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Avoiding and Minimizing Impacts to Aquatic Resources through Construction Design Standards

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16. Abstract The primary objective was to summarize best management practices that avoid and minimize impacts on aquatic resources through construction design standards. The study involved a literature review and discussions with experts to identify knowledge gaps regarding the effects of road and bridge construction on aquatic resources. We examined how other states responded to similar challenges and the standard specifications they used. These recommendations were based on findings from different states and best practices accepted by regulatory agencies. The research reviewed each state's processes and guidelines for stream-road crossings, focusing on culvert and bridge designs that affect aquatic resources. We identified that impacts on aquatic resources were commonly framed from the context of aquatic organism passage. Our report emphasizes the importance of bridges and culvert design specifics for maintaining ecological connectivity and the long-term health of aquatic ecosystems while also considering road crossings' structural integrity and safety. Information on the design specifics of culverts and bridges is described within our report. We provided a foundation for future studies and improvements to construction standards, aiming to reduce adverse effects on aquatic resources while meeting public safety and use demands.		
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- Scott Marlow, Illinois Department of Transportation
- Kamren Metzger, U.S. Army Corps of Engineers
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EXECUTIVE SUMMARY

Our research addresses the need for compliance with federal and state regulations, such as the Endangered Species Act and the National Environmental Policy Act, to protect threatened and endangered species. We identified inadequate data within agencies to meet these regulatory milestones effectively. Our primary objective was to summarize best management practices that avoid and minimize impacts on aquatic resources through construction design standards.

We conducted a thorough literature review and discussions with aquatic ecologists and professionals about the effects of specific road and bridge construction types on aquatic resources. We also examined how other states responded to similar challenges and the standard specifications they used. Our project aimed to develop a report with recommendations for updating the Illinois Department of Transportation's *Standard Specifications for Road and Bridge Construction*. These recommendations were based on findings from other states and best practices accepted by regulatory resource agencies. Our research provides a foundation for future studies and ongoing improvements to construction standards, ultimately aiming to reduce adverse effects on aquatic resources while meeting public safety and use demands.

Our research reviewed each state's processes and guidelines for stream-road crossings and focused on identifying culvert and bridge types and designs that affect aquatic resources under different conditions. Impacts on aquatic resources were commonly framed within the context of aquatic organism passage (AOP). AOP was used as a surrogate for all impacts on aquatic resources at bridge and culvert crossings because it is the most addressed issue in the literature. When natural streambeds and surrounding floodplains are altered, negative impacts on habitat and ecological value are inevitable. Water quality degradation, increased sedimentation, and turbidity were identified as immediate effects of construction. Changes to hydrological processes, such as altered flow regimes and increased erosion, were also noted as significant impacts. These changes can lead to extensive flooding upstream and intermittent streams downstream of the barrier. In the United States, East and West Coast states have contributed significantly to AOP science at stream crossings. West Coast states, driven by economically important anadromous fisheries, have comprehensive guidelines for fish passage. East Coast states focus on general connectivity for all aquatic organisms. Interior states have fewer specific documents, with Minnesota leading efforts in design and implementation, including performance assessments and climate change considerations.

Illinois has approximately 12,000 crossings coded as culverts under its jurisdiction. IDOT addresses AOP and aquatic natural resources, though it does not provide a specific document on the issue. The *Culvert Manual* and *Bridge Manual* include guidelines to set culvert invert elevations below the streambed to prevent barriers to fish migration during low water. However, these guidelines may result in undersized culverts that are ineffective long term. The recommendation is to use larger structures to maintain natural stream functions, including hydrological flow and sediment movement. The Illinois State Toll Highway Authority (ISTHA) also includes AOP-related guidelines in its *Drainage Design Manual*. It emphasizes the alignment of culverts with natural drainage paths and using embedded culverts to mimic natural water depth and velocity. IDOT has many tools for implementing AOP recommendations, but a stand-alone guidebook or handbook presenting information from an

ecological perspective would benefit the state. Examples include the *Minnesota Guide for Stream Connectivity and Aquatic Organism Passage Through Culverts* and *Stream Crossings in Georgia: A Handbook for Connectivity and Resilience*. These resources would support a forward-thinking approach to managing and informing residents about IDOT's work.

Various culvert designs were reviewed, each with modifications to suit different needs. Our report aimed to provide general, easily readable information on culvert design and implementation, emphasizing considerations to minimize impacts on aquatic resources. Aquatic organisms often face challenges when passing through road crossings—particularly culverts, which can act as barriers due to perched outlets, excessive flow velocity, low water, and sediment accumulation. Recognizing these problems, there has been growing interest in methods to facilitate AOP through road crossings, benefiting endangered and commercially valuable species. While the structural integrity of road crossings and public safety are top priorities, AOP can often be accommodated without compromising these concerns. Over the past two decades, various AOP approaches have been developed, refined, and implemented. The most practical and effective methods are now widely recommended in the United States. The primary goal is to maintain the natural continuity and function of streams through road crossings, ensuring natural hydrology, sediment movement, and debris flow. This approach supports the movement of aquatic organisms and preserves stream connectivity, enhancing the resilience of aquatic resources. Bridges are generally considered optimal for aquatic crossings and minimize impacts on aquatic resources due to their larger spans and ability to cross entire floodplains. While bridges are typically less problematic and require less ecological permitting, certain conditions, such as reducing scouring, must be met to minimize their impact on aquatic resources.

Our report emphasizes the importance of design standards for bridges and culverts for maintaining ecological connectivity and the long-term health of aquatic ecosystems while also considering the structural integrity and safety of road crossings.

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CHAPTER 1: INTRODUCTION

NEED AND BACKGROUND

Under the federal and state Endangered Species Act and the National Environmental Policy Act, regulatory stipulations must be met to minimize, avoid, or mitigate effects on threatened and endangered species. However, there is insufficient data within the agencies that deal with and must then meet these regulatory milestones on what efforts and designs best meet these standards. Specifically, there is a need to evaluate Illinois Department of Transportation's (IDOT) *Standard Specifications for Road and Bridge Construction* and associated special provisions and their ability to address the need to avoid and minimize impacts to creeks and rivers (herein "streams") and the aquatic species that depend on those water bodies (e.g., fishes, crayfishes, and freshwater mussels).

Research Objective

The primary research objective was to summarize known activities that avoid and minimize impacts on aquatic resources through best management practices in construction design standards. Through a thorough literature review and discussions with aquatic ecologists, environmental engineers, and department of transportation professional contacts, we identified design types and construction standards that IDOT could implement to minimize effects on aquatic resources by allowing sufficient aquatic organism passage (AOP). We summarize the known activities that avoid and minimize impacts on aquatic resources through best management practices in construction design standards. This will help enhance the existing *Standard Specifications for Road and Bridge Construction* and any associated special provisions.

The goal of the research was to identify knowledge gaps in the effects on aquatic resources from specific road and bridge construction types by examining how other states have responded to similar challenges and what standard specifications they used for design, including how they identify what types of avoidance and minimization measures they implemented to reduce impacts on aquatic resources. It will provide bridge and road design concepts and observed effects on aquatic resources. The data from the study can be used to further develop more in-depth research at a state level on when and how to best implement specific construction and design standards. We hope that this research and the resulting future research will provide IDOT with a toolbox of design and construction types that will reduce the adverse short- and long-term effects on aquatic resources while also providing a cost-effective structure that meets the safety and use demands of the public for many years.

Project Goals

We developed a report that synthesizes our findings. The findings are separated by design type (e.g., culvert, bridge, etc.), and the pros and cons of each type are discussed. Recommendations for revision are based on gaps in the existing IDOT specification book and what other standard design elements are currently being implemented by other DOTs or similar industries that have been accepted as avoidance and minimization measures by the regulatory resource agencies. After recommendations have been compiled, future research may be needed to study additional products or methodologies to update IDOT's *Standard Specifications for Road and Bridge Construction* and to create databases or models that compile various hydro-fluvial processes using different stream-crossing scenarios. The focus was not to update the specification book but to provide the necessary information so that IDOT can move forward with that process internally.

CHAPTER 2: LITERATURE REVIEW

We reviewed and investigated each state's processes and guidelines for stream-road crossings. We focused most of our efforts on identifying culvert and bridge types and designs that affect aquatic resources under different conditions. Early in the review process, we identified that impacts on aquatic resources throughout literature were framed from the context of aquatic organism passage. AOP is the most common impact noted in the literature and the basis of most stream-crossing guidelines for aquatic resources. If barriers impede organisms, then the stream is not functioning in an environmentally sound or natural way. If AOP is restored, then the stream-road crossing does not inhibit the natural flow of the stream to the point where organisms cannot traverse the crossing and the connectivity of the stream network is restored. For these reasons, we use AOP as a surrogate for all impacts on aquatic resources at bridge and culvert crossings because it is the most addressed issue. See the appendix for a complete list of manuals or guidebooks found during this review.

GENERAL IMPACTS OF STREAM-CROSSING STRUCTURES

When the natural streambed and its surrounding bank's floodplain are anthropogenically altered, some degradation and loss of ecological value of the habitat will undoubtedly occur. Water quality will be one of the first and most noticeable effects of riverscape alteration. Sediments will become suspended, and turbidity will increase during and after construction. This will have local and downstream effects by removing valuable sediment within the immediate area, causing local erosion while transporting those sediments downstream, leading to increased sedimentation and siltation of downstream aquatic habitats. Negative effects on water quality can also occur during construction from open soil being washed into the stream. Future issues could be chemicals washing in from the roadway that are detrimental to water quality. Thus, they can create future and continuing organism die-offs due to the toxicity of pollutants.

Negative impacts from changes to the hydrological processes of the stream will also be immediately noticeable and, once construction is finished, could have a longer-lasting impact for the lift of the structure. Changes in the natural flow regime could cause extensive flooding upstream of the barrier while leading to streams becoming intermittent below the barrier. Changing river hydraulics could also lead to more erosion up and downstream of the crossing. Rivers and tributaries upstream can be impacted by headcutting, which is a common issue in poorly designed culvert crossings that do not consider the hydrology of a river. Additionally, river and stream systems typically have multiple crossings, which can lead to a cumulative negative effect on the hydrology of a stream. Unfortunately, multiple crossings can have compounding effects across the entire length of a stream but also can result in no net benefit even with well-functioning stream crossings.

Changes to the water quality and hydrological process of a stream also have negative effects on the ecological processes and the organisms within them. The most common and well studied are impassible barriers for fish due to physical structures, the increase or disconnection of flow, or the change in water quality that no longer allows species to persist or transverse the area. Additionally, barriers can lead to loss or sedimentation of certain habitats that are needed for fish species to carry out important life history stages. These impacts are also negative for most other aquatic or semiaquatic fauna. Crayfish, mussels, and other macroinvertebrates can be impacted negatively by sedimentation, and, thus, loss of habitat, barriers to movement, and altered flow regimes can make them more susceptible to desiccation or predation. Mussels are also unique as many species rely on a fish host for reproduction, and if a barrier limits the movement of fish upstream, it will also hinder the mussels' ability to move upstream, limiting dispersal. Amphibians and reptiles can also be negatively impacted by the disconnection of the river from its floodplain, including loss of important spawning habitats and barriers to upstream movement. A longer-term impact for aquatic species is changes in species assemblages and loss of resiliency. This is noticeable in the loss of genetic variation within species or the loss of biodiversity in general in heavily altered systems.

GLOBAL REVIEW

Determining the exact number or even approximate number of global road crossings and streams is a monumental challenge. However, it is safe to assume that every country in the world must engineer, plan, and build stream crossings for transportation infrastructure. Underneath or through those bridges flows a very scarce resource when it is put into a global context. Freshwater makes up 3% of the earth's water, while only 0.3%–0.5% is usable. That number gets even smaller when you exclude lakes and consider just rivers and streams; 0.0001% of earth's water is in its rivers and streams (Gleick 1993). However, this water is needed by almost all organisms and forms the basis of life processes. Protecting this freshwater by using the best design standards to limit the many aspects of habitat degradation and alteration of water quality will not only protect freshwater species that inhabit these waters and carry out at least parts of their lives within them, but also protect and preserve the natural world. By making it high quality for them, we, in turn, make it high quality for us.

Freshwater species are under unparalleled pressure; a recent study found that one-fourth of all freshwater species on earth are threatened with extinction (Sayer et al. 2025). The dominant threats for species worldwide are pollution, dams and water extraction, agriculture, and invasive species (Sayer et al. 2025; Jelks et al. 2008; Taylor et al. 2007). Within the European Water Framework Directive that was put into effect in 2000, member states had to ensure that there was no degradation in water quality by 2015 (Cocchiglia 2012). However, though the information is extensive on short-term impacts, knowledge of long-term impacts and effective mitigation remains limited, especially on the creation of suspended solids from stream crossings. Similar to other parts of the world, European countries generally acknowledge that bridges that span the water body are best-case scenarios, but given cost and resources, culverts often remain the only option.

