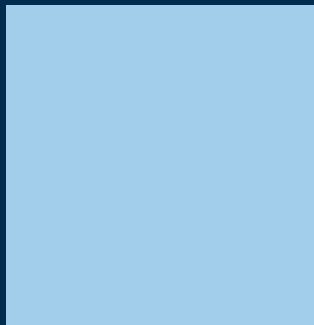
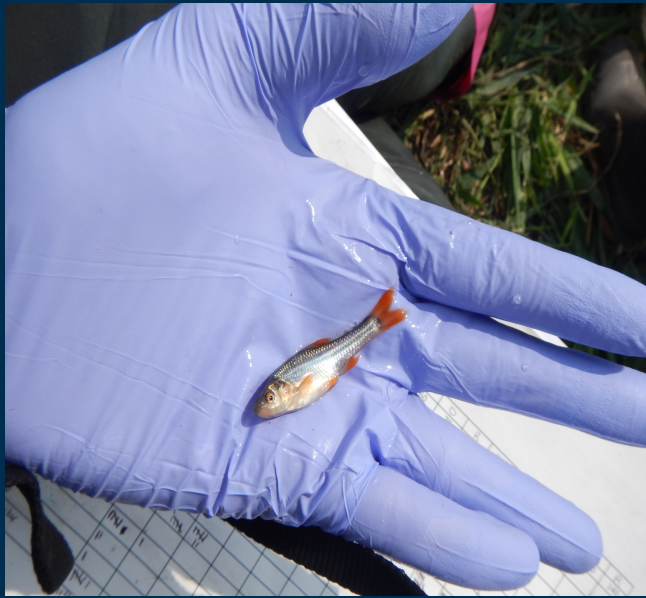
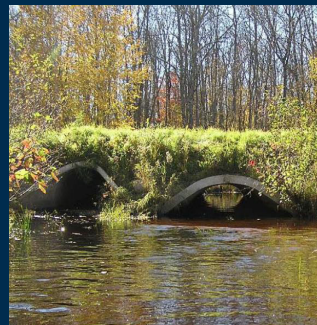


Minnesota Guide for Stream Connectivity and Aquatic Organism Passage Through Culverts



Authors: Matthew Hernick, Christian Lenhart,
Jessica Kozarek and John Nieber

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MINNESOTA GUIDE FOR STREAM CONNECTIVITY AND AQUATIC ORGANISM PASSAGE THROUGH CULVERTS

Final Report

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EXECUTIVE SUMMARY

Purpose and Audience

This Minnesota Guide for Stream Connectivity and Aquatic Organism Passage (AOP) through Culverts has been compiled to assist culvert designers in identifying, selecting, and implementing culvert designs appropriate for maintaining AOP and stream connectivity at road-stream intersections. In addition to meeting traditional hydraulic and roadway capacity goals, these culverts are intended to facilitate the movement and lifecycle needs of fish and other aquatic organisms at road-stream intersections. This includes addressing the closely related need to maintain healthy stream connections for movement of water, sediment, and debris through stream networks. The intended audience is typically hydraulic engineers with a working knowledge of hydraulic culvert design. However, of necessity, the guidance draws on the fields of fluvial geomorphology, biology, and other related fields.

Background and Methods

In the past several decades, there has been considerable research in Minnesota and throughout the United States documenting detrimental effects of AOP blockage at road-stream intersections where in-place culverts are incompatible with the stream and landscape. Culvert designs that create excessive velocity, physical barriers, or shallow depth can block AOP. Disruptions to the continuity of habitat, water flow, and sediment transport processes can also interfere with AOP. In response to these problems, various transportation and natural resource agencies have developed recommendations to improve ecological outcomes at road-stream intersections. Selecting a design method must be based on what is appropriate to the stream, including slope and substrate composition. It is clear that these parameters vary for streams across Minnesota's landscapes.

The current document focusing on public road crossings of public waters in Minnesota was developed by University of Minnesota (UMN) researchers with input from the Minnesota Department of Transportation (MnDOT) Technical Advisory Panel including state and federal agency representatives (MnDOT, Minnesota Department of Natural Resources (MN DNR), United States Department of Agriculture Forest Service (USFS)), and an independent panel of regional aquatic organism passage and geomorphology experts. It was informed by published guidance, research results, and an original survey of Minnesota practitioners involved in stream crossing design and builds on several previous MnDOT / UMN projects.

