfull widths ranging between 13 feet and 16 feet and constructed banks. The structure tied the upstream and downstream stream slopes together at a gradient of 3.4 percent. This design slope was then matched to a reference reach within Red Sandstone Creek from which the design criteria was copied with respect to cross sectional width, streambed material, bedform features and dimensions, bank height, streambed rock size and shape, and other characteristics.

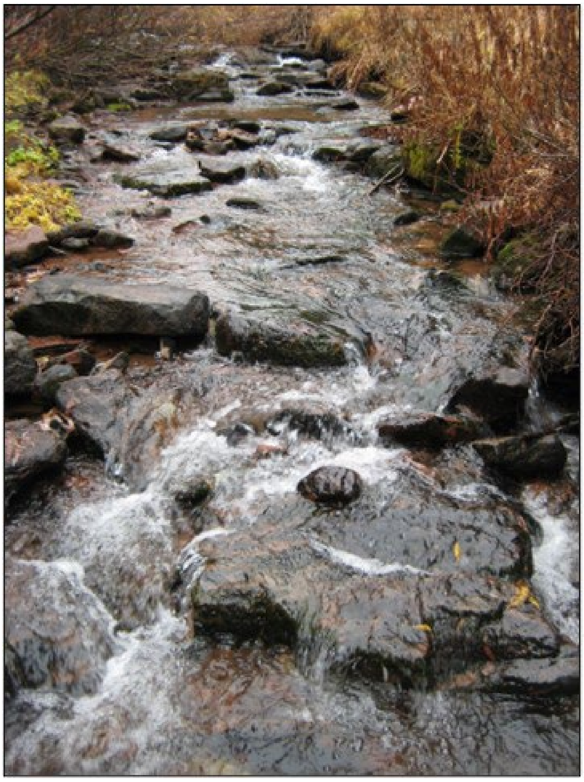
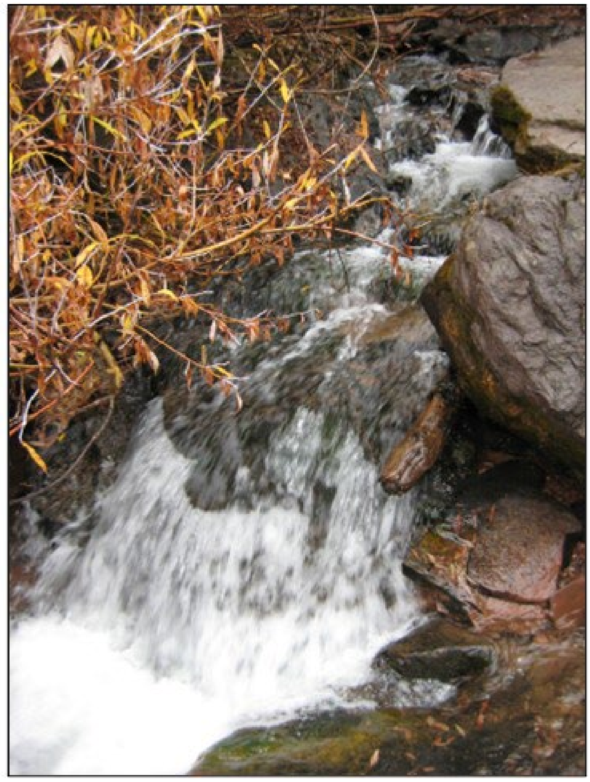



Figure 3. Observed reach downstream (left) and observed drop downstream (right).

Project Hydraulics

In addition to utilizing a BFW to estimate a structure span, which would allow for natural processes, a hydraulic analysis was conducted utilizing WinXSPro. The hydraulic analysis was based on the existing topography, using ground survey and field measurements and observations to better model the reach. From the existing conditions model, a post-project analysis was conducted utilizing the proposed structure span and channel design. The hydraulic analysis demonstrated that the new water crossing provided 4.2-feet of clearance between the approach water surface elevation and the top of the structure (freeboard) to pass ice and debris at the 1% annual exceedance probability (AEP) discharge (Q_{100}). Velocities estimated through the hydraulic analysis also demonstrated that the velocity barrier created from the pre-construction crossing would be eliminated.

Scour Analysis

The footings were sized and placed below the lower vertical adjustment potential (VAP), which was determined by analyzing the existing scour depths of the deepest pools outside of the culvert influence. At this site, a scour multiplier was applied to account for scour processes that occur during floods. Despite a portion of the footings being placed on bedrock, the scour analysis did not account for the presence of bedrock.

Water Crossing Construction

Construction Window

Construction occurred between September 28 and October 24, 2022, which was approved by Colorado Parks and Wildlife, the agency which sets the in-stream fisheries work window. Construction timing was balanced between access to a private in-holding that hosts weddings, hunting seasons, peak recreation use, low-flow, and the in-stream work window.

Maintenance of Traffic

Red Sandstone-Muddy Pass Road is a through-road accessible from Vail, Colorado and north of Wolcott from Colorado State Highway 131. A Road Closure Order was issued during construction for a section of road in the vicinity of the crossing. Due to alternative access, the narrow canyon, and the expense of a bypass road, the Forest Service decided a road closure was most prudent for this location.

Construction Sequencing

The subsequent construction process was followed for the removal of the pre-construction culvert and installation of the new water crossing (Figure 28 through Figure 30):

1. Structure and precast footings were ordered and scheduled for installation.
2. Installed traffic control signs and closed Red Sandstone-Muddy Creek Road.
3. Installed erosion control measures on Red Sandstone Creek.
4. Installed the stream-flow diversion system on Red Sandstone Creek.
5. Removed the existing culvert.
6. Excavated for the footing and structure placement.
7. Placed precast footings ensuring grade and level foundation.
8. Backfilled the footings and installed the streambanks and streambed.
9. Placed the structure on the footings and secured with grout on the receiving channel.
10. Removed stream-flow diversion system and returned flow to the channel.
11. Installed headwalls and wingwalls.
12. Backfilled the structure per manufacturer’s requirements.
13. Placed aggregate on the road surface.
14. Installed object markers.
15. Removed traffic control signs and barricades and re-opened Red Sandstone-Muddy Creek Road.
16. Seeded and finalized site work.