UNITED STATES REVIEW

Within the United States, East or West Coast states have contributed the most to the research on aquatic organism passage at stream crossings (Figure 1, Table 1). On the West Coast, 4 of the 5 states (all states but Hawaii) have documents written from the ecological perspective on guidelines and functions of water crossing infrastructure, while 7 of the 14 along the East Coast meet these criteria. No states bordering the Gulf of Mexico have manuals or guidebooks specifically addressing bridge and culvert designs on aquatic resources. In the interior of the U.S., only 5 of the 27 states had manuals explicitly designed for aquatic organism passage.

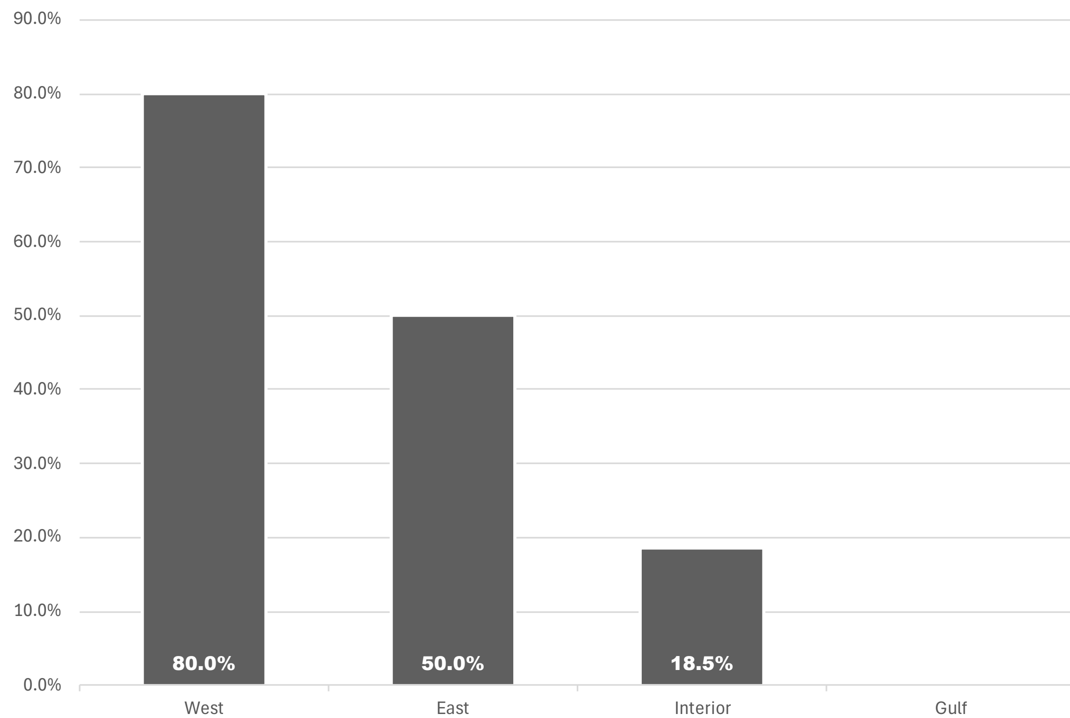

Figure 1. Graph. Percent of states within the East Coast (50%), West Coast (80%), Interior (18.5%), and Gulf Coast (0%) that had specific documentation for aquatic natural resource impacts.

West Coast stream-crossing work is primarily funded by anadromous fisheries worth hundreds of millions of dollars. For example, the Columbian River basin fishery alone is worth approximately $142 million (IEAB 2005). This largely explains why the guidelines and manuals are written explicitly to benefit fish passage to native spawning areas of anadromous fishes. Washington has one of the most elaborate manuals and general approaches to stream-crossing construction. Outside of their formal guidebook, they also have training modules and annual status reports for the recent construction of new and improved culverts that allow for fish passage. Alaska, Oregon, and California similarly emphasize stream crossing and allowance of organism passage in specific documents highlighting organism passage within infrastructure guidelines. However, all four states have guidebooks written from the ecological perspective with engineering terminology.

We found that 50% (7 of 14) within the East Coast states have specific documentation addressing impacts to aquatic passage through culvert and bridge design (Figure 1). We describe East Coast states as states that have a coastal boundary with the Atlantic Ocean. Among the East Coast states, there is less emphasis on anadromous fishes (i.e., Atlantic Salmon and American Eel). However, unlike the West Coast, an increased effort is placed on general connectivity for all aquatic organisms. For instance, the scope of the Rhode Island manual is the “design of safer, cost-effective stream crossing to meet the transportation needs, improve hydraulic function, reduce maintenance cost, and enhance natural stream functions and wildlife migration.” East Coast states with specific manuals have statements similar to this within their documents.

Table 1. States with Specific Manuals, Guidebooks, or Documents Addressing AOP

ST	Loc.	
AK	W	https://dot.alaska.gov/stwddes/desenviron/assets/pdf/procedures/dot_adfg_fishpass080301.pdf
CA	W	https://dot.ca.gov/-/media/dot-media/programs/design/documents/f00020339-200705-fpm-complete-a11y.pdf
CT	E	https://portal.ct.gov/-/media/dot/finalcrossingguidelinesfeb262008highrespdf.pdf
GA	E	https://www.fws.gov/sites/default/files/documents/Stream-Crossings-in-Georgia-2021-508.pdf
IA	Int.	https://www.iowadnr.gov/media/7076/download?inline
ME	E	https://www.maine.gov/mdot/publications/docs/brochures/pocket_guide_stream_smart_web.pdf
MD	E	https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendations_for_aquatic_organism_passage_at_maryland_road-stream_crossings_june_2021.pdf
MA	E	https://www.mass.gov/files/documents/2018/08/23/Stream%20Crossings%20booklet%20Web.pdf
MN	Int.	https://files.dnr.state.mn.us/waters/publications/culvert-stream-connectivity.pdf
NH	E	https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/lrm-culvert-assessment-protocol.pdf
OH	Int.	https://www.transportation.ohio.gov/wps/wcm/connect/gov/bb0c9d78-0c99-420a-b1cb-d9c97d3e9c6e/Ecological+Manual+2014.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_79GCH8013HMOA06A2E16IV2082-bb0c9d78-0c99-420a-b1cb-d9c97d3e9c6e-oBUzb.7
OR	W	https://www.dfw.state.or.us/fish/passage/
RI	E	https://www.dot.ri.gov/business/documents/Road_Stream_Crossing_Design_Manual_8_2021.pdf
VT	Int	https://vtfishandwildlife.com/sites/fishandwildlife/files/documents/Learn%20More/Library/REPORTS%20AND%20DOCUMENTS/AOP/GUIDESLINES%20FOR%20DESIGN.pdf
WA	W	https://wsdot.wa.gov/sites/default/files/2022-07/Env-StrRest-FishPassageAnnualReport.pdf
WI	Int.	https://www3.uwsp.edu/cnr-ap/UWEXLakes/Documents/ecology/shoreland/background/fish_friendly_culverts.pdf

Georgia has also compiled a detailed handbook on the connectivity and resilience of Georgia rivers through stream crossings. The Nature Conservancy has worked closely with state and federal agencies in Georgia to identify poor design impacts, assess barriers, and initiate funding efforts to help with barrier replacement or removal. They also identify well-designed structures and use case studies to highlight the positive progress that the state is making. Though this resource does not detail the specific crossing designs, it provides all necessary information for managers to look for when starting a stream-crossing project.

INTERIOR STATES REVIEW

Among interior states, only 18.5% (5 of 27) have specific documentation for impacts from stream crossings (Figure 1). Minnesota has been the most proactive in addressing the issue at stream crossings. The centerpiece of their efforts is a guide devoted to design and implementation. The guiding documents have been revised and refined several times over the years (e.g., MDOT 2013) and even consider species-specific biology and regional differences (Hansen et al. 2009). The current guide (Hernick et al. 2019) begins by describing a protocol for a thorough site assessment. It then covers additional analyses (e.g., flooding potential, etc.) at the site. Designing the bridge/culvert is addressed. Finally, there is a section that details any additional considerations. Minnesota's overall approach is similar to what is recommended by various federal reports (e.g., FSSSWG 2008; Kramer et al. 2024; USFWS 2024) and implemented by some states, most notably those in the Pacific Northwest and New England. (See the previous section, United States Review.)

Minnesota has taken the extra step of conducting performance assessments on a subset of their culverts to determine which are fish passage barriers at high and low flows and assess what design factors most influence the possibility. Other states have conducted similar assessments, but they require thoughtful planning and collection of baseline conditions to assess performance adequately. Without knowing initial conditions, it can be difficult to determine causal factors for AOP deficiencies. However, some lessons can be learned (Hansen et al. 2011), and Minnesota has integrated these lessons into its recent methods (Hernick et al. 2019). Furthermore, Minnesota is looking ahead by incorporating climate change into hydrological models to assess the future performance of culvert designs (Kozarek et al. 2021). Finally, Minnesota has conducted a cost analysis (Hansen et al. 2009). In short, incorporating AOP designs into a new project or retrofitting an existing culvert to AOP specifications raised the project cost by −5% to 33%. The exact amount is very site and situation specific.

Iowa also has a document focusing on guidelines for implementing AOP into stream-crossing projects (IaDNR 2018), although this document is one-sixth the size of what Minnesota has produced. The general approach between the two states is consistent with federal publications (e.g., FSSSWG 2008; Kramer et al. 2024; USFWS 2024). Some of these guidelines are incorporated into Iowa Department of Transportation manuals (IaDOT 2024a, 2024b). Missouri recognizes AOP issues. Its approach is short and succinct, effectively condensed into one table and figure (MDOT 2024, sec. 750.7.3 Environmental Requirements). The guidelines appear to be in response to regional U.S. Army Corps of Engineers requirements, although it is unclear how and if guidelines are implemented.

Wisconsin has considered AOP for many years but has only published basic guidelines readily available over the past few decades (WTIC 2004). However, the Wisconsin Department of Transportation and the Wisconsin Department of Natural Resources work together on AOP projects (instead of AOP, they use the acronym ACONN, which stands for aquatic connectivity), and there are detailed instructions on how they are to work together (WDNR and WDOT 2021; WDOT 2020-2024). For actual design and implementation, they refer to federal regulatory guidance (e.g., FSSSWG 2008; Kramer et al. 2024; USFWS 2024).

Outside of state agencies, the University of Wisconsin–Extension released a publication on fish-friendly culverts (UWE 2003). Also, researchers with the Center for Limnology at the University of Wisconsin–Madison and collaborators developed an optimized model using a return-on-investment framework to prioritize which barrier-removal projects could be implemented within a watershed to maximize the amount of habitat improvement and minimize cost (Neeson et al. 2015; Moody et al. 2017; Neeson et al. 2018). This is the type of information that could be of considerable value for regional planning initiatives.

A typical scenario in most interior states or the Midwest region was typically a few pages to a couple of paragraphs devoted to AOP or crossing impacts on aquatic resources. These pieces of information are usually found scattered throughout hydraulic, bridge, or culvert design manuals that state departments of transportation draft. Some states that have this approach are Michigan, Indiana, Kentucky, and Ohio, which briefly mention AOP approaches, but little to no detailed information is readily available. We found it much more helpful and informative if that information was provided in more detail in a stand-alone document. These stand-alone documents could be written using ecological terminology but with the guidance of engineers. Having both types of documents would benefit both the natural resource and engineering and construction sides by facilitating better communication. We believe this would lead to better and more friendly stream-crossing designs that benefit the aquatic and natural resources and are safer, cost-effective, and elicit pride from all stakeholders.

ILLINOIS REVIEW

Illinois Department of Transportation

The state of Illinois has approximately 12,000 crossings coded as culverts under its jurisdiction (Figure 2). Illinois Department of Transportation addresses AOP and aquatic natural resources though it does not provide a specific document addressing the issue. Specifically, the following paragraph can be found in the *Culvert Manual* (IDOT 2017, p. 2–13) and *Bridge Manual* (IDOT 2023, p. 211):

> The invert elevations of all culverts at stream crossing locations shall be set a minimum of 3 in. below the lowest point in the stream cross section. The intent is [alternatively 'This will ensure'] that culvert inverts will not become a barrier to fish migration during low water. The size of the culvert opening does not need to be increased to compensate for lowering the invert 3 in. Locations which may warrant lower invert elevations shall override this policy.

The embedding of the culvert into the stream bottom is consistent with AOP strategies. But as will be discussed in Chapter 3, the above guidelines may result in an undersized culvert that may not be effective over the long term. Indirectly, AOP is also addressed in relation to debris in the *Culvert Manual* (IDOT 2017, p. 2-1) and in more detail in the following section from the *Bridge Manual* (IDOT 2023, p. 200):

> Culverts generally have low future maintenance; however, culverts should not be considered for waterways with a history or potential of debris to avoid channel

> cleanout maintenance. In these cases, a three-sided precast concrete structure may be more appropriate. Three-sided precast concrete structures have the advantage of larger single and multiple openings, ease of construction, and low future maintenance costs.