Guidance

From an ecological standpoint, the best culvert is one that most resembles the stream segments it connects, assuming the stream is reasonably healthy and stable. Identifying relevant stream characteristics from a reference reach and building on these metrics is critical to design success. A set of best practices captures critical elements for AOP and stream connectivity design:

1. Design the culvert slope to match stream channel slope
2. Place the culvert to best match stream alignment

3. Design the culvert opening to bankfull channel width or slightly greater
4. Provide culvert flow depth comparable to channel flow depth for aquatic organism passage (not over-wide and too shallow)
5. Provide a continuous sediment bed with roughness similar to the channel
6. Maintain continuity of sediment transport and debris passage, similar to adjoining reaches
7. Design for safety to the general public, longevity, and resilience

Several design procedures – geomorphic simulation (US Forest Service Stream Simulation), and hydraulic simulation (Federal Highway Administration, Hydraulic Engineering Circular 26 (FHWA HEC 26) – are explained and referenced. Generalized methods of a bridge, recessed or embedded culverts, and hydraulic design retrofits are presented to provide designers with tools they need in varying culvert and landscape situations. Information on topics including multiple barrel culverts, floodplains, and stream grade control forms an additional section of guidance that is critical in some situations. Physical and biological stream information and references and suggestions for engineering analysis support culvert designers in answering ‘why’ and ‘how’ questions when considering inevitable trade-offs in the design process.

Implementation

As a guide, recommendations herein do not carry the weight of law or rule. While inclusion of criteria related to AOP and stream connectivity increases the complexity of design and construction, the resulting culvert infrastructure can require less maintenance and be more resilient in the long term. Favorable project outcomes at road-stream crossings are best achieved through cooperation across project roles and technical disciplines.

PREFACE

Minnesota has over 92,000 miles of streams and rivers and approximately 142,000 miles of roads. These two networks intersect numerous times often with a stream passing beneath the roadway in a culvert (figure 1.). Historically these crossings have been designed for only safe passage of roadway traffic, peak hydraulic design flows, and low construction cost in mind.

Recently there has been widening acknowledgement that allowing for passage of aquatic life “traffic” through culverts (fish and other aquatic organisms, natural streambed sediment material, and stream debris) is important for the health of fisheries and streams, as well as long-term landscape and infrastructure stability.

This document has grown out of a desire on the part of Minnesota Department of Transportation (MnDOT) and the Local Road Research Board (LRRB) to compile recent research on the design of culverts to accommodate aquatic organism passage into a single guide. This guide does not seek to create new content, but rather synthesize or illuminate existing recommendations for aquatic organism passage that are appropriate and effective in Minnesota.

This guide was developed by University of Minnesota researchers at St. Anthony Falls Laboratory and the Department of Bioproducts and Biosystems Engineering, with input from the MnDOT Technical Advisory Panel (TAP) including state and federal agency representatives, and an independent panel of regional aquatic organism passage and geomorphology experts. It has been informed by published guidance, research results, and a survey of Minnesota practitioners involved in stream crossing design. It builds on several previous projects funded by MnDOT and the LRRB in collaboration with the University of Minnesota staff.

Therefore it is impractical to capture in one document all the information relevant to aquatic organism passage, so this document is intended to serve as a guide, referencing the extensive work done in the area already, not as a comprehensive encyclopedia. It is also impossible to represent all the potential variations involved in natural stream systems across the state. Careful observation of local conditions, supplementing one’s own experience by drawing on the knowledge of other disciplines, and exercise of professional judgement is required for good project outcomes.