Figure 4. Construction 2022: assembling the structure.

Figure 5. Construction 2022: Setting precast footings with a crane.

Figure 30 shows the constructed streambed through the Red Sandstone water crossing after construction.

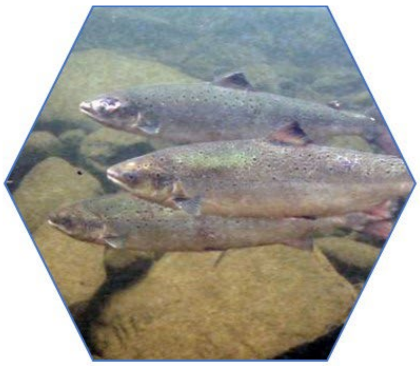
Figure 6. Streambed through water crossing in 2022.

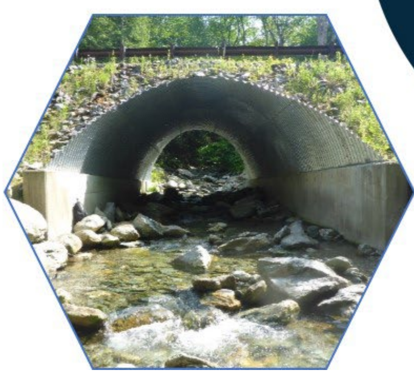
Water Crossing Monitoring

No monitoring of the new water crossing has been conducted.

Perkins Meadow Brook (Walden, VT)

Case Study 4.





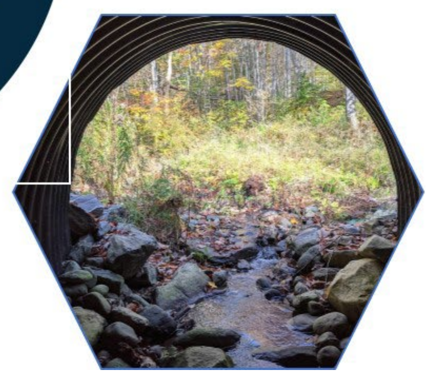


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Table of Contents

List of Figures

Acknowledgements

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Project Owner

Project Owner: United States Fish and Wildlife Service (USFWS), Caledonia County Natural Resource Conservation District (CCNRCD), Town of Walden, Vermont Department of Ecological Conservation, and Vermont Fish and Wildlife Department.

The design agreement was managed through the CCNRCD and the construction contract was managed by the Town of Walden.

Project Location

Stream Name: Perkins Meadow Brook

Town, State: Walden, Vermont

Latitude-Longitude: 44°28'22.3"N 72°17'24.5"W

Road: Cabot Road

Structure Type: Concrete Box Culvert

Aquatic Species of Concern

The main species of concern is the Brook Trout, however, the crossing was designed to allow passage for other aquatic and terrestrial species.

Co-Benefits

In addition to addressing aquatic organism passage, additional co-benefits included:

- Wildlife crossing.
- Infrastructure resiliency to flood and maintenance requirements.
- Improved water quality

Pre-Construction and Post-Construction Photos

Figure 1. Pre-construction (left) and post-construction (2019) (right).

Design and Construction Cost

- Total Cost: $287,800
    - Design: $12,100
    - Construction: $275,700

Pre-Construction Conditions

Background

Cabot Road crosses Perkins Meadow Brook south of the intersection of Cabot Road and Route 15, approximately 6 miles north of Cabot, Vermont. The water crossing is located within a rural setting.

Pre-Construction Structure

The previous crossing was an 11-foot diameter multiplate circular pipe that was perched 2.7 feet from the channel bed and approximately 40 percent of the estimated bankfull width. The inlet had a deteriorated rock and concrete headwall around the lower portion of the pipe and there was erosion occurring down the banks from the road to the channel. There was also scour occurring at the outlet of the pipe.

Utilities

There were no underground utilities at the water crossing but overhead lines spanned the site.

Right-of-Way

The Town of Walden owns the right-of-way (ROW). The project did not encounter any ROW issues.

Water Crossing Design

Roadway Geometric Alignment

Cabot Road consists of an approximately 25-foot-wide paved surface at the crossing. No changes to the horizontal or vertical alignment were made as part of the new water crossing; the skew of the structure to the road is approximately 85 degrees.

Reach Geomorphology

Perkins Meadow Brook is a step-pool channel morphology at the location of the water crossing. The step-pool channel is dominated by a cobble and gravel bed, with local boulder and bedrock control upstream and downstream of the culvert. Sediment transport was severely disrupted by the structure. A large mound of gravel and cobble exists over 500 feet upstream of the structure. Very little sediment is visible downstream and the channel bed is scoured and incised.

Project Hydrology

The drainage area of Perkins Meadow Brook at the crossing was estimated as 3.53 square miles using the USGS StreamStats program.

Water Crossing Design

The Perkins Meadow Brook crossing was designed such that the slope of the buried concrete box culvert was set to match the existing stream slope of 4.7 percent. The bottom was buried to provide continuous stream substrate upstream, downstream, and within the culvert. The width of culvert barrel was set at the estimated bankfull width. Overall, the design complied with the Vermont Stream Alteration permit requirements and the project restored six miles of fish habitat and passage.

Project Hydraulics

The project design did not conduct specific hydraulic analyses.

Scour Analysis

The project design did not conduct specific scour analyses.