Although AOP focuses on the movement of animals, especially fishes, the underlying strategy is to maintain the natural function of the stream continuously through the road crossing. This includes the hydrological flow, bottom sediment movement, and debris movement (e.g., ice, wood from fallen trees, etc.). To achieve these goals, it is often recommended to install a slightly larger structure than traditionally used, as described in the excerpt above, where a three-sided precast concrete structure is considered more appropriate than the typical culvert. This will also be discussed in Chapter 3.

AOP is also addressed indirectly in the following sentences from the *Illinois Construction Manual* (IDOT 2021, p. 500–88):

> The skew angle should be checked to ensure that the angle matches the existing channel. If it does not, the designer should be contacted to ensure that the plans are correct. The grade of the channel, both upstream and downstream from the pipe, should be checked to determine the proper elevation for each end of the pipe.

Although the impetus for this directive is probably to minimize erosion and maintain the integrity and safety of the road crossing, aligning the culvert with the stream channel and matching the upstream and downstream stream channel grades also facilitate the natural continuity of the stream through the road crossing. Finally, the overall approach used in Illinois to select what type of structure to construct can be summarized in the following excerpt from the *Culvert Manual* (IDOT 2017, p. 2-1) and *Bridge Manual* (IDOT 2023, p. 200):

> The determination [or 'selection'] of whether a structure over a waterway should be a culvert, a three-sided precast concrete structure or a bridge is heavily influenced by the hydraulic opening [requirements]. As the hydraulic opening becomes larger, the selection process for structure type progresses from culvert to three-sided precast concrete structure to bridge. [Initial] cost, future maintenance, profile grade, staging, skew, soil conditions and alignment are also important variables which should be considered.

This is very similar to many AOP techniques, except using criteria different from hydraulic opening. The recommendation from many AOP assessments is similar to the following from the *Bridge Manual* (IDOT 2023, p. 209):

> Three sided structure design and construction should maintain the shape and location of the natural channel beneath and throughout the structure, preserving the natural flow characteristics in the channel to the extent feasible.

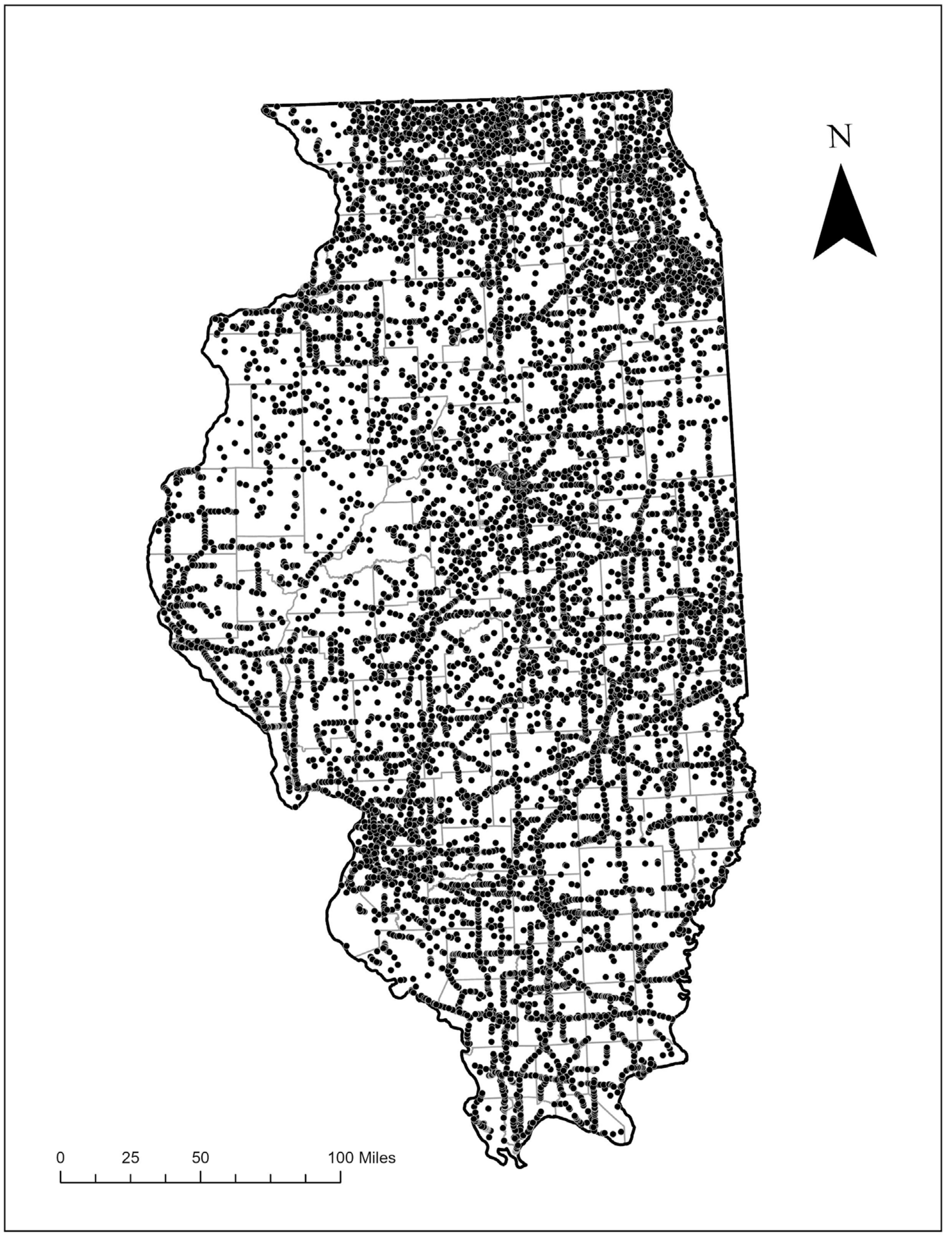

Figure 2. Illustration. Culvert locations in Illinois.

Interestingly, only a handful of states and manuals consider the potential movement of terrestrial or semiaquatic animals (e.g., turtles, snakes, salamanders, etc.) through culverts/bridges. Illinois is one of them, emphasizing reducing wildlife/vehicle collisions (IDOT 2024, sec. 26-16.04(c)).

In summary, IDOT already has many of the “tools” that are routinely used when implementing AOP recommendations. The primary difference between what has traditionally been done in Illinois and what an AOP perspective would recommend is how the tools are applied within a given context. This can be achieved by creating a stand-alone guidebook or handbook that presents the information from an ecological perspective that can be used to inform the general public and constituents involved in the construction of stream crossings. A detailed example of this would be the *Minnesota Guide for Stream Connectivity and Aquatic Organism Passage Through Culverts*. A more reader-friendly and publicly approachable document would look like *Stream Crossings in Georgia: A Handbook for Connectivity and Resilience*. Either resource would benefit the state of Illinois as well as developing a forward-thinking approach to manage and inform Illinois residents of IDOT's work.

Illinois State Toll Highway Authority

The *Drainage Design Manual* of the Illinois State Toll Highway Authority (ISTHA 2024) contains multiple references directly or indirectly related to AOP. For example, the skew angle of the culvert should be along the "natural drainage path of the flow" and "aligned with upstream and downstream channels" (p. 30). For wider stream crossings, a bridge or bottomless culvert is preferable. However, multiple culverts could be used to avoid forcing water through a narrower single culvert (p. 30). If multiple cells are used, there should be a "low flow cell similar in width to the adjacent stream channel" (p. 32). The overall goal is that the "natural water depth and velocity shall be mimicked throughout the structure" (p. 32). When an embedded culvert is installed near an environmentally sensitive area, the culvert should be embedded around 1 foot into the stream bottom. This additional 1 foot of depth is not included in the hydraulic calculations. Hence, the box or pipe will need to be larger to accommodate both the hydraulic needs and the buried sediment volume (p. 32). Furthermore, hydraulic calculations should use an n-value of ~0.03 for natural soil, instead of n-values for concrete or other artificial materials (p. 32).

Riprap is sometimes placed in embedded culverts to control flows. In these situations, the riprap is to extend about 5 feet into the downstream and upstream ends of the culvert and then taper off (p. 33). Besides regulating flows, the design is meant to "allow for soils to naturally fill up the embedded depth throughout the rest of the culvert bottom" (p. 33). The overall intent is that "embedded culverts shall be designed so as not to impede low water flows or the safe passage of fish and aquatic organisms and allow for the natural substrate to colonize the structure's bottom, encourage fish movement and maintain the existing channel slope" (p. 33).

Appendix K of the *Drainage Design Manual* (ISTHA 2024) is "Guidelines for the Design of Stream Crossings for Sensitive Resources" (p. 149–163). This section contains general information, with much of it directed toward satisfying U.S. Army Corps of Engineers permit requirements. A detailed design matrix for environmentally sensitive stream crossings is provided in the ISTHA *Drainage Design Manual* (p. 155). One potential output from this design matrix is to evaluate alternatives to standard box culverts (p. 156). In this situation, design alternatives include the following design considerations:

1. Designs with soft bottoms;
2. Designs that span the design discharge top width at the project site;
3. Designs that do not form a backwater upstream of the project site;
4. Designs that do not cause increased velocities through or downstream of the crossing;
5. Designs that do not locally cause significant changes in sediment transport capacity;

6. Designs that minimize or avoid impacts to habitat;

7. Designs that do not impede migration of fish and other species (ISTHA 2024, Appendix K).

Design elements that may be utilized to address these considerations include the following, when appropriate:

1. Three-sided structures;

2. Designs which include abutment placement outside WOUS [Waters of the United States];

3. Utilization of grade control elements;

4. Structures designed to avoid orifice flow;

5. Employment of lateral erosion protection;

6. Designs which avoid deposition upstream of the structure (ISTHA 2024, Appendix K).

All these above considerations are discussed in more detail (ISTHA 2024, Appendix K).

U.S. Army Corps of Engineers

Implementing AOP recommendations is often in response to satisfying permit requirements, such as from the USACE (e.g., as found in ISTHA 2024). In some instances, AOP qualifies as mitigation. Each case is unique, and the regulatory landscape can change. However, USACE has provided some insights, such as in *Illinois Stream Mitigation Guidance: Stream Mitigation Method for Processing Section 404 Clean Water Act Permit Applications in the State of Illinois* (USACE 2010). One of the more pertinent sections is the following definition (p. 8):

> Below Grade (embedded) Culvert – means to route a stream through pipes, box culverts, or other enclosed structures (≤ 100 linear feet of stream to be impacted per crossing). Below grade culverts should be designed to pass bankfull flow. The culvert bottom, including head-walls and toe-walls would be designed to be embedded to a depth of no less than 12-inches below the streambed. Improperly designed culverts will be evaluated under the activity for "piping." Culverts should be designed to allow fish passage and other aquatic life movement.

Regarding net benefits related to culverts when assessing stream restoration factors, the following guidelines are presented:

> Good Net Benefits
>
> - Replacement of inappropriately designed culverts (undersized or impassable by fish) with open span bridges or structural arch culverts.

- “Daylighting” of piped or culverted stream segments into an appropriately designed open channel.

- Removal of culverts, weirs, pipes and other minor instream structures (USACE 2010, p. 10–11).

Moderate Net Benefits

- Replacement of undersized culverts with appropriately sized closed culverts.

- Removal of culverts, weirs, pipes and other minor instream structures (USACE 2010, p. 11).

The degree of net benefit from the removal of culverts is ambiguous, as can be seen by it being listed under Good Net Benefits and Moderate Net Benefits. To be clear, this seems to be just the removal of the structure, not replacement (i.e., removal of structure and then installation of another structure). Further guidance related to culvert removal is as follows (p. 11):

> Structure Removal refers to removal of existing pipes, culverts, dams, weirs, and other manmade structures that alter a stream’s geomorphology or flow. A series of grade control structures may be needed to reconstruct the channel profile to avoid headcutting, slope failure, and to not restrict fish passage. The proposed structural removal will be assigned a net benefit depending on the ecological lift associated with the specific action. The net benefit selected for a specific structural removal must be supported by information necessary to document ecological lift. Selection of an appropriate net benefit is at the sole discretion of the reviewing Corps district. Credit for removal of manmade structures will be based on total length of stream impacted directly or indirectly by the structure (i.e., dam fill plus length of impounded stream; culvert fill plus upstream and downstream areas where aggradation/degradation can be attributed to the culvert).

In summary, mitigation opportunities associated with AOP culvert projects exist, but these need to be discussed with USACE and other agencies during the permitting process.

CHAPTER 3: AQUATIC ORGANISM PASSAGE CONSTRUCTIONS

CULVERTS

This report defines a culvert as a three- or four-sided, man-made structure connecting a stream or drainage segments to facilitate water movement across a barrier. Culverts come in numerous designs with modifications that can be made to suit a wide range of needs (Figure 3). The following list is meant to provide the base of standard culvert designs, but please note that there are numerous modifications that can be made to each type. At the same time, the following section will cover the considerations that need to be made when implementing culverts to have the least impact on aquatic resources. This list and the preceding section are meant to provide general and easily readable information on culvert design and implementation. This list is not to be used in place of professional judgment and services.