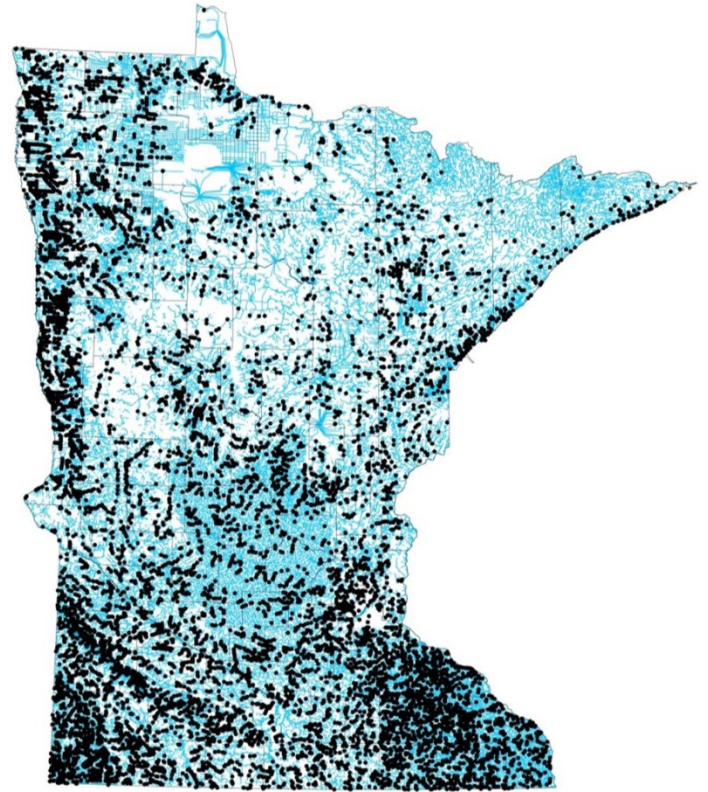


Figure 1. Streams (blue) and culverts (black dots) in MN. Culverts are a common feature across the state; this figure represents only larger culverts, which are a small subset of all the stream crossings in Minnesota.

CHAPTER 1: BACKGROUND

1.1 PURPOSE AND ORGANIZATION

This document is intended to guide culvert designers in selection of appropriate strategies to address aquatic organism passage (AOP) through culverts and associated needs for geomorphic stream connectivity at roadway crossings. The intended primary audience is culvert designers, typically hydraulic engineers, with a working knowledge of traditional hydraulic culvert design but less experience with the elements of design for AOP and stream connectivity. Due to the variety of landscapes, biological communities, and landuse patterns in Minnesota, there is not a single method or set of steps that will be appropriate for all culverts. This document attempts to provide designers with some of the tools they need to address the additional design criteria raised by consideration of AOP and stream connectivity through culverts, as well as the context in which various tools or methods are appropriate. Culvert design for AOP and stream connectivity is an interdisciplinary challenge; communication and coordination between transportation engineers, hydrologists, resource managers, landowners, and other stakeholders is most likely to result in successful projects for those involved.

The initial section of this document frames the need for, and context of, culvert designs that consider AOP and stream connectivity. The remaining sections are more technical in nature and intended to inform a designer's choices without dictating a specific solution.

A brief summary of each chapter is below:

- Chapter 1 – Background. This initial chapter introduces the need for consideration of AOP and stream connectivity to help answer ‘why?’ questions. Sections include biological and physical impacts culverts have on aquatic organisms and the streams they inhabit, and the regulatory context of this guide.
- Chapter 2 – Culvert Design for Aquatic Organism Passage and Stream Connectivity. Starting with an overview of culvert design in general, several categories of design methods for AOP are presented. The heart of this chapter is a list of best practices for culvert design for AOP and stream connectivity (Table 2.4.1). A brief explanation of each best practice completes the chapter.
- Chapter 3 – Site Characteristics. Chapter 3 presents a summary of physical and hydrologic characteristics important to culvert design for AOP and stream connectivity, including guidance on how to obtain each measurement or estimate. As with any engineering project, reliable data is the basis for informed decisions.
- Chapter 4 – Analysis and Tools. This chapter presents selected information related to energy dissipation, hydraulic analysis for AOP, and sediment transport. This chapter is not comprehensive but will hopefully help designers to connect theory and practice.
- Chapter 5 – Design Methods. This a ‘how’ chapter that includes a design method selection chart and information on several design methods, with references for further information.

- Chapter 6 – Additional Considerations. Chapter 6 includes guidance on important design issues not fully addressed in the methods in Chapter 5, including multiple barrel culverts, floodplain culverts, grade control, and discussion of items such as retrofits and cost considerations.
- Chapter 7 – References. This chapter is a list of guidebooks, papers, and reports referenced in the main document, many with web links.
- Appendices. The appendices present supplemental information including a glossary of terms, physical and biological basis for connectivity and passage, and other material.

The document map in Figure 1.1.1 illustrates a general design flow, proceeding from left to right and top to bottom, and, more importantly, indicates where information on specific topics is located within the document. Engineering design is typically an iterative process; some looping through the design process is to be expected at any point.