Water Crossing Construction

Construction Window

Project construction started in August 2019 and continued for three weeks. In-stream construction could only take place between June 1 and October 1.

Maintenance of Traffic

The road was closed during construction.

Construction Sequencing

As depicted in through Figure 2 through Figure 13, the project followed the subsequent construction process for the removal of the pre-construction culvert and installation of the new water crossing. Specifically, (A) removing roadway embankment fill removed and exposing old pipe (Figure 2); (B) prepping the site for the new culvert (Figure 3); (C) placing the new culvert (Figure 4); (D) setting new wing walls; beginning of channel restoration (Figure 5); (E) restoring channel, setting culvert, and beginning of site restoration (Figure 6); and (F) Completing the project, including restoring the site and opening the roadway for travel (Figure 7).

Figure 2. Fill removed and old pipe exposed.

Figure 3. Site prepped for new culvert.

Figure 4. New box culvert placement.

Figure 5. New wing walls set, beginning of channel restoration.

Figure 6. Channel restored, culvert set, beginning of site restoration.

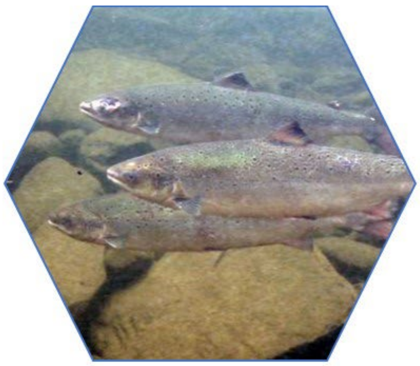
Figure 7. Project completed: site restored and road open.

Water Crossing Monitoring

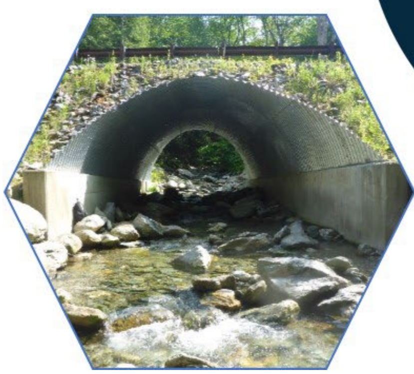
After construction, the project team electro-fished, marked, and released those fish below the structure and returned to sample above the structure to ensure fish passage. An as-built longitudinal profile was provided after construction. Periodic photos were taken to record status.

Logger Brook (Essex County, VT)

Case Study 5.



Culvert AOP Program



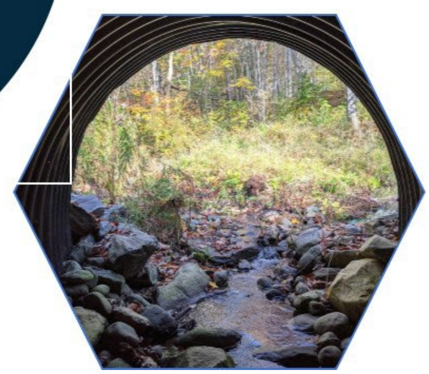


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Table of Contents

List of Figures

Acknowledgements

All photos and imagery by FHWA (FHWA Eastern Federal Lands, Figure 1 and 4. Western Federal Lands, Figures 2, 3, 4, 6, and 6).

Project Owner

Project Owner: USFWS (Silvio O. Conte National Wildlife Refuge)

Project Location

Stream Name: Logger Brook

Town, State: Lewis, Vermont

Latitude-Longitude: 44°53'55.5"N 71°47'01.6"W

Road: Lewis Pond Overlook Road (Route 103)

Structure Type: Concrete Box Culvert

Aquatic Species of Concern

- Non-specific (however, the pre-replacement culvert was identified as an aquatic organism passage (AOP) barrier).

Co-benefits

Intended co-benefits included:

- Increased resiliency
- Flood risk reduction
- Reduction of Maintenance Costs & Risks

The co-benefits of the replacement structure were anticipated based on the proposed structure providing a larger opening than the existing structure and because the concrete box would be more stable than the existing structure. Increased resiliency would result from reduced scour potential and flood risk reduction would result from increased hydraulic conveyance. HY-8 analysis showed that the proposed culvert would pass a 100-year flood event with more than 1.5 feet of freeboard.

Maintenance reduction was anticipated by the larger opening reducing potential for capture of woody material, though given the size of the woody material at the site, its capture and other maintenance would not be eliminated.

Pre-Construction and Post-Construction Photos

Figure 1. Pre-construction (left) and post-construction (2013) (right).

Design and Construction Cost

- Total Cost: $979,090
  - Design: $384,090
  - Construction: $595,000

Pre-Construction Conditions

Background

The project site is located within the Silvio O. Conte National Wildlife Refuge in Northern Vermont.

Pre-Construction Structure

The previous crossing was a corrugated metal arch pipe culvert with equivalent diameter of 7 feet. The culvert was perched 2 feet at the culvert outlet creating the AOP barrier.

Utilities

There were no underground or overhead utilities at the water crossing.

Right of Way

The project site is wholly owned by the U.S. Fish and Wildlife Service.

Water Crossing Design

Roadway Geometric Alignment

Lewis Pond Overlook Road consists of an approximately 15-foot-wide gravel surface at the crossing. No changes to the horizontal or vertical alignment of the road were made as part of the new water crossing; the skew of the structure to the road is approximately 80 degrees.

Reach Geomorphology

Logger Brook is a step-pool channel morphology at the location of the water crossing. The estimated pre-construction downstream average channel slope was approximately 5 percent for use in the culvert analysis program HY-8. The pre-construction upstream average channel slope used in the time of concentration analysis for the hydrology was 16.5 percent. As reported in the section on monitoring below, 2019 field measurements resulted in an estimate for the downstream channel gradient of approximately 3.8 percent. The upstream channel slope, shown in Figure 2, was estimated in 2019 as approximately equal to 5.2 percent. The differences in pre-construction slope estimates and post-construction monitoring estimates likely result from differences in location for the measurements, measurement methods, and, potentially, stream adjustment over time. The reach consists of sediment ranging from sand up to boulders as indicated in Figure 3.