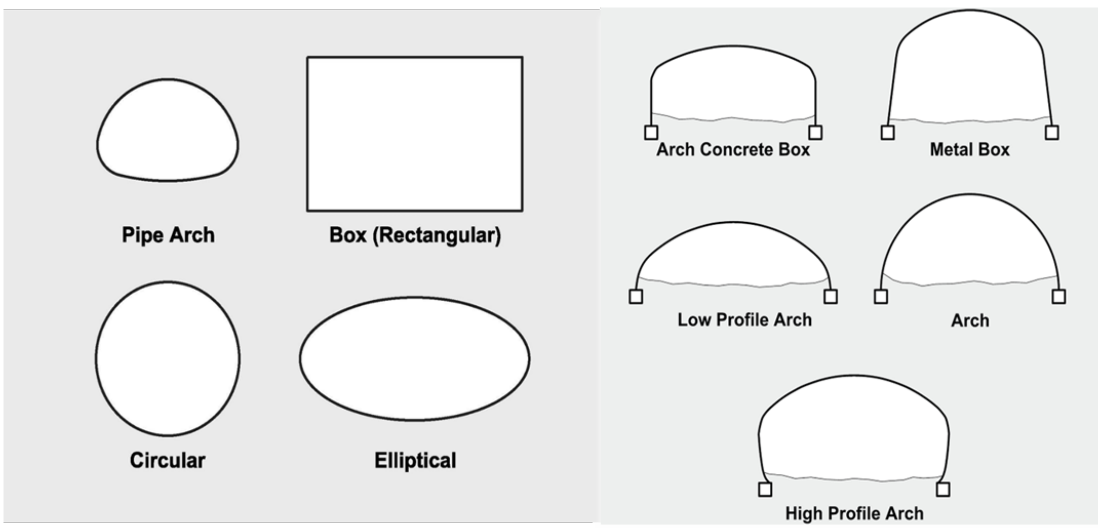

Figure 3. Illustration. Culvert and open-bottom culvert types.

Source: Schall (2012)

Pipe Culvert

Also known as round pipe culverts (Figure 4), pipe culverts are the most common type of culvert used throughout the U.S. because they are frequently used in ditches and storm drain systems. They are typically made of one of three materials: concrete, corrugated metal, or plastic. Pipe culverts are advantageous because they are cost-efficient, come in a wide range of sizes to meet multiple needs, can withstand a wide range of forces, and are easy to install. Pipe culverts are susceptible to the build-up of gases and crown erosion. They are more susceptible to clogging and build-up of material upstream of the culvert. If the proper size is not selected, it can cause barriers, because high flows are forced through the opening or cause lack of flow within the culvert to occur. If not correctly installed, they can fail or be ineffective. The appropriate size needs to be selected to allow for the natural movement of the streambed. Typically, it requires more maintenance and monitoring than other types of culverts.

Figure 4. Photo. Example of a pipe culvert.

Pipe-Arch Culvert

Pipe-arch culverts are similar to pipe culverts but with a more compressed design, creating a wider span, allowing for more contact area with the streambed, and becoming more hydrologically efficient at lower flows (Figure 5). They are typically made from corrugated metal or concrete. These are typically used on more significant streams and can have multiple openings to allow for more water passage and varying flow levels. These are typically more expensive than pipe culverts and must be installed correctly and with the correct dimensions to be effective for AOP. Similar to pipe culverts, they do need to be maintained regularly and monitored to extend the life of the culvert and to check for unwanted blockage or sedimentation.

Figure 5. Photo. Example of a pipe arch culvert.

Arch Culvert

Similar to a pipe-arch culvert, arch culverts often lack a bottom, allowing for more stream channel migration and maintaining natural flows (Figure 6). They can often be constructed without extensive instream work, allowing for quicker construction. They are most commonly made from concrete or stone and can be designed to be more aesthetically pleasing to the public. Depending on customization and size, they can be more expensive than the previous two options, and they have a more limited scope of use.

Figure 6. Photo. Example of an arch culvert.

Box Culvert

Box culverts are one of the most popular culvert types, especially on small- to medium-sized streams with varying seasonal flows (Figure 7). Box culverts are typically made of reinforced concrete, but they can also be metal, though infrequently. Box culverts are easily customizable to fit specific site needs, allowing multiple openings at different heights for more water movement during high seasonal flows. They also are less prone to clogging and require less maintenance than other culvert types. Because they are generally larger and sturdier, they typically last longer than the pipe culvert types, and their design can span stream width to allow for natural stream channel movement, but natural substrate must be added or allowed to accumulate to further benefit AOP. However, this larger and more robust design leads to a larger expense and are more time-consuming to install. A lot more dirt work and excavation are needed to install the box culvert, leading to a longer construction phase. Additionally, because they are four-sided and must be installed within the stream channel, measures must be taken to address environmental concerns during installation.

Figure 7. Photo. Example of a box culvert.

Three-sided Culvert

Also called bridge culverts, when the span is greater than 20 feet in some states, three-sided culverts are often the most environmentally friendly of the culvert types (Figure 8). They are often made from reinforced concrete, though metal options are available. These culverts allow for the natural stream substrate to stay in place and are not as susceptible to perching from streambed erosion. When constructed properly, they allow for natural stream migration and meandering. Because they do not have a floor, instream work is often minimal unless multiple barrels are needed or during the anchoring of the culvert. Unfortunately, they are the most robust and expensive option of all culvert types, but they typically require less long-term maintenance and are the best for AOP.

Figure 8. Photo. Example of a three-sided culvert or bridge culvert.

Culvert Use Conditions and Implementation

Aquatic organisms sometimes have trouble passing upstream or downstream through road crossings. Bridges are generally not problematic, unless there is a dam or some other type of structure associated with them that acts as a barrier. Many culverts also permit the unhindered movement of aquatic organisms. But there are also a significant number of culverts that act as partial or near total barriers. The issues vary from culvert to culvert and include perched outlet (that acts as a miniature waterfall), excessive flow velocity, low water, excessive culvert length, sediment and debris accumulation within a culvert or at an inlet, excessive turbulence, perched inlet, too dark, etc. With the recognition of these problems, and their potential to impact endangered species and recreationally or commercially valuable species, there has been growing interest in methods for facilitating AOP through road crossings and thus promoting a positive impact on aquatic resources.

Whenever AOP recommendations are considered for stream crossings, the top priority is always the structural integrity of the road crossing and public safety. These concerns outweigh all others. But in many cases, structural integrity, public safety, and environmental issues can all be accommodated. AOP has been discussed, studied, and implemented for over two decades. A variety of approaches have been promoted, tried, discarded, and refined. Over that time, there has been a narrowing of consensus on what is most practical to implement and appears to work the best for the long term. Every road-stream crossing is unique, and AOP methods will continue to be adjusted. What is presented in this report is the most common and widespread AOP approach currently recommended in the United States. The description below is based largely on the following publications: FSSSWG (2008), Kramer et al. (2024), USFWS (2024), and manuals and publications from Minnesota and other Midwest states adjacent to Illinois. (See the Interior States Review section.)

The overall philosophy is to maintain the natural continuity and function of the stream through the road crossing. This includes natural hydrology, bottom sediment movement, and debris movement (e.g., coarse wood from fallen trees, ice, etc.). If these conditions are met, aquatic organisms should also be able to move through the road crossing, and the connectivity of the stream will be intact, leading to the resiliency of the aquatic resources. A variety of road structures can be constructed to meet these conditions, depending on site requirements and how they are installed (Figure 9).

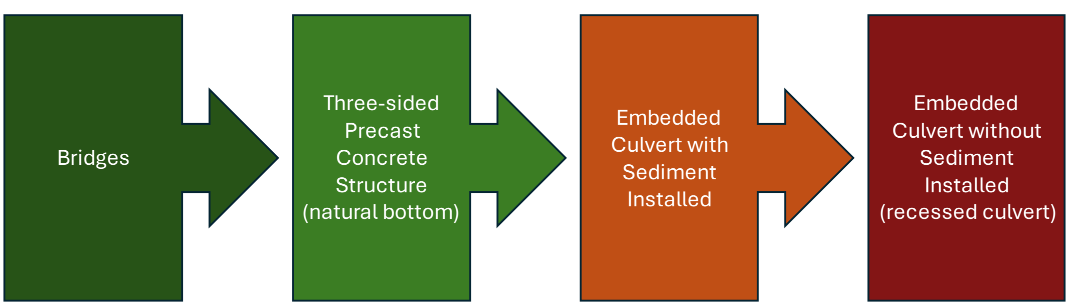

Figure 9. Diagram. General road-stream crossing structure descriptions from environmentally preferred to least preferred.

Bridges are usually the preferred solution for AOP and help to minimize aquatic resource issues at a crossing, but they are typically the most complicated to design, most costly to build, and require more long-term maintenance. (See the Bridges section.) In some instances, there is minimal difference between options—for example, a small bridge and a larger three-sided culvert may be very similar and function in a similar way. The term embedded refers to a culvert being installed with the bottom of the inlet and outlet below the natural level of the stream bottom. In some instances, natural sediment or substrate is placed in the culvert at the time of construction to create a natural flow break and flow rate that would mimic the natural stream bottom. At other times, just the culvert is installed, and sediment is anticipated to naturally fill the culvert over time. Regardless of the structure built, some general AOP principles are involved with the implementation. Many of these principles are already considered by the Illinois Department of Transportation, but they are elaborated upon in this report to make the information more readily available.

Culvert Design Considerations

Skew Angle

It is best to align the culvert with the stream channel. Any sharp angles or bends in the stream channel resulting from construction design will increase the likelihood of unnatural erosion and scouring, which could hinder AOP. It is preferable from both an environmental and construction perspective for the road and stream to meet at right angles. As the skew angle increases, the necessary length of the culvert increases. Longer culverts are more expensive and hinder AOP. In situations where the road infrastructure is already established, there may be limited alternatives. But in situations where novel roads are being constructed, it may be preferable to consider road placement and design and possibly to reconfigure road placement so the stream crossing occurs at a more favorable location.

Slope (Gradient)

Like skew angle, it is best to align the culvert with the stream channel, but in this case, alignment is vertical instead of horizontal. In other words, the slope of the culvert (or streambed in the case of three-sided structures or bridges) should match the upstream and downstream slopes. This criterion should be relatively simple to fulfill when a stream is straight, even, and level. A general tolerance recommendation is to keep the culvert slope within 25% of the adjacent stream slope (FSSSWG 2008; USFWS 2024).

At slopes less than roughly 0.2% all structure options are feasible, from bridges to embedded culverts without sediment installed. The most cost-effective option would be the embedded culvert without sediment installed because sediment in this type of stream is usually sand, silt, etc. that will naturally and quickly distribute itself throughout the length of the culvert. At greater slopes (roughly 0.2%–3%), an embedded culvert with sediment installed is a better option because sediment in this type of stream contains more gravel and cobble that could take years to naturally distribute itself throughout the length of the culvert (Hernick et al. 2019, sec. 5.1). When slopes exceed 3% or slopes change dramatically over short distances, the complexity of designing the project can increase greatly. In situations like this, it is best to more seriously consider installing a bridge or three-sided structure. The usual safety precautions, such as conducting a scour analysis to prevent undermining of footings, etc., are important.

If the decision is made to install a box or pipe culvert, then stable grade control anchor points (structures that control the slope and water level of a stream) should be located upstream and downstream. Ideally these points are natural, such as a bedrock outcrop, but they could be constructed riffles, etc. The culvert should be positioned between these grade controls in such a way that erosion and aggradation do not occur immediately adjacent to the culvert. See Section 6.1.2 in FSSSWG (2008) for more details.

Most streams in Illinois will have relatively low slopes (Figure 10). Streams with higher slopes are rarer and mostly restricted to locations along river valleys like the Mississippi, Illinois, Rock, Fox, Vermilion Rivers, etc. Even though these higher slope streams are rarer, they may also be the homes for rarer aquatic organisms (Hernick et al. 2019) and, hence, could draw more scrutiny from certain groups, such as permitting agencies.