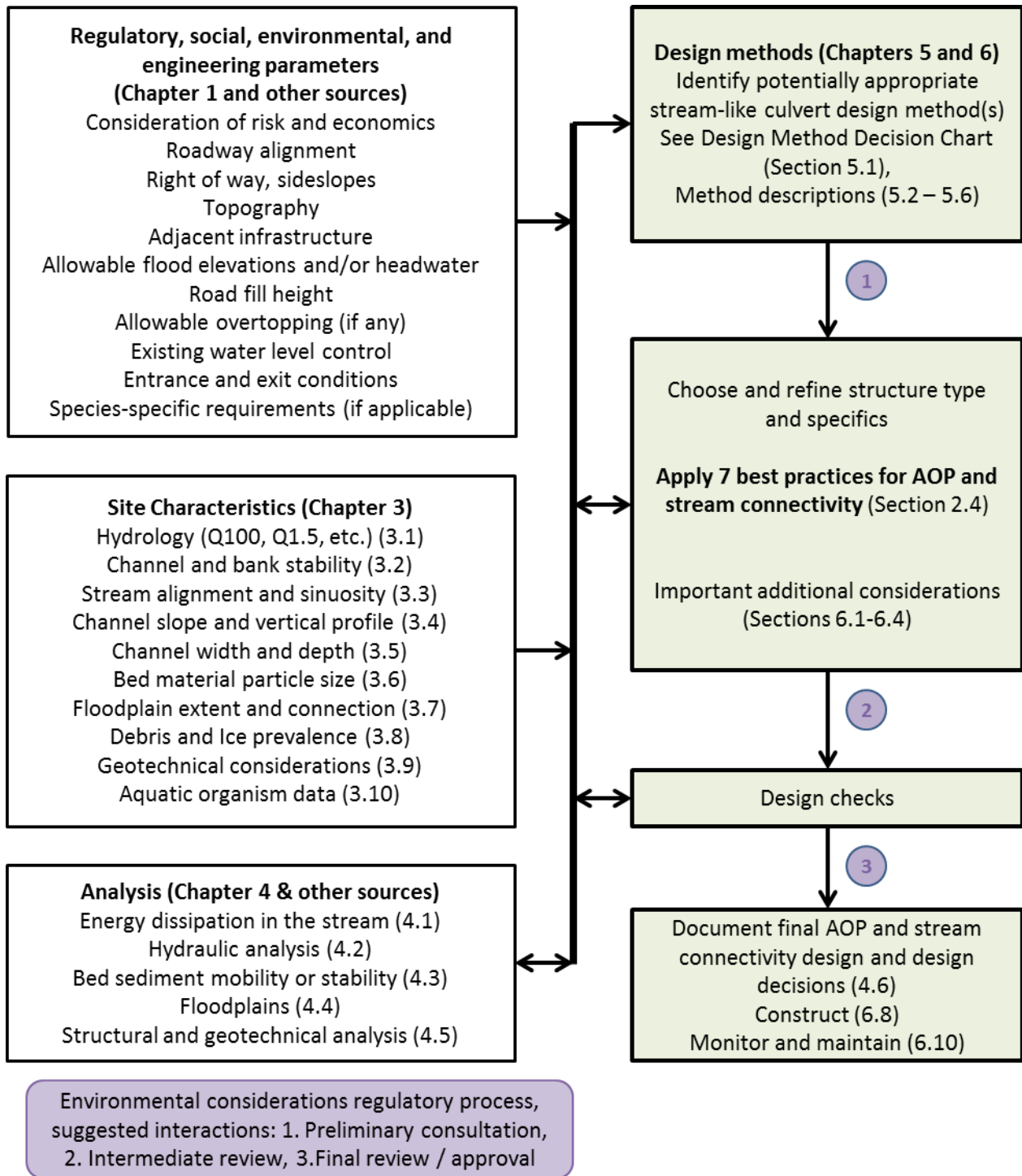


Figure 1.1.1. Design process chart / document map

1.2 INTRODUCTION: CONNECTIVITY AT ROAD-STREAM CROSSINGS

1.2.1 The Importance of Aquatic Habitat Connectivity

Aquatic organisms need to move in stream networks for a variety of reasons to maintain their health, reproduce, and sustain viable populations. Mobile aquatic species such as fish need to move for feeding, to obtain shelter from unfavorable environmental conditions such as high temperatures or low oxygen levels, to spawn, and to find conditions suitable for juvenile rearing. Populations need to move to maintain genetic diversity – this is especially critical for threatened or endangered species. The classic image of a migratory fish is the salmon swimming upstream in rugged coastal systems to spawn – quite unlike the inland landscape in much of the Midwestern U.S. The landscape of much of Minnesota is relatively flat, and native fish species are adapted to a landscape with relatively low stream velocity and few vertical drops. Fish may be effectively blocked by a stream obstruction that would be easily passed by a migratory salmon. Many stream fish need to move within a stream or between lakes, wetlands, and streams to find suitable spawning, feeding, or overwintering sites (Fausch et al. 2002). Northern pike (*Esox Lucius*), for example, move upstream in small creeks and even ditches to spawn in wetlands or shallow, well-vegetated lakes. Fish often have to move to aquatic environments with more favorable conditions, a concept referred to as “refugia” (Sedell et al. 1990). In Minnesota, streams often dry up or become too warm in late summer or fall, requiring fish movement to lakes, deeper pools, or other refugia for survival (Matthews and Marsh-Matthews 2003).