Figure 2. Logger Brook (looking upstream from the culvert site).

Figure 3. Logger Brook bed material.

Project Hydrology

The drainage area of Logger Brook at the crossing of approximately 208 acres. In addition to considering low passage flow (1.0 ft^3/s) and high passage flow (8.6 ft^3/s) in the design of the replacement culvert, it was also designed for a 25-year flood event using the Rational Method (175 ft^3/s). The analyses applied regression and TR-55 approaches to evaluate flows sensitivities but used the Rational Method for the design flow value.

Water Crossing Design

The crossing was designed following the FHWA HEC-26 design procedure. HEC-26 compares cross sections in the representative reach to cross sections within the structure and simulates the shear stresses. The slope of the structure is carefully selected to match the representative reach of the stream. The slope of the buried concrete box culvert (8-foot span, 10-foot rise) invert as well as the embedment were set to approximately 9.4 percent. The embedment consisted of a 3-foot sub-layer of material sized to be stable at the 25-year event with a 1-foot layer of streambed material to match the native material to provide continuous stream substrate upstream, downstream, and within the culvert. The top layer bed material gradation was guided by a sample of the existing material.

Project Hydraulics

The project was designed using a tractive force approach as described in HEC-26. At the recommendation of the refuge, boulders were hand placed inside the culvert during construction. The boulders were not a part of the original design. Culvert hydraulics were analyzed by HY8.

Scour Analysis

Scour analysis was not required since the design was for an embedded box culvert.

Water Crossing Construction

Construction Window

Construction occurred between June and August 2013.

Maintenance of Traffic

The road was closed during construction.

Construction Sequencing

The subsequent construction process was followed for the removal of the pre-construction culvert and installation of the new water crossing.

Figure 4. Culvert construction placing the base (left) and top sections (right).

Water Crossing Monitoring

The Lewis Pond Overlook Road crossing of Logger Brook was assessed with the FHWA Western Federal Lands AOP monitoring protocol during a site reconnaissance in July 2019. The upstream channel (~ 200 ft upstream) and the constructed bed in the culvert had a similar gradient (~5.6 percent) and was observed to be a step-pool system consisting of sand, gravel, cobble, and boulders. The active channel width was estimated to be 7.5 feet with an average depth of 16 inches.

The downstream channel consisted of a milder gradient (~3.8 percent) stream with an estimated active channel width of 8.5 feet with an average depth of 18 inches. The downstream channel was modified by USFWS restoration efforts. The refuge manager described to the reconnaissance team that the refuge staff had implemented a "chop and drop" stream restoration, which the inspection team observed consisting of random felling of trees into the channel (see Figure 5).

Figure 5. "Chop and drop" stream restoration downstream of culvert looking upstream.

The channel within the structure had a steeper slope than downstream (~5.6 percent versus ~3.8 percent) which seemed to be controlled by the downstream rock sill and was evolving as the stream seemed to be reaching a quasi-equilibrium state. Random large roughness features, which were a component of the streambed mix, provided roughness within the culverts constructed channel.

The streambed material within the culvert was notably coarser than the observed native materials upstream and downstream of the crossing. The inspection team believed that the observable coarser streambed material was the stable sublayer component proposed in the HEC-26 guidelines. The streambed material which would have matched the native material to provide continuous stream substrate upstream, downstream, and within the culvert was observed to have been washed out of the culvert (see Figure 6) and not replenished.

It was not known to what degree the original as-built bed improved AOP, but it did eliminate the previous drop barrier and reduced velocity in the embedded culvert barrel compared with the replaced clay pipe. It is not known to what degree the bed status shown in the Figure 6 has influenced passage compared with the culvert that was replaced.

Figure 6. Smaller bed material washed out leaving larger material.

The reconnaissance team discussed the crossing with the USFWS manager for the refuge. They noted that the culvert had required on-going maintenance from the refuge staff, particularly due to the degrading conditions of the concrete work and due to the bed sediments being washed out after storm events. The runoff peak flows from these storms, compared to the design discharges, are unknown.

Lessons Learned

This AOP culvert replacement was completed over ten years ago and knowledge of effective approaches for AOP continues to grow. This site illustrates several lessons learned related to:

- Bed material gradation and placement
- Long term bed degradation and channel adjustment
- Scour
- Large woody material

As noted in the monitoring section, a site visit was conducted in 2019. Figure 43 shows that the streambed layer placed on top of the sub-layer of larger material has washed away and not been replenished. Elimination of the smaller fractions of the bed material allows flow amongst the voids in the larger materials. It can be difficult for aquatic organisms to swim through a coarse layer if there is insufficient flow.

The HEC-26 procedure relies on bed replenishment during the receding limb of a flood hydrograph to replace sediment washed out during the rising limb and peak of the hydrograph. If there is sufficient bed material upstream, the culvert bed may be replenished, but a sufficient supply has not been evident at this site. This is particularly important in supply limited reaches such as steep mountain streams, urban streams, and streams with wetlands, lakes, and other sediment sinks upstream of the culvert. In cases where there is uncertainty about upstream supply, it can reduce the risk of bed material loss to thoroughly mix these sediment sizes rather than installing separate coarse and fine layers.