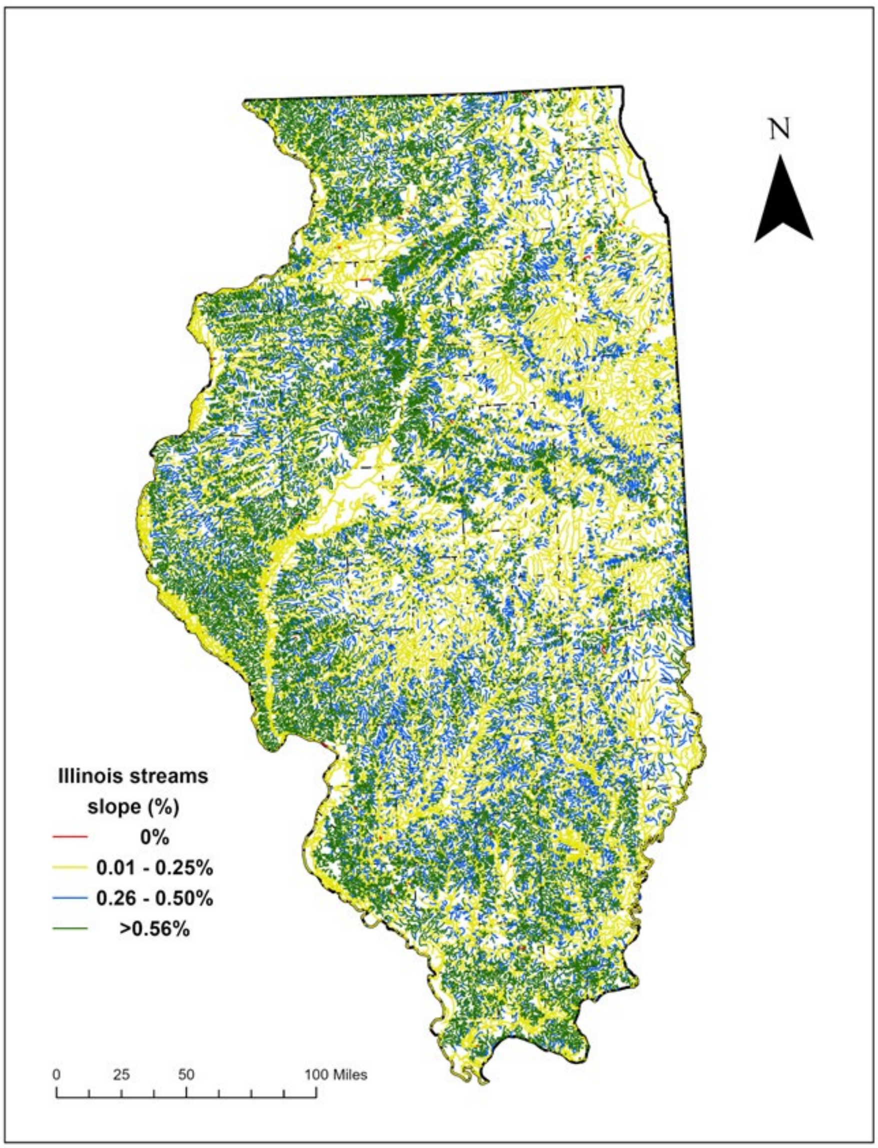

Figure 10. Illustration. Percent slope of Illinois streams.

Culvert Width

Many AOP issues associated with road crossings are traced back to "undersized" culverts, with the term undersized being a matter of perspective. Traditionally, it was common to build a culvert according to a particular hydraulic design criteria that allowed for the passage of peak flows (for example, 50-year peak flows or 75-year peak flows). During high flows, it was considered permissible for the water level to overtop the culvert as long as this did not endanger the integrity of the road. The water velocities through a submerged culvert are usually much higher than natural peak velocities, resulting in the sediment in the culvert being flushed out and significant scouring at the outlet. Both factors can significantly hinder AOP (Kramer et al. 2024).

Bankfull width is the current practice that is commonly used for stream connectivity and AOP design criteria for culvert width. To determine bankfull width, first, identify the top of the stream bank at which point water would spill into the adjacent flood plain. Then, measure the distance across the channel from the top of the stream bank to the top of the opposite stream bank; that distance is bankfull width. This criterion generally works well because, through erosion and deposition, streams reach a natural equilibrium design that accommodates their high and low natural flows. By carrying this natural design through the road crossing, AOP should be facilitated. From a hydrological perspective, bankfull width is roughly equivalent to 1.5 year flows (Q1.5), but this can vary from stream to stream (Hernick et al. 2019). For more details on determining bankfull width, see pages 5-20 to 5-21 in FSSSWG (2008) and sections 2.1.1.1–2.1.1.4 in USFWS (2024).

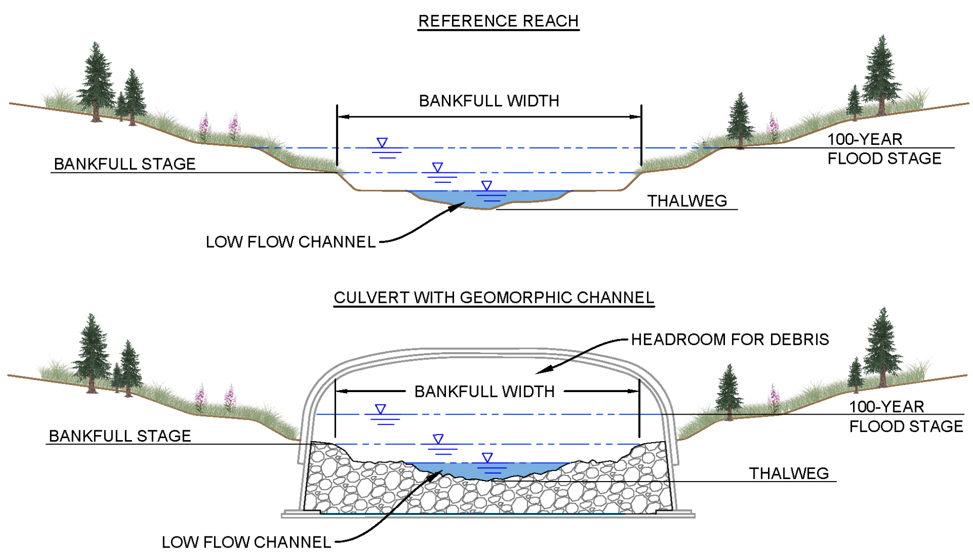

Figure 11. Illustration. Example of culvert placement relative to geomorphic channel features.

Source: USFWS (2024), Figure 2-3

Bankfull width is considered the minimum width of the culvert. Additional recommendations include adding small banks on either side of the stream within the culvert and, hence, suggest a culvert width of around 1.2 × bankfull width, with the extra 0.2 split between the two sides (FSSSWG 2008, sec.

6.3.1; Hernick et al. 2019; USFWS 2024, sec. 2.1.1.1) (Figure 11). These banks could facilitate the movement of terrestrial and semiterrestrial animals and could serve as a safety factor for streams that may experience infrequent higher floods.

Embedded Culverts (Bottom Sediment)

Although much of the focus is on flows and hydrology, it is also important that the bottom sediments or substrates throughout the road crossing be natural. A similar size and compositional structure to what is found upstream and downstream is also preferred. One reason for this practice is because if the stream flow is consistent with natural conditions, then the bottom sediment would be as well. Also, aquatic organisms are unlikely to swim nonstop through a culvert, especially small-bodied fish and crayfish. It is more likely that they would swim partially into the culvert, rest, forage, and hide from a predator before exiting the culvert through the way they came or passing entirely through. Natural sediment would facilitate this behavior by providing heterogeneity in flow velocities, whereas bare concrete or metal does not. Furthermore, natural stream bottoms are uneven, creating sheltered areas of slower flow. Fishes often swim from sheltered areas to sheltered areas to avoid predation, especially for smaller-bodied non-game species.

With embedded culverts, there is a choice between placing sediment into the culvert during construction or leaving the culvert empty during construction and assuming sediment will naturally fill the culvert. For smaller pipe culverts, there is no feasible way to add sediment during construction. For larger pipe culverts or precast box culverts, especially those that have separate top and bottom pieces, then there is an opportunity to add sediment during construction (Kramer et al. 2024). If there is an opportunity to add sediment during construction, then that is the preferred method. It could take months to years for cobble and gravel to accumulate in an empty culvert, especially for longer culverts. Silt and sand substrates would take less time to naturally accumulate. Another problem is the increased movement of sediment from upstream to fill an empty culvert could result in increased erosion and the formation of a headcut. To protect against this, one can create a grade control structure by placing rock immediately upstream of the culvert inlet, or if there is an upstream pool, then place rock where the channel enters the pool. A similar strategy can be deployed downstream of the culvert (Hansen et al. 2011).

When adding sediment, the composition of the sediment should be a similar mix of larger, medium, and smaller particles that are found upstream and downstream of the culvert. Larger particles should be added first, especially if they are fist-sized or bigger. This is to provide the foundational stability of the streambed through the culvert. Smaller particles (i.e., sand, silt, etc.) are then added. Spraying water over the smaller particles helps to get them to flow down and fill in the spaces among the larger stones (Kramer et al. 2024). Otherwise, the smaller particles tend to sit on top of the larger particles and are immediately swept away once flow is restored. The smaller particles are necessary for ensuring water stays on top of the sediment matrix. If only larger stones are present, then water levels may drop below the level of these stones. It is unlikely that fish or other aquatic organisms would be able to pass through the narrow gaps between stones, creating a barrier to movement. The sediment should be placed to create a streambed with a U-shape and a smaller V-notch at the bottom apex of the U (Figure 12). This process is done so water is concentrated toward the center of the culvert, ensuring that water depth is sufficient for the passage of aquatic organisms even during times of low flow (Kramer et al. 2024; USFWS 2024, sec. 2.1.4.2). For more details on determining appropriate particle sizes, matrix composition, and placement, see sections 6.2.1.1 and 8.2.11 in FSSSWG (2008), section 3.6 in Hernick et al. (2019), and section 2.1.4.2 in USFWS (2024).

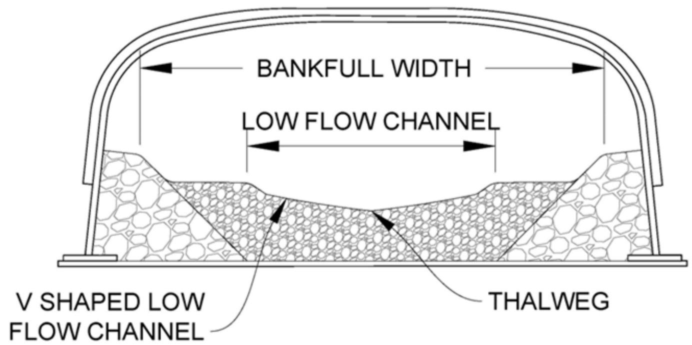

Figure 12. Illustration. Two-stage channel with V-shaped low flow channel.

Source: USFWS (2024), Figure 2-7

Bridges and three-sided precast concrete structures already have natural stream bottoms. This is not necessarily the situation with standard box or pipe culverts. The AOP recommendation is to embed or partially bury the culvert so that the bottom of the inlet and outlet are below the level of the stream bottom. Suggestions for how deep to embed the culvert vary from manual to manual. The most exacting method is to create a diagram of the longitudinal elevation profile of the stream, both upstream and downstream from the work site. This elevation profile will indicate the depth of all the pools. Ignoring any artificial or unusual pools, such as a scour pool at the outlet of the culvert, one draws a line parallel to the average slope of the stream channel and sets it along the deepest portions of the stream profile (e.g., bottom of pools). This line is called the lower vertical adjustment potential (lower VAP) (FSSSWG 2008, sec. 5.2.2.2 and 6.3.2; USFWS 2024, sec. 2.1.3.4) (Figure 13).

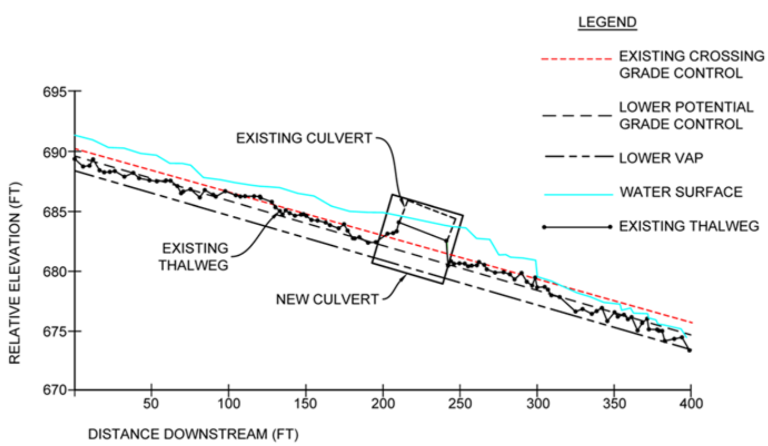

Figure 13. Illustration. Vertical adjustment potential example.

Source: USFWS (2024), Figure 2-5

Under natural conditions, this is assumed to be the deepest potential scour points. A safety factor can be incorporated by lowering the elevation of the VAP by 1 to 2 times the depth of the deepest natural pool (FSSSWG 2008, sec. 6.3.2; Hernick et al. 2019; USFWS 2024, Figure 2-5). The culvert then needs to be embedded far enough below the lower VAP to ensure that if any scour occurs within the culvert, the depth of the scour will not reach the bottom of the culvert. In some situations, stream slope can change dramatically over a short distance. A common example is a road running along the base of a bluff, where the stream slope is steeper when coming down the bluff but relatively level below the bluff. In instances like this, there could be two lower VAPs, and one must closely examine where the culvert is to be placed (FSSSWG 2008, Figures 5-16 and 6-8).