Some freshwater fish species, such as walleye (*Sander vitreus*) and lake sturgeon (*Acipenser fulvescens*), traverse long distances to spawn, often moving up from lakes into rivers (Figure 1.2.2) (Ferguson and Derksen 1971; Pritt et al. 2013). For example, lake sturgeon were found to have migrated 70 to 280 km (43 to 174 miles) in a Lake Superior tributary (Auer 1999).

Elm Creek, located in south central Minnesota, provides an example of the importance of lake-river connectivity. The creek is connected to a chain of lakes that provides year-round aquatic refuge from drought. Elm Creek often dries up in late summer becoming a discontinuous series of pools, despite having a 270 mi² drainage area (Lenhart et al. 2012). During this time fish and other aquatic organisms may need to move through culverts located at lake outlets to enter the deep-water refuge for overwintering.

Other species, such as brook trout (*Salvelinus fontinalis*), have a shorter range with mostly localized movements, though they spawn from October to November which typically coincides with the lowest water levels of the year. In northeast Minnesota, brook trout and other fish species can experience thermal stress during summer months and movement to refuge locations such as springs or tributary stream can be critical. A summary of Minnesota-specific AOP issues and organisms of interest can be found in Appendix B.

Aquatic organisms and AOP concerns in Minnesota encompass more than just fish, including macro-invertebrates, freshwater mussels, reptiles, and amphibians. It is generally thought that most aquatic insects, such as mayflies (order *Ephemeroptera*) or dragonflies (order *Odonata*), can migrate by flying as

they hatch from their larval stages to adult forms and thus are not blocked by culverts. Freshwater mussels are relatively sedentary, but their dispersal can be blocked by culverts. Since their larval stage is transported on the gills of fish, it is generally thought that if the fish species that carry the mussel larvae can pass culverts, then the mussels can be transported as well. In Minnesota 28 of 50 mussel species are state-listed as threatened or endangered, including the Creek Heelsplitter (*Lasmigona compressa*), shown in Figure 1.2.1. Barriers to migration such as culverts are a major issue for survival of these species.

Other benthic (bottom dwelling) aquatic organisms such as the mud puppy salamander (*Necturus maculosus*), may be blocked by high velocities and/or lack of streambed substrate in culverts (Figure 1.2.1, lower left). Semi-aquatic organisms, such as turtles, also need to cross roadways, especially during seasonal movements or nesting migrations (MN DNR 2011). The threatened Blanding's turtle, (*Emydoidea blandingii*) (Figure 1.2.1) is frequently found in small Minnesota streams and ditches often near lakes or wetlands. Often turtles need to move out of streams to nest and deposit eggs in sandy areas adjacent to water bodies. Their movement may also be impacted by the design of the road-crossing berms or the presence of curbs.