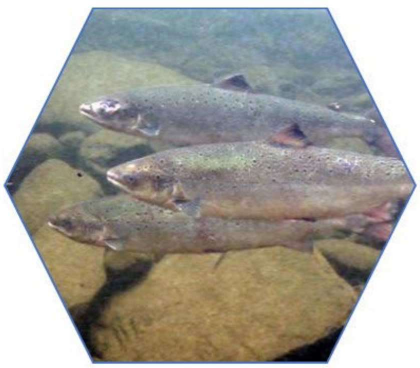
In addition, having a larger stable sub-layer at a site with long-term degradation trends can create a barrier within the culvert. The bed depth of native-sized materials needs to be sufficiently deep to account for vertical channel adjustments.

Although scour has not been a problem documented at this site, depth of footings for open bottom culverts and scour at either end of a well-designed AOP should be considered not only for as-built conditions but also for conditions that occur with channel bed degradation.

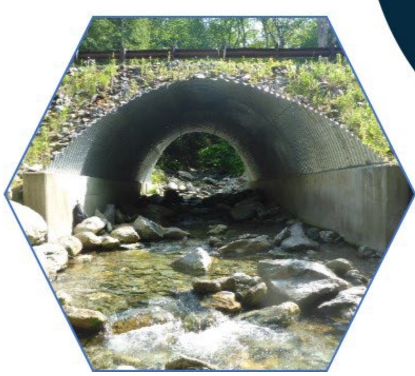
Finally, as shown in Figure 39, this site generates large woody material. The new culvert improves the passage of large woody material because of its increased size. Analysis of trade-offs between larger culverts for increased passage of large woody material versus smaller culverts and more maintenance to remove blockages at the culvert inlet are part of a comprehensive design process.

Half Mile Pond Brook (Amherst, ME)

Case Study 6.



Culvert AOP Program



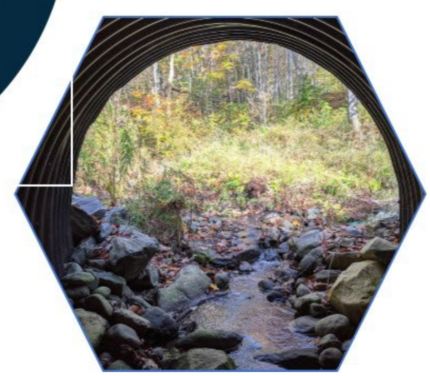


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Table of Contents

List of Figures

Acknowledgements

Photos in Figures 1 through 14 courtesy of Maine DOT (used with permission). All remaining photos and imagery by FHWA.

Project Owner

Project Owner: Maine Department of Transportation

Project Location

Stream Name: Half Mile Pond Brook

City, State: Amherst, Maine

Latitude-Longitude: 44°49'27.8"N 68°24'17.4"W

Road: State Route 9

Structure Type: Concrete Box Culvert

Aquatic Species of Concern

- Atlantic Salmon
- Brook Trout

Co-Benefits

- Resilient Infrastructure
- Reduction of Flood Risk
- Reduction of Maintenance Costs & Risks
- Improvements to Water Quality
- Wildlife Crossing – Small Terrestrial Animals

Pre-Construction and Post-Construction Conditions

Figure 1. Pre-construction (left) and post-construction (2021) (right).

Design and Construction Cost

- Total Cost: $1,413,949
  - Preliminary Engineering: $207,401
  - Right of Way: $21,856
  - Construction: $1,067,606
  - Construction Engineering: $117,086

Pre-Construction Conditions

Background

The Half Mile Pond Brook Bridge (#6246) carries State Route 9 over the Half Mile Pond Brook in Amherst, Maine. The crossing is located approximately 3.6 miles east of the Clifton town line. The previous structure was built in 1968 and consisted of a 16 foot, 7-inch span steel structural plate pipe arch supported by a layer of granular borrow. The previous structure had a 10-foot, 1-inch rise and was covered by approximately 8 feet of fill. The previous structure was perpendicular to the roadway alignment.

The roadway section over the previous structure was comprised of two 12-foot travel lanes with two 8-foot shoulders for a clear distance between the face of the guardrail, equal to approximately 40 feet. The pre-construction roadway embankments outside of the guardrail were set at an approximate 2:1 slope. The pre-construction structure was 100 feet in length along its centerline at the invert.

Species of Concern

Half Mile Pond Brook is designated to be a Tier 1 priority area and a critical habitat for the Atlantic Salmon Gulf of Maine Distinct Population Segment. In addition to Atlantic Salmon, the removal of the pre-construction culvert provided benefits to brook trout and other aquatic species.

Pre-Construction Structure

The previous structure was built in 1968 and was in poor condition (using NBIS appraisals) (Figure 45). The bottom plates were deteriorating with some noted holes, rust nodules with moderate pitting, and scaling. The structure was structurally deficient but in serviceable condition. The last inspection prior to replacement reported approximately 4 feet of undermining at the outlet. In addition to being structurally deficient, the previous structure was a barrier to fish due to the drop at the outlet and low flow depths through the structure.

Figure 2. Previous structure inlet (left) and previous structure outlet (right).

Utilities

There were no utilities attached to the previous structure; however, aerial utilities are present along the north side and include Emera Maine (power) and Union Telephone. The site has no known underground utilities. Further utility coordination was conducted during final design to coordinate construction activities, including the temporary relocation of Route 9 to the north during construction.

Right of Way

The new structure was installed within the existing Maine DOT right of way (ROW). Slope work for placing riprap aprons and clearing limits also stayed within the existing Maine DOT ROW. Two parcels required temporary easements for construction of the temporary road that provided a detour for the travelling public during construction.

Water Crossing Design

Roadway Geometric Alignment

The new roadway profile matches the pre-construction roadway at the project limits. Within the limits of work, the roadway profile is slightly raised to accommodate stopping site distance for a 50-mph design speed. The new horizontal alignment matches the pre-construction alignment and did not require any roadway widening. The roadway cross-section matches the pre-construction cross section, which is comprised of two 12-foot lanes at a 2-percent cross slope and two 8-foot shoulders to the face of guardrail.