This process can be overly complicated and time-consuming to measure and calculate. As an alternative, many manuals just provide a blanket recommendation, like a culvert should be embedded a minimum of 3 inches into the sediment (IDOT 2017, p. 2–13; IDOT 2023, p. 211), approximately 1 foot (ISTHA 2024, p. 32), no less than 12 inches (USACE 2010, p. 8), or 40% of the diameter of round pipes and 20% of the rise of box and pipe arch culverts (USFWS 2024, sec. 2.1.3.4). General blanket recommendations may work in areas with low slopes, such as throughout much of Illinois. However, special attention should be paid to areas of higher slopes, such as along river valleys like the Mississippi, Illinois, Rock, Fox, and Vermilion Rivers where a general application may not have the desired effect.

Note that although this discussion of composition and placement of sediment was given within the context of embedded culverts, similar guidelines could be useful if additional stream sediment needs to be added during the construction of a bridge or three-sided structure.

Culvert Height

After culvert width, embedment, and elevation have been estimated, use of traditional hydraulic models to check if the culvert can handle peak high flows during flooding events is recommended. If necessary, adjust culvert height as needed. It is recommended to retain some freeboard (open space at the top) to allow for the movement of debris during high flows. A maximum of 80% submergence (headwater depth/height of culvert inlet above streambed ≤ 0.8, represented as HW/D) is suggested, with values closer to 70% for streams that tend to carry more coarse debris (FSSSWG 2008, sec. 6.3.2; Hernick et al. 2019, sec. 2.4.6; USFWS 2024, Appendix C).

Multiple Barrel (Multi-cell) Culverts

There are many instances where two or more culvert openings (often referred to as barrels or cells) are installed next to each other (Figure 14). This configuration can have the desired effects of reduced flow velocities, reduced flooding potential, and reduction in erosive potential, but at other times, it does not. When it does not, what typically happens is that one or more of the barrels has been clogged with debris and sediment, forcing the entire flow through the remaining cell at velocities greater than initially projected (Hansen et al. 2011). The increased velocities increase scour and other issues that impede AOP and are detrimental to the aquatic resources in the area. A clogged barrel may only be partially clogged, and there may only be a partial increase in flow through the remaining barrel. Whether this partial increase in flow is problematic for AOP depends on the circumstances at the site. It is not always obvious beforehand when these problems may occur. It does seem to happen more frequently when the combined width of all the barrels is greater than the width of the stream channel. In this situation, the flow is spread out over a wider area, and flow velocity subsequently decreases to a less than naturally occurring velocity and depth. As a result, sediment settles near the culvert, potentially clogging a barrel or barrels. If the stream gets too shallow, then aquatic organisms may not be able to pass (Hernick et al. 2019). A scenario with a similar outcome is that barrels could get clogged with coarse wood that cannot pass through, causing fine sediment to build up around the structure and become clogged. This potential problem can be partially avoided by regular maintenance and monitoring of problematic culverts.

Figure 14. Photo. Example of multi-cell box culvert.

The preferred solution is to consider and recommend installing a bridge or three-sided structure. If these structures are not economically or structurally feasible for the situation, then designs should be considered where one barrel can sufficiently handle routine high and low stream flows (ISTHA 2024, p. 32), while additional barrels are installed at a slightly higher elevation so they can function during flooding situations. These higher elevation barrels allow the flood water to pass through but do not hinder the function of the main barrel during normal or low flow. The invert elevation of these additional barrels should be just above the elevation of routine high flows, but below bankfull elevation, and they should be dry most of the time except under extreme conditions (Hernick et al. 2019, sec. 6.1). It is also advisable to align the barrels with the stream channel and keep the combined width of all the barrels as close to the bankfull width as possible.

A related situation is when there is a relatively small stream flowing through a relatively large floodplain (Figure 15). The recommendation here is to design the primary culvert so it can handle routine high and low stream flows. Additional culverts of sufficient size are installed at widely separated appropriate locations, such as at floodplain channels, throughout the floodplain, with the anticipation that they will remain dry except during extreme flooding events.

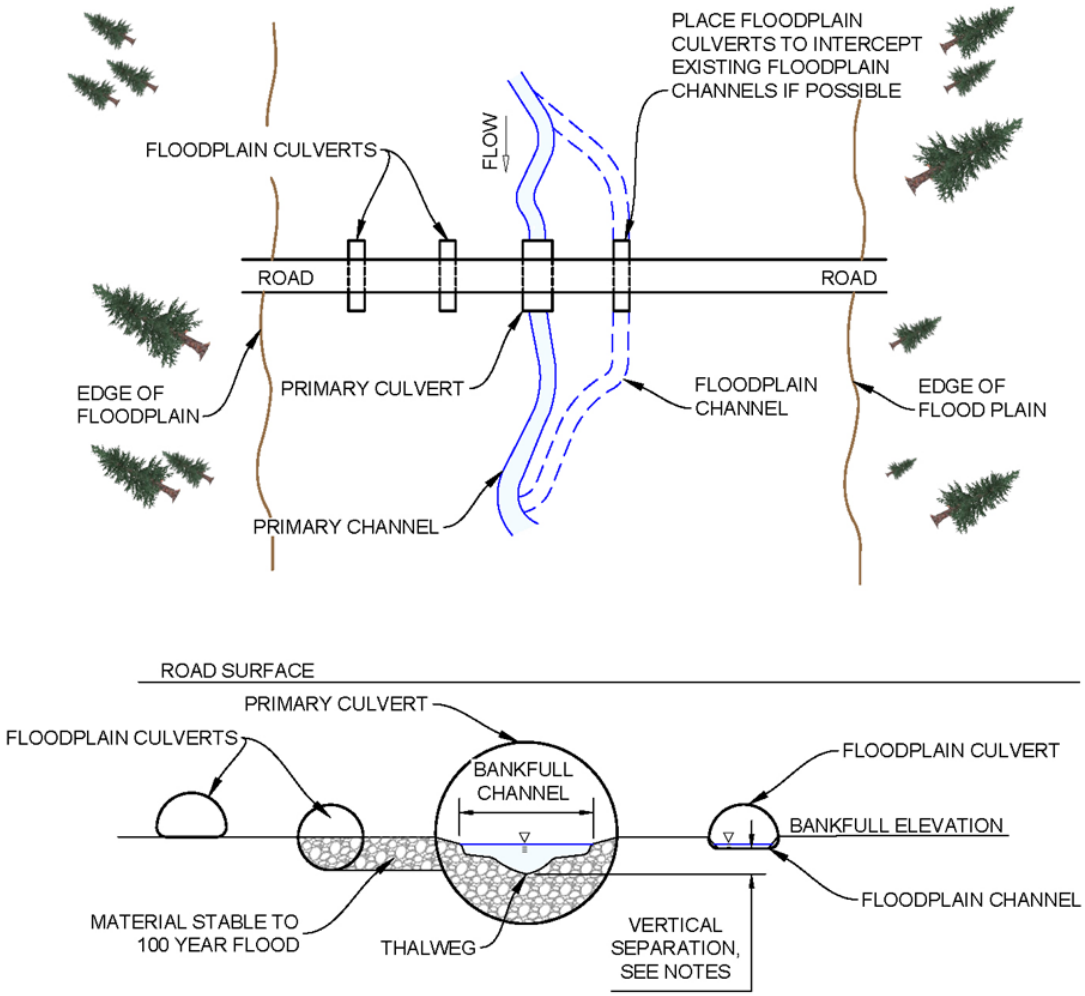

Figure 15. Illustration. Example of placement and position of floodplain culverts.

Source: USFWS (2024), Figure 2-4

Grade Control Structures

Grade control structures are sturdy elements (e.g., riprap, boulders, logs, artificial materials, etc.) that are used to prevent general erosion of the stream bottom or headcutting (significant erosion of the stream bottom in a confined area) usually by adjusting water levels or sedimentation rates. These can be used when there is a perceived stream bottom erosion or in a preventative capacity, such as if there is a concern that headcutting may occur. Their use associated with culverts to facilitate AOP is situationally dependent. For example, creating a series of riffles downstream of a culvert with a perched outlet could raise stream levels enough to submerge the outlet and solve the AOP issue (Figure 16). Another scenario is if AOP is hindered when water levels are too shallow in a culvert during low flow periods. Using grade control structures to raise water levels slightly would facilitate AOP. Some grade control structures, such as riffles or intentionally placed log jams, would have the additional benefit of acting as aquatic organism habitats. However, care must be taken that the grade control structures do not act as dams or barriers, which would hinder AOP. Their impacts may also extend upstream and downstream outside the project area with unintended consequences. Grade control structures are not meant as replacements for properly designed culverts for AOP as they often can degrade in usefulness over time. See Appendix F in FSSSWG (2008), section 6.3 in Hernick et al. (2019), and pages 156–157 in ISTHA (2024) for more details.

Figure 16. Photo. Example of grade control structure to assist with AOP.

Source: The Nature Conservancy (2024)

Inlet/Outlet Control Structure

Similar to grade control structures, there are numerous types and designs of inlet and outlet control structures for culverts (Figure 17). These structures, similar to grade control structures, help control or limit erosion specifically from the road bank or downstream. The purpose of these structures is to help with the hydraulic efficiency of the culvert. The type, placement, and size of these structures is largely dependent on the hydraulic analysis that is performed on the site. Improper installation or type of these control structures can result in complete blocking of the culvert, damage to the roadway, increased erosion, flooding, and as barriers to terrestrial and aquatic organisms. See Texas Department of Transportation’s *Hydraulic Design Manual* (2019) Chapter 8, Section 8-4 for more details.

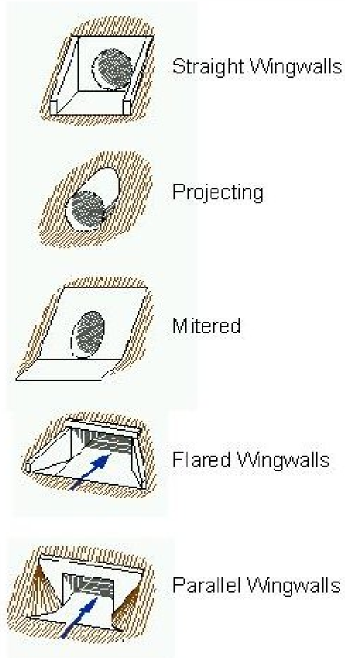

Figure 17. Illustration. General design types of inlet and outlet control structures.

Source: Texas Department of Transportation (2019)

Culvert Retrofits

To make a culvert AOP-friendly, there have been attempts to retrofit existing culverts with baffles, weirs, sills, boulders, or numerous other additions. The intent is to slow water velocities, retain sediment, and facilitate a more natural stream flow. Although these elements may be less expensive than installing a new culvert, they tend to fail by either breaking, increasing turbulence, increasing flow velocities, or increasing the likelihood of debris clogging the culvert completely. There may be situations where these elements could be beneficial. But in general, their long-term feasibility has led to their lack of usefulness for AOP (Hansen et al. 2009; Hernick et al. 2019, sec. 5.6).

Hydraulic Analysis

Hydraulic analysis is essential for designing crossings that support AOP and other aquatic resource functions. Traditional methods (hand calculations) are not suitable for assessing stream function and sediment transport at lower flows. It is always recommended that the crossing design be double-checked with traditional hydraulic models and flow specifications to verify the safety of the road crossing. Current designs and best practices often require complex calculations, which are now typically done using modern computer software. Key outputs include slope, depths, velocities, and shear stress. Accurate roughness estimation (Manning's n) is crucial, especially for culverts with natural materials. It is important to note that the space occupied by sediment should NOT be included in hydraulic calculations. Flow calculations should only include the open space within the culvert through which water would move. Furthermore, velocity calculations, such as Manning's equation, should use Roughness Coefficient "n" values for the natural sediment of the site (e.g., ~0.03) rather than "n" values for construction materials (e.g., 0.012 for concrete). Additional best practices include using reliable data, documenting assumptions, maintaining consistency in analysis methods, opting for simpler models when possible, and conducting sensitivity analyses (Hernick et al. 2019, Chapter 4; ISTHA 2024).

BRIDGES

As mentioned in the previous section, bridges are typically not problematic for aquatic resources and stream function. Most states consider bridges the optimum standard for aquatic crossing and minimizing impacts on aquatic resources as they often have larger spans (> 20 ft) that cross stream banks and, in some cases, entire floodplains. For our purposes, we will loosely define bridges as open-span structures that span the width of a waterbody and its banks and do not cause flow alteration by enclosing the stream on three or more sides. Though typically less problematic and often requiring less permitting (from an ecological standpoint), some conditions still need to be met for the bridge to have minimal impact on aquatic resources. Because we already mentioned bridges in the culvert section, we will only discuss scenarios unique to bridges with a summary of the key differences. See the Culvert section for applicable scenarios for bridges as well.

Bridge Use Conditions and Implementation

The most critical reason to use a bridge over a culvert is when the water flow or volume is too high for a culvert to handle safely. Culverts can become overwhelmed during heavy rainfall or flooding, leading to potential washouts, blockages, and compromised structural integrity. Bridges, with their elevated design and greater span, allow high volumes of water to pass underneath without obstruction, ensuring safety and durability. Bridges are fabricated and designed specifically for each unique scenario. This flexibility means that engineers can tailor the bridge to meet the specific requirements of the site, whether it is the length needed to span a wide river or the height required to clear floodwaters. This customization ensures that bridges can handle a wide range of environmental and structural conditions effectively. Bridges can span entire obstructions, such as rivers, valleys, and floodplains. By spanning the bankfull width of a stream, bridges allow for natural stream migration, preserving the natural flow and reducing the impact on the aquatic ecosystem. This is crucial for maintaining the health and movement of aquatic species and preventing erosion and sediment buildup. Bridges can span entire floodplains and associated wetlands, which are crucial habitats for various plant and animal species. Wetlands play a vital role in water filtration, flood control, and providing habitats for wildlife. By using bridges, we can minimize disruption to these ecosystems and maintain their ecological functions. Bridges typically have smaller footprints compared to culverts because they do not always require extensive excavation and fill material. Culverts often need significant earthwork to create a stable base and channel for the water flow, while bridges can be designed to minimize ground disturbance. This reduced footprint helps preserve the surrounding environment and reduces construction impact. In areas where larger debris and ice flows are a major concern, bridges are the preferred solution. Culverts can easily become clogged with debris, leading to blockages and potential flooding. Bridges, with their open-span design, allow debris and ice to pass through without obstructing the waterway. This is particularly important in regions with harsh winter conditions or where natural debris movement is common. Finally, bridges are built on-site and are not restricted by the rigidity of precast culverts, so they can be installed on curves and significant elevation changes. This allows bridges to blend in with the natural topography better than culverts, often making them more aesthetically pleasing and engineering marvels.

One of the biggest issues with bridge construction is localized scour due to the changing of the flow during different scenarios around the bridge's pier of embankments. Some construction standards need to be accounted for when designing bridges related to stream flow. The first is the clearance, which is not only important on navigable rivers, but also when considering flooding and passage of debris under the bridge during those highwater events. Suppose large amounts of debris or water accumulate upstream or around the bridge embankments or piers. In that case, it can cause erosion around the structures, reducing the integrity of the foundation of the bridge. Another design of bridges that needs to be considered is the position of bridge piers. Piers that are not in the appropriate position can cause stream flows to be diverted, causing erosion of sediment and scouring. Similarly, bridges that do not have the appropriate span width can cause flow constriction, leading to increased water velocities, which can erode entrances and exits of a bridge. Some common approaches to minimizing scour are placing riprap, using articulating block mats, or using concrete or sheet piling. These methods are meant to absorb water energy and stabilize the bank and base of the bridge. However, instream scour can be minimized by designing bridges with appropriate pier sizes, placement, and orientation, in combination with appropriate bridge width and height. Conducting a full scour analysis based on thorough hydraulic and hydrological assessments is the best way to determine short- and long-term scour potential.

Bridges typically last longer than culverts with proper maintenance. Bridges can last anywhere from 50 to 100 years, and this number is increasing as new methods and materials are being designed for construction. However, the initial cost of bridges can be significantly higher than culverts, even when spanning the same length of obstruction. However, over time, the difference in cost will be reduced as bridges often require less maintenance, especially if the goal is to benefit aquatic resources. Finally, bridges are often safer than culverts because they can handle higher traffic loads and speeds. They can also be constructed to meet the unique safety and structure guidelines required by a specific stream, city, or road. Bridges are also subject to more rigorous safety standards to meet compliance. This increased attention on bridge structure and safety can lead to expensive maintenance, monitoring, and retrofitting over the extended life of the bridge.

Generally, bridges have a lower impact on aquatic and terrestrial taxa when constructed to appropriate standards with environmental impacts taken into consideration than culverts under identical scenarios. Because bridges rarely stop flow or create barriers for movement, aquatic taxa are able to pass under them with little to no change in behavior. This is also the case for many terrestrial species.

CHAPTER 4: STREAM AND WATERSHED EQUILIBRIUM

The provided guidelines assume the stream and watershed are in equilibrium, or that at least no significant changes are anticipated at the project site over the lifetime of the bridge or culvert. Many times, this will be the case, but sometimes it is not. To hopefully prevent any future complications, it is recommended to examine the larger surrounding area for any factors that could change stream flow patterns. Streams are often best viewed as part of the larger watershed and surrounding landscape instead of a singular intensity. For example, the watershed upstream from a project site may be in the process of shifting from predominantly agriculture to a suburban / urban setting. A possible outcome of this transition would be an increase in the flashiness of stream flows during storm events and reduced erosion over the landscape, leading to reduced sedimentation in the stream. Another example would be erosion of the streambed downstream, manifesting itself as an incised channel or headcut. This type of erosion has the tendency to move upstream until it hits a stable structure, such as a culvert, at which point it could erode the structure and negate any AOP efforts (FSSSWG 2008, sec. 6.1.2.5). These landscape and watershed factors should be included when determining a structure design and implementation at a crossing (ISTHA 2024).

A corollary to this discussion is the observation that a culvert could impact the surrounding watershed. Ideally, a culvert designed following the guidelines in this report would seamlessly blend into the natural stream and have negligible impacts upstream and downstream. A poorly designed culvert could increase the rates of sediment aggradation or erosion, the impacts of which could propagate outside the project site, for example. Replacement of a culvert could result in significantly different flow patterns. If culverts or other structures downstream from the replaced culvert were designed according to the previous culvert's influence on the stream, then the new flow regime could create structural integrity or environmental issues at the downstream sites (WTIC 2004).

Proposing solutions is difficult because there are so many potential scenarios. In some instances, modifying the design of the culvert (e.g., adjusting skew, slope, width, embedment depth, height, etc.) may be deemed sufficient. Installing grade control structures adjacent to the culvert may mitigate negative impacts. Perhaps constructing a bridge or three-sided structure over a box or pipe culvert is preferable. A more extreme option would be an entire stream restoration effort outside the road-crossing project site.

AQUATIC ORGANISMS

A variety of aquatic organisms benefit from moving freely upstream and downstream through road crossings. For example, Lake Sturgeon *Acipenser fulvescens* and Northern Pike *Esox lucius* will swim upstream during spring spawning migrations. Northern Pike also move out of larger rivers into smaller creeks to feed on smaller fishes during the warmer months of the year. Smallmouth Bass *Micropterus dolomieu* routinely move up and downstream from habitat to habitat. American Eel *Anguilla rostrata* make epic spawning migrations from the Atlantic Ocean to Illinois and back, passing through many road crossings during their journey. This is but a small sample of Illinois fishes that benefit from AOP (Metzke et al. 2022; Veraldi et al. 2025).

The following is a list of species in Illinois that are endangered, threatened, or in greatest conservation need, with references that specifically mention culvert-related issues as problematic for their recovery:

- Northern Brook Lamprey *Ichthyomyzon fossor* (Endangered) (Willink and Dreslik 2023a)
- Least Brook Lamprey *Lampetra aepyptera* (Threatened) (Willink and Dreslik 2023b)
- Gravel Chub *Erimystax x-punctatus* (Threatened) (Willink and Dreslik 2023c)
- Bigeye Chub *Hybopsis amblops* (Threatened) (Willink et al. 2023)
- Mottled Sculpin *Cottus bairdii* (Threatened) (DeBoer et al. 2015; Willink 2017)
- Iowa Darter *Etheostoma exile* (Species in Greatest Conservation Need) (Bland and Willink 2018)
- Salamander Mussel *Simpsonaias ambigua,* Rabbitsfoot *Quadrula cylindrica* and numerous other listed mussel species *(*Threatened and Endangered*)* (USFWS 2022, 2023)

SEMITERRESTRIAL AND TERRESTRIAL ORGANISMS

The focus of this report is on aquatic organism passage. But there are opportunities for semiterrestrial species (e.g., turtles, snakes, salamanders, etc.) and terrestrial species (e.g., deer, raccoons, foxes, etc.) to use culverts and bridges for passage underneath road crossings. Besides the environmental benefits, there could also be a reduction in wildlife-vehicle collisions (FSSSWG 2008; IDOT 2024, p. 26-14.4) by ensuring there are banks alongside the stream in the culvert for the terrestrial animals to traverse. This is consistent with many AOP recommendations for culvert width. But care needs to be taken not to make the culvert too wide. Unless there is a designed low-flow channel, an overly broad culvert could lead to water levels that are too shallow for AOP. Furthermore, riprap is hazardous to walk on and should not be considered passable by terrestrial species. Using riprap as a base and then covering it with finer soils could be a suitable solution.

Another aspect is utilizing culverts as habitats, such as for bats and birds. IDOT has already taken this into consideration by incorporating ledges into some culverts so they can be used by phoebes and swallows for nesting sites (IDOT 2017, sec. 2.2.1.3; IDOT 2023, sec. 2.3.11.5). It has also documented the use of culverts and bridges as endangered bat roosting locations.

CONCLUDING REMARKS

The general principles described above are applicable to “typical” Illinois streams and road crossings. But every stream is different, and it is impossible to anticipate every contingency. There are always unusual cases, like braided channels, actively meandering channels, large wetlands crossed by a causeway, urban settings in the middle of large cities, and any number of other unanticipated situations. In these instances, one should consult the references provided for additional guidance.

Even if there is not an exact match in these references with one's particular situation, then the general principles provided in this report combined with any additional details from cited references should provide enough information to formulate a solution. One can also contact local and regional experts, as well as the authors of the references, for advice. Furthermore, we did not include every minute detail in this report. If we did so, this report would be hundreds of pages long and largely repetitive of other publications. (For example, there are many extremely elaborate methods for determining streambed substrate particle sizes.) We did not include this detailed information because we felt that it would be distracting and possibly not useful to the reader. But we did cite specific page numbers and sections of various publications in case one wishes to review a more in-depth discussion of various topics, and we encourage readers to do just that.

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APPENDIX: STATE DOCUMENTATION

Table 2. List of State Specific Documentation Used to Create This Report and If That Documentation Was AOP Specific

State	AOP	Guiding documents
AL	N	https://www.dot.state.al.us/publications/Bridge/pdf/StructuralDesignManual.pdf
AL	N	https://rosap.ntl.bts.gov/view/dot/35192/dot_35192_DS1.pdf
AL	N	https://www.dot.state.al.us/publications/Design/pdf/HydraulicManual.pdf
AK	N	https://dot.alaska.gov/stwddes/desbridge/assets/pdf/manual/bridge_manual.pdf
AK	Y	https://dot.alaska.gov/stwddes/desenviron/assets/pdf/procedures/dot_adfg_fishpass080301.pdf
AK	N	https://dot.alaska.gov/stwddes/desbridge/hwy_drainage_manual.shtml
AK	Y	https://www.arlis.org/docs/vol1/F/FishPassage/Frei-2006.pdf
AZ	N	https://azdot.gov/sites/default/files/2019/07/2014_adot_hydrology_manual.pdf
AZ	N	https://azdot.gov/sites/default/files/2019/07/highway-drainage-design-manual-hydraulics.pdf
AR	N	https://www.ardot.gov/wp-content/uploads/2020/11/Bridge-Division-Guidelines.pdf
AR	N	https://www.ahtd.ar.gov/roadway_design_division/Roadway%20Design%20Plan%20Development%20Guidelines%2009-16-2020.pdf
AR	Y	https://www.fws.gov/sites/default/files/documents/20220321_Final-Doc_SPMs%20for%20Bridge%20and%20Culvert%20Projects.pdf
AR	N	https://www.ahtd.ar.gov/consultant_services/publications/Design_Build%20Procedures_Final.pdf
CA	Y	https://dot.ca.gov/-/media/dot-media/programs/design/documents/f00020339-200705-fpm-complete-a11y.pdf
CA	N	https://dot.ca.gov/-/media/dot-media/programs/design/documents/dib83-04-a11y.pdf
CA	N	https://dot.ca.gov/programs/engineering-services/manuals/bridge-standard-details
CA	N	https://highways.dot.gov/federal-lands/pddm/Chapter_07.pdf
CO	N	https://www.fhwa.dot.gov/codiv/final_pea.cfm
CO	N	https://www.codot.gov/programs/bridge/bridge-manuals/design_manual/cdot_bridge_design_manual_2024_02.pdf
CT	Y	https://portal.ct.gov/-/media/dot/finalcrossingguidelinesfeb262008highrespdf.pdf
CT	N	https://portal.ct.gov/dot/-/media/dot/documents/ddrainage/85pdf.pdf?rev=cf80013d9c38448d955ada7cbf3e0f86&hash=3C1355CDB8C621432C872F8F87F97669
CT	N	https://portal.ct.gov/dot/-/media/dot/policy/waterresources/connecticutusacestreamcrossingbmpsaugust2016pdf.pdf?rev=e31b9258e1a046afb4c962554c2217bf&hash=7FAF919F8B0A8215BF79E6DDF7AAD9ED
DE	N	https://bridgedesignmanual.deldot.gov/index.php/104_-_Hydrology_and_Hydraulics#104.3.1.4_Environmental_Considerations
DE	N	https://www.fhwa.dot.gov/engineering/hydraulics/pubs/12026/hif12026.pdf?cache=1731352264454
FL	N	https://www.fdot.gov/docs/default-source/roadway/drainage/files/2016Jan-DrainageManual.pdf
GA	N	https://www.dot.ga.gov/partnersmart/designmanuals/drainage/drainage%20manual.pdf
GA	Y	https://www.dot.ga.gov/PartnerSmart/DesignManuals/FishPassage/Ecologist's%20guidance%20for%20Fish%20passage.pdf
GA	Y	https://www.fws.gov/sites/default/files/documents/Stream-Crossings-in-Georgia-2021-508.pdf
HI	N	https://www.stormwaterhawaii.com/wp-content/uploads/2021/10/Construction-BMP-Field-Manual_October-2021.pdf
ID	N	https://apps.itd.idaho.gov/Apps/bridge/manual/Hydraulics.pdf
ID	N	https://apps.itd.idaho.gov/apps/manuals/roadwaydesign/files/RoadwayDesign600.pdf
IL	N	https://idot.illinois.gov/content/dam/soi/en/web/idot/documents/doing-business/manuals-guides-and-handbooks/highways/bridges/design/culvert-manual-2017.pdf