Reach Geomorphology

Project reach slopes, ranging from 1- to 2-percent, and typical bedform material suggest Half Mile Pond Brook is classified between a pool-riffle and plane bed channel morphology (Figure 3).

Figure 3. Upstream reach.

Stream geometry and streambed material were measured in the upstream reach to aid in the design of the channel within the new water crossing (Figure 4). Bankfull widths (BFW) were also measured to assist in determining a structure span that would allow for natural processes to occur through the crossing and meet regulatory requirements. The Maine DOT and the United States Fish and Wildlife Service (USFWS) agreed upon a BFW of 16 feet.

Figure 4. Streambed material (left) and bankfull width measurement (right).

Project Hydrology

The watershed area for this project is 3.28 square miles with 0.2 square miles of wetlands. The watershed is located primarily to the north and west of the bridge location. Peak flows were calculated with techniques described in the United States Geological Survey (USGS) Water-Resources Investigations Report 99-4008, "Estimating the Magnitude of Peak Flows for Streams in Maine" for Selected Recurrence Intervals (Hodgkins, 1999) and "Peak flow regression equations for small, ungaged streams in Maine— Comparing map-based to field-based variables," U.S. Geological Survey Scientific Investigations Report 2015–5049 (Lombard/Hodgkins, 2015).

The Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) that covers the Town of Amherst, Maine was published July 20, 2016, and is a comprehensive report covering many communities in Hancock County. The FIS and Maine Flood Hazard Map indicate that Bridge 6246 is in unshaded Zone X, which is an "area of minimal flood hazard.". Unshaded Zone X is defined in the FEMA FIS as "areas determined to be outside the 0.2% annual chance flood hazard.". Therefore, there are no base (1% annual chance) flood elevations (BFEs) or depths within this zone.

Water Crossing Design

Half Mile Pond Brook is designated as a Tier 1 priority area and a critical habitat for the Atlantic Salmon Gulf of Maine Distinct Population Segment. Per Maine DOT's Maine Atlantic Salmon Programmatic Agreement (MAP), a culvert replacement in a Tier 1 priority area is required to follow 1.2 BFW and incorporate Habitat Connectivity Design (HCD) into the design of the project. The agreed upon measured BFW of Half Mile Pond Brook at the crossing is 16 feet. Considering a design cross-section of 1.2 BFW, the new structure provided a minimum clear span equal to 19 feet, 3 inches. The pre-construction culvert span of 16 feet, 7 inches did not meet 1.2 BFW criteria.

Based on the above parameters, three design alternatives were developed to replace the pre-construction steel plate pipe arch structure. Repair of the pre-construction culvert utilizing a reinforced concrete or fiber reinforced polymer (FRP) invert lining or sliplining was not considered a viable alternative due to the further reduction in hydraulic opening. These rehabilitation techniques would also produce a pre-construction structure opening that was inadequate to satisfy BFW requirements. Among the initial full replacement alternatives discussed, a steel plate pipe arch (similar to the pre-construction structure) was eliminated from consideration due to longevity concerns and future maintenance costs.

The three replacement alternatives include a precast concrete box culvert, 3-sided precast concrete frame, and a single-span bridge on pile-supported integral abutments. The sections below discuss each alternative.

Alternative 1: Precast Concrete Box Culvert

This alternative assessed replacing the pre-construction 16-foot, 7-inch steel plate pipe arch with a 20 foot span, 100 foot rise and 108 foot long precast concrete box culvert. The proposed roadway cross section over the culvert matched the pre-construction condition with two 8-foot shoulders and two 12-foot travel lanes. The alternative assumed slopes to have plain riprap up the slope to the top of the proposed box culvert. Ten-foot riprap aprons were assumed to be utilized at each end of the structure. Inside the box culvert, simulated streambed material was assumed to be installed to simulate natural banks and streambed throughout the structure. The culvert streambed material was covered and mixed in with the riprap aprons.

Route 9 crosses over Half Mile Pond Brook with no skew. The proposed box culvert was assumed to be installed with the headwall normal to the centerline of stream and parallel to the alignment. The box culvert was assumed to be bedded on a minimum 1-foot-thick layer of compacted granular borrow material for underwater backfill, per geotechnical recommendations. The pre-construction culvert invert elevations were proposed to be adjusted for the new structure to satisfy the requirements of the habitat connectivity design. The box culvert was proposed to have a minimum 2-foot-thick layer of simulated streambed material in the bottom of the structure as part of the habitat connectivity design. An interpretive subsurface profile, developed from the two field borings, estimated that the proposed bottom of the new box culvert would be in a glacial till layer. Rock excavation was not anticipated.

This alternative considered a temporary on-site detour for the culvert replacement. At the completion of the road closure, the new bridge would be re-opened to two lanes of traffic and the bypass would be removed and restored with natural materials. As a buried structure, the precast concrete box culvert was anticipated to have significantly lower maintenance costs over its service life compared to a traditional bridge.

This design alternative addressed the structural deficiencies noted for the pre-construction culvert by completely replacing the structure with a new precast box culvert. The proposed structure has an increased span length, satisfying the 1.2 BFW criteria.

The overall construction cost estimate for this alternative was approximately $1,440,000.

Alternative 2: Three-sided Concrete Frame Structure

This alternative assessed replacing the pre-construction steel plate pipe arch with a three-sided concrete frame structure. Some 3-sided concrete frames have sloped legs that are canted inward, requiring a structure spanning longer than 20 feet to provide a clear span of 20 feet at the estimated BFW elevation. A 20-foot span, vertical leg 3-sided rigid frame would provide a more economical solution and shorter span width.