State	AOP	Guiding documents
IL	N	https://public.powerdms.com/IDOT/documents/1975606/Construction%20Manual
IL	N	https://public.powerdms.com/IDOT/documents/1881647
IL	N	https://public.powerdms.com/IDOT/documents/2504297/Bridge%20Manual
IL	N	https://agency.illinoistollway.com/documents/20184/238191/Drainage+Design+Manual_04202017.pdf/498191e4-6457-43a5-b4b3-5c601d4c2478
IL	N	https://www.mvr.usace.army.mil/Portals/48/docs/regulatory/mitigation/IllinoisMethod.pdf
IN	N	https://www.in.gov/dot/div/contracts/design/Part%202/Chapter%20203%20-%20Hydraulics%20and%20Drainage%20Design.pdf
IA	Y	https://www.iowadnr.gov/media/7076/download?inline
IA	N	https://iowadot.gov/bridge/policy/03-01-00Prelim.pdf
IA	N	https://iowadot.gov/bridge/policy/04-01-00Prelim.pdf
IA	N	https://iowadot.gov/bridge/policy/07-00-00CulvertLRFD.pdf
KS	N	https://www.ksdot.gov/bureaus/burRoadDesign/toc.asp
KS	N	https://www.ksdot.gov/Assets/wwwksdotorg/bureaus/KdotLib/2017/KU_16_2_Summary.pdf
KY	N	https://transportation.ky.gov/Highway-Design/Drainage%20Manual/DR%20600%20Culverts.pdf
LA	N	http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Bridge_Design/BDEM%20New%20Manual/Full%20Manual/BDEM_Revision%209_Full%20Manual.pdf
LA	N	http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Standard_Specifications/Standard%20Specifications/2016%20Standard%20Specifications%20for%20Roads%20and%20Bridges%20Manual/00%20-%202016%20-%20Standard%20Specification%20(complete%20manual).pdf
LA	N	http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Public_Works/Hydraulics/Documents/Hydraulics%20Manual.pdf
ME	Y	https://www.maine.gov/mdot/publications/docs/brochures/pocket_guide_stream_smart_web.pdf
ME	N	https://www.maine.gov/mdot/bdg/docs/bpdg/Complete2003BDGwithUpdatesto2018.pdf
MD	N	https://www.roads.maryland.gov/OHD2/HDM_design_guidelines_culverts.pdf
MD	N	https://roads.maryland.gov/mdotsha/pages/Index.aspx?PageId=38
MD	Y	https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendations_for_aquatic_organism_passage_at_maryland_road-stream_crossings_june_2021.pdf
MA	N	https://www.mass.gov/doc/chapter-1-bridge-site-exploration/download
MA	Y	https://www.mass.gov/files/documents/2018/08/23/Stream%20Crossings%20booklet%20Web.pdf
MA	Y	https://www.mass.gov/doc/massachusetts-river-and-stream-crossing-standards/download
MI	N	https://www.michigan.gov/mdot/business/design/drainage-manual
MN	N	https://www.dot.state.mn.us/bridge/hydraulics/drainagemanual.html
MN	N	https://www.dot.state.mn.us/bridge/lrfd.html
MN	Y	https://mdl.mndot.gov/_flysystem/fedora/2023-01/trs1302.pdf
MN	Y	https://files.dnr.state.mn.us/waters/publications/culvert-stream-connectivity.pdf
MN	Y	https://www.lrrb.org/pdf/200920.pdf
MN	Y	https://mdl.mndot.gov/index.php/_flysystem/fedora/2023-01/201119.pdf
MN	Y	https://cts-d8resmod-prd.oit.umn.edu/pdf/mndot-2021-29.pdf
MN	Y	https://files.dnr.state.mn.us/waters/publications/stream-crossing-guidelines.pdf
MS	N	https://opcgis.deq.state.ms.us/Erosion_Stormwater_Manual_2ndEd/Volume1/V1_Chap4_BMP_Design.pdf
MO	N	https://epg.modot.org/index.php/750.7_Non-Hydraulic_Considerations#750.7.3_Environmental_Requirements
MT	N	https://www.mdt.mt.gov/other/webdata/external/hydraulics/manuals/Chapter-11-Culverts.pdf
NE	N	https://dot.nebraska.gov/business-center/design-consultant/rd-manuals/
NV	N	https://www.dot.nv.gov/home/showpublisheddocument/1663/636183602579530000
NH	N	https://www.dot.nh.gov/sites/g/files/ehbemt811/files/inline-documents/manual-drainage-design.pdf
NH	Y	https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/co-20-04.pdf

State	AOP	Guiding documents
NH	Y	https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/lrm-culvert-assessment-protocol.pdf
NH	N	https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/lrm-unh-stream-crossing.pdf
NJ	N	https://www.nj.gov/transportation/eng/documents/BDC/pdf/2015RoadwayDesignManual20200319.pdf
NJ	N	https://dep.nj.gov/njfw/wp-content/uploads/njfw/CHANJ_GD_2019_V1_BMPs_WildlifePassageSystems.pdf
NJ	N	https://nj-dot.nj.gov/transportation/eng/documents/SEM/pdf/DrainageDesignManual2006s.pdf
NM	N	https://www.dot.nm.gov/infrastructure/program-management/drainage-design/
NY	N	https://www.dot.ny.gov/divisions/engineering/structures/repository/manuals/brman-usc/NYSDOT_Bridge_Manual_2021.pdf
NY	N	https://www.dot.ny.gov/divisions/engineering/design/dqab/hdm
NC	N	https://www.deq.nc.gov/water-quality/surface-water-protection/401/certs-and-permits/2017-gcs-4000s/gc4153/download
NC	N	https://connect.ncdot.gov/resources/roadside/FieldOperationsDocuments/Best%20Management%20Practices%20for%20Construction%20and%20Maintenance%20Activities.pdf
NC	N	https://connect.ncdot.gov/resources/hydro/DrainageStudiesGuidelines/2022%20Guidelines%20for%20Drainage%20Studies%20and%20Hydraulic%20Design.pdf
ND	N	https://www.dot.nd.gov/construction-and-planning/construction-and-contractor-resources/design-manual
OH	Y	https://www.transportation.ohio.gov/wps/wcm/connect/gov/bb0c9d78-0c99-420a-b1cb-d9c97d3e9c6e/Ecological+Manual+2014.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_79GCH8013HMOA06A2E16IV2082-bb0c9d78-0c99-420a-b1cb-d9c97d3e9c6e-oBUzb.7
OH	N	https://www.dot.state.oh.us/Divisions/Engineering/Structures/standard/Maintenance/Documents/CMM_12-2003.pdf?Mobile=1&Source=%2FDivisions%2FEngineering%2FStructures%2Fstandard%2FMaintenance%2F_layouts%2Fmobile%2Fview.aspx%3FList%3Dd78629f9-2c0c-477f-9162-ed3f7f497c5d%26View%3Dfee7af1f-d2b8-4709-a86d-77dede91e71a%26CurrentPage%3D1
OH	N	https://rosap.ntl.bts.gov/view/dot/20619
OK	N	https://oklahoma.gov/odot/business-center/pre-construction-design/roadway-design/support-units/oklahoma-roadway-drainage-manual.html
OR	N	https://www.oregon.gov/odot/Bridge/Guidance/BDM-2024-04.pdf
OR	N	https://www.oregon.gov/odot/hydraulics/pages/hydraulics-manual.aspx
OR	Y	https://www.dfw.state.or.us/fish/passage/
PA	N	https://www.dot.state.pa.us/public/PubsForms/Publications/PUB%2015M.pdf
PA	N	https://www.dot.state.pa.us/public/pubsforms/Publications/PUB%20584/June%202022-Change%201.pdf
PA	N	https://www.dot.state.pa.us/public/pubsforms/Publications/PUB%2013M/May%202020%20Change%20No.%205.pdf
RI	Y	https://www.dot.ri.gov/business/documents/Road_Stream_Crossing_Design_Manual_8_2021.pdf
SC	N	https://www.scdot.org/content/dam/scdot-legacy/business/technicalpdfs/hydraulic/requirements2009.pdf
SC	N	https://pubs.usgs.gov/sir/2020/5021/sir20205021.pdf
SD	N	https://dot.sd.gov/doing-business/engineering/design-services/forms-manuals#listItemLink_1897
SD	N	https://dot.sd.gov/doing-business/engineering/design-services/forms-manuals#listItemLink_1187
TN	N	https://www.tn.gov/tdot/structures-/structural-design-office/structural-design-guidelines.html
TN	N	https://www.tn.gov/tdot/engineering-division/engineering-production-support/design-standards/drainage-manual.html

State	AOP	Guiding documents
TX	N	https://ftp.txdot.gov/pub/txdot/crossroads/des/documents/roadway-and-hydraulics-design/hh-2019-hdm.pdf
UT	N	https://drive.google.com/file/d/1YSUKgvnoGIQ1xKzcVnNgBvMUckoGiYnl/view
VT	N	https://vtrans.vermont.gov/sites/aot/files/highway/documents/structures/VTrans%20Hydraulics%20Manual.pdf
VT	Y	https://vtfishandwildlife.com/sites/fishandwildlife/files/documents/Learn%20More/Library/REPORTS%20AND%20DOCUMENTS/AOP/GUIDESLINES%20FOR%20DESIGN.pdf
VT	Y	https://vtfishandwildlife.com/conserve/aquatic-habitat-conservation/aquatic-organism-passage-at-road-stream-crossings
VT	N	https://vtrans.vermont.gov/highway/structures-hydraulics/hydraulics/designcriteria-standards
VA	N	https://www.vdot.virginia.gov/doing-business/technical-guidance-and-support/technical-guidance-documents/drainage-manual/
WA	N	https://wsdot.wa.gov/engineering-standards/all-manuals-and-standards/manuals/hydraulics-manual
WA	N	https://wsdot.wa.gov/engineering-standards/all-manuals-and-standards/manuals/bridge-design-manual-lrfd
WA	Y	https://wsdot.wa.gov/sites/default/files/2022-07/Env-StrRest-FishPassageAnnualReport.pdf
WA	Y	https://wsdot.wa.gov/engineering-standards/project-management-training/training/hydraulics-hydrology-training#2022FishPassageandStreamRestoration
WA	Y	https://wdfw.wa.gov/publications/01501
WA	N	https://wdfw.wa.gov/publications/01867
WV	N	https://transportation.wv.gov/highways/engineering/files/WVBDML%202006.pdf
WV	N	https://transportation.wv.gov/highways/engineering/Manuals/Drainage/WVDOH%202007%20Drainage%20Manual%20with%20Addendum%201%20and%202.pdf
WI	N	https://wisconsindot.gov/Pages/doing-bus/eng-consultants/cnslt-rsrces/strct/bridge-manual.aspx
WI	N	https://wisconsindot.gov/rdwy/fdm/fd-13-01.pdf
WI	N	https://wisconsindot.gov/Documents/doing-bus/eng-consultants/cnslt-rsrces/environment/Aquaticconnectivityattachment.pdf
WI	N	https://interpro.wisc.edu/tic/wp-content/uploads/sites/3/2019/12/Bltn_015_Culverts.pdf
WI	Y	https://www3.uwsp.edu/cnr-ap/UWEXLakes/Documents/ecology/shoreland/background/fish_friendly_culverts.pdf
WY	N	https://www.dot.state.wy.us/home/engineering_technical_programs/bridge/bridge_design_manual.html
WY	N	https://www.dot.state.wy.us/home/engineering_technical_programs/manuals_publications/road_design_manual.html
WY	N	https://www.dot.state.wy.us/files/live/sites/wydot/files/shared/Construction/2021%20Standard%20Specifications/Wyoming%202021%20Standard%20Specifications%20for%20Road%20and%20Bridge%20Construction.pdf

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