This option was not considered further given the need to excavate to the required 7-foot frost depth for the footings and the time and cost increases required for dewatering.

Alternative 3: Integral Abutment Bridge

This alternative assessed replacing the pre-construction 16-foot, 7-inch steel plate pipe arch with a 65-foot integral abutment bridge. The bridge span was based on the required 20-foot clear span at the BFW elevation with 1.75:1 slopes up to the stem walls. The proposed cross-section would include two 12-foot travel lanes and two 8-foot shoulders with a total out-to-out structure width equal to 43 feet, 4 inches. A steel 3-bar bridge rail would be installed on concrete brush curbs and would likely consist of either steel girders or NEXT-beams. An 8-inch cast-in-place composite concrete deck would be placed with a high-performance waterproofing membrane and hot mix asphalt wearing surface. The integral abutments would not have any joints or bearings, decreasing typical bridge maintenance requirements. The substructure would be comprised of cast-in-place concrete abutment stems on piles with a cast-in-place end diaphragm/backwall. Concrete wingwalls would be utilized to retain the approach fill.

This option was qualitatively ruled out given the associated cost and need for a span length that is approximately three times longer than the culvert span given the depth of the structure. Similar span integral abutment bridges were advertised in 2016 and 2017 with costs ranging from $845,000 to $1.4 million. A similar span with traditional abutments containing an on-site bypass was given a bid of $1.86 million in January 2017, and costs were expected to further increase by the time this alternative would be constructed. The direct comparison of construction costs indicates that alternative 1 would be a more economical solution than an integral abutment bridge.

Selected Alternative

Alternative 1 was selected as it had the lowest expected construction cost. Both Alternatives 1 and 2 are buried structures which were expected to result in lower maintenance costs over the service life of the structures when compared to a bridge alternative. Alternative 1 is comprised entirely of precast elements, allowing for a more rapid construction duration. The preferred maintenance of traffic was the full closure of Route 9, with construction of a temporary bypass upstream.

The alternative 1 structure, a 20-foot span (10-foot rise) precast concrete box culvert, was designed to best match the stream profile, assuring there would be sufficient flow in the culvert during low-flow conditions. Constructed streambed material, based off pebble counts and observations of the reference reach, was installed in the culvert to closely simulate existing streambed material. The structure, in conjunction with the constructed stream banks, also allowed for passage of smaller terrestrial animals. The structure rise allowed for a sufficient height so that maintenance personnel would have easier access to inspect the structure.

Project Hydraulics

In addition to utilizing a BFW to estimate a structure span, which would allow for natural processes, a hydraulic model was developed for the reach. The hydraulic model allowed a comparison of hydraulic conditions through the reach and provided hydraulic parameters to assure a safe water crossing for the traveling public. The hydraulic model was based on the existing topography, using ground survey data, and supplemented with aerial LiDAR and field measurements and observations, to better model the reach. From the existing conditions model, two additional post-project models were developed. The first post-project conditions model was based on the proposed channel geometry to be built within the 20-foot span structure. The second post-project conditions model was developed to assess possible future hydraulic conditions due to the potential for long-term aggradation of the channel. For this model, the channel inside the 20-foot span structure was modeled assuming 2-feet of channel aggradation inside the structure. Results from both post-project conditions demonstrated the 20-foot span by 10-foot rise structure meets Maine DOT's preferred freeboard criteria of at least 2-feet over the 50-year flow and at least 1-foot over the 100-year flow.

Scour Analysis

The structure is a four-sided box culvert and is therefore not susceptible to scour. As determined from the hydraulic analysis, most of the upstream reach indicated either no change or a slight reduction in channel velocities, although a few channel velocities for the 500-year flow increased by up to 10 percent. Rock aprons were placed under the streambed materials at the structures' inlet and outlet. Additionally, a 2-foot-deep concrete toe wall was installed at both ends of the structure, providing additional protection against undermining.

Water Crossing Construction

Construction Window

Due to working in a fish bearing stream, work in the water was limited between July 15 and September 30, 2021.

Maintenance of Traffic

Several alternatives were evaluated to maintain traffic during construction, including full closure with an off-site detour; single lane of traffic with alternating one-way signals; and a temporary realignment of Route 9. Given the length of the off-site detour at this location, a single-phase reconstruction with a temporary on-site relocation of the Route 9 alignment was selected. This option relaxed schedule pressures on the contractor, improved traffic flow at the project site, and likely resulted in a lower user-cost during construction. This alternative also improved the safety of the traveling public and construction crews by separating work activities from motorists and eliminating the stop condition caused by temporary signals, which was a concern due to the high volume of truck traffic and high rate of speed that has been observed on this roadway. Though the estimated construction cost of this alternative was approximately 10% higher than the phased alternative, risks associated with traffic management, schedule, and safety were reduced.

Temporary Stream Diversion and Construction

A temporary stream diversion was constructed to keep water and aquatic organisms out of the construction work area. The diversion consisted of an earthen berm with sandbags and visqueen to limit seepage into the work area (Figure 5, left). A diversion pipe was properly sized based on the estimated anticipated flows during the constructions window. After construction, the earthen berm was removed and water was allowed to enter the site which assisted mixing in fine sediment to keep low flows on the surface of the newly constructed streambed (Figure 5, right).

Figure 5. Upstream diversion dam (left) and upstream diversion removed (right).

After the stream diversion and temporary alignment of Route 9 was in place, the pre-construction culvert was removed. The site was excavated and proper backfill was placed for the new structure. A split box culvert was utilized and placed in sections (Figure 6).

Figure 6. Placing structure segments (left) and placing ends of structure (right).

The split box culvert allowed streambed material to be placed without the top of the structure, allowing placement of the material with an excavator. The stream geometry, including channel banks and boulders serving as roughness elements, were constructed to design elevations (Figure 7, left). After the streambed geometry was constructed, water was introduced with a hose to assist in watering in fines into the newly constructed streambed (Figure 7, right).

Figure 7. Constructing streambed (left) and constructing streambed and boulders (right).

After the streambed was constructed, the top of the structure was placed and the rock scour aprons at the inlet and outlet of the structure were constructed (Figure 8).

After the scour aprons were constructed, the remainder of the streambed was constructed. The roadway was then reconstructed and traffic was routed to the permanent alignment of Route 9. Once traffic was routed to the newly constructed roadway, the temporary alignment of Route 9 was removed and the stream was reintroduced to the new channel and water crossing. Figure 9 shows the final constructed water crossing after flows had been reintroduced. Note the channel banks which assisted in keeping sufficient water depths during low flows.

Figure 8. Constructing scour apron.

Figure 9. Final constructed water crossing.

Figure 10 shows a closer view of the constructed streambed with banks. The banks also allow small terrestrial animals to safely cross the stream cooridor rather than on on the roadway.

Water Crossing Monitoring

The Maine DOT has a monitoring program to assess the effectiveness of AOP water crossings over time. They are working collaboratively with local and Federal resource agencies on the monitoring program. In 2019, several AOP sites were assessed with the FHWA Western Federal Lands Highway Division's AOP monitoring protocol. Maine DOT is working on implementing some aspects of the FHWA AOP monitoring protocols into their monitoring program. As part of their monitoring program, a long profile of the stream is surveyed to assess how it changes over time. Figure 11 shows a measuring tape being utilized to determine consistent stationing of the creek. Figure 12 shows the auto level survey equipment, which is used to survey elevations of the thalweg along the stationing.

Figure 10. Final constructed streambed with banks.

Figure 11. Upstream reach channel survey.

Figure 12. Upstream reach channel survey (looking downstream).

Figure 13 shows natural sources of woody material that is now freely able to move through the new water crossing to create aquatic organism habitat and enhance channel morphology. The ability to freely transport woody material has also reduced maintenance to the water.

Figure 13. Upstream reach natural woody material (looking downstream).

Figure 14 depicts the stream profile prior to construction and one year after construction. This comparison, along with future years of monitoring, will show how the stream profile is adjusting over time. Also shown on the graphic are the roadway surface, locations of previous and new structures, and the water surface during the year one survey.

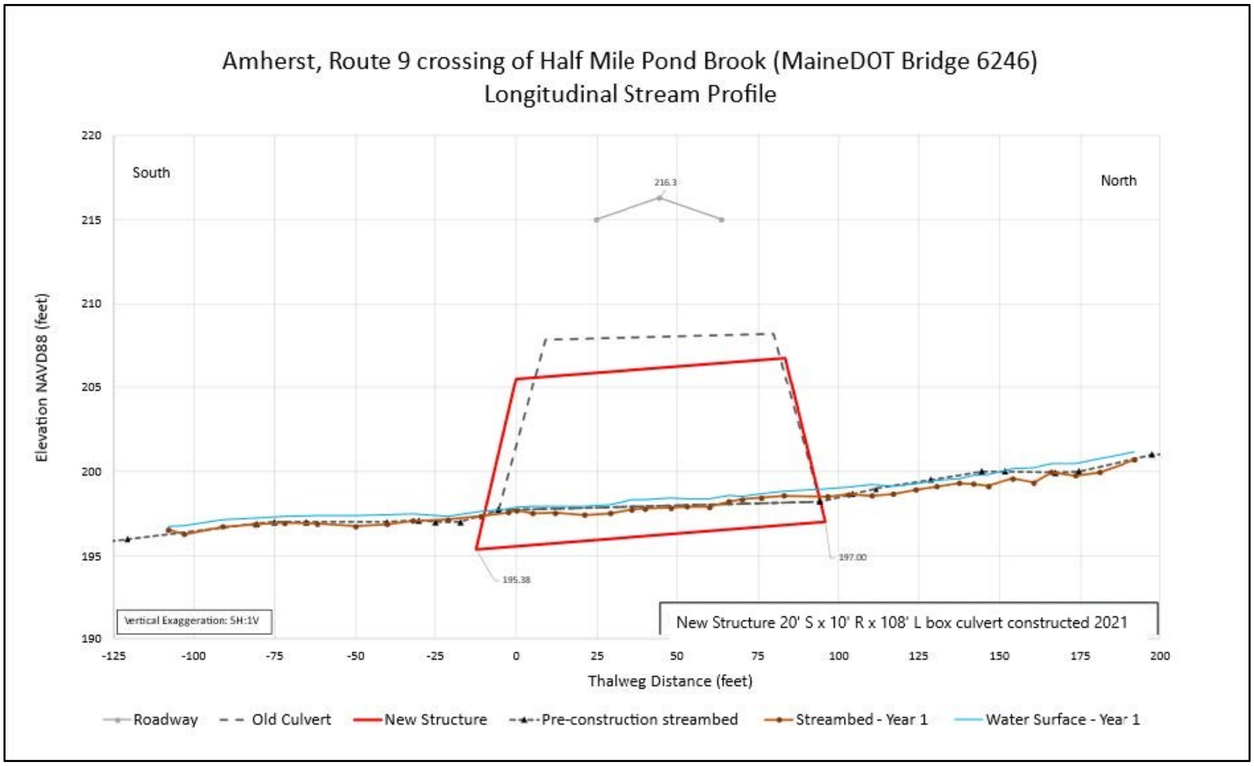

Figure 14. Longitudinal stream profile.

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U.S. Department of Transportation
Federal Highway Administration

Culvert AOP Program

AQUATIC ORGANISM PASSAGE AT HIGHWAY CROSSINGS:

AN IMPLEMENTATION GUIDE

July 2024 FHWA-HIF-24-054

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