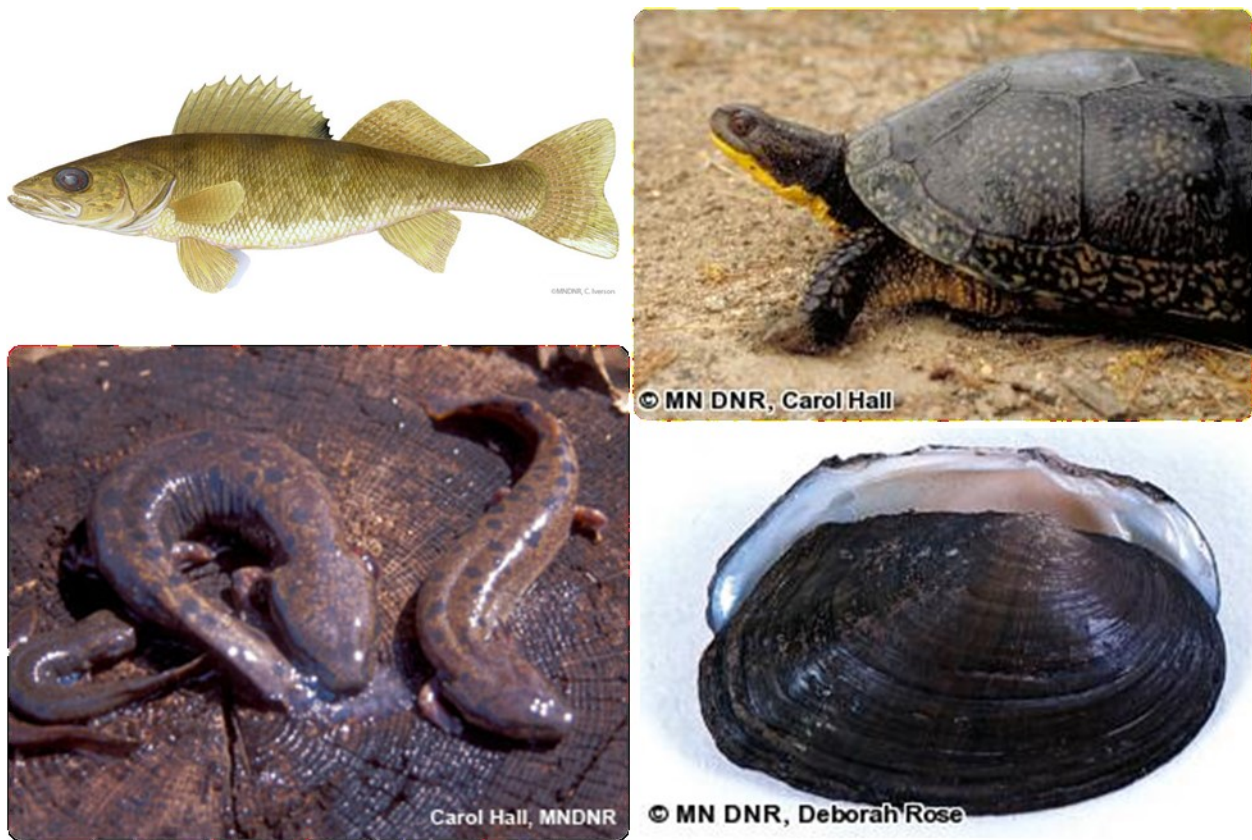


Figure 1.2.1. Minnesota aquatic life that migrates and/or may be blocked by culverts: upper left – walleye (*Sander vitreus*, photo C. Iverson), upper right – Blanding's turtle (*Emydoidea blandingii*, photo Carol Hall), lower left – mud puppy (*Necturus maculosus*, photo Carol Hall), and lower right, the Creek Heelsplitter (*Lasmigona compressa*, photo Deborah Rose).

Stream aquatic habitat connectivity refers to the ability of an organism to move throughout a stream network by connected habitat. Culverts can create a discontinuity by creating conditions that organisms cannot pass, or by altering the habitat upstream or downstream of a culvert (scour holes, headcuts, or sediment deposition). The effect of culverts on habitat connectivity is usually considered in a longitudinal (upstream/downstream) direction. However, lateral connectivity between the stream channel and the floodplain may be important for species movement and ecological processes as well (Kondolf et al. 2006; Zytovicz and Murtada 2013). Culverts at road/stream crossings can disrupt flow across a floodplain locally reducing floodplain connectivity with ecological, hydrological, and sediment transport impacts (see Section 6.2 for a discussion of floodplain culverts).



Figure 1.2.2. Lake and stream connectivity is important for fish life cycle maintenance in Minnesota and much of the upper Midwest. Elm Creek in Martin County, MN is connected to a chain of lakes via the culvert shown in red providing an important habitat linkage for walleye and other fish to escape dry conditions in the creek. (Google Maps image)

1.2.2 Barriers to Aquatic Organism Passage

Barriers to fish passage at road-stream crossings may be classified in one or more of these four categories: physical, hydraulic, chemical, and behavioral (NSW DPI 2017). Examples of potential barriers to fish and other aquatic organisms are listed in Table 1.2.1. Whether any aspect of a stream crossing is an actual barrier to movement is a function of many factors including species, age and characteristics of an individual organism, season, flow rate, etc. While chemical or water quality barriers such as localized pollution are not considered in this document, water quality concerns such as elevated temperature or lack of dissolved oxygen may prompt organisms to move to refuge habitat.

Table 1.2.1 Examples of potential barriers to aquatic organism passage at culverts.

Potential Barrier	Physical	Hydraulic	Behavioral
Excessive drop at outlet (perch) (Figure 1.2.3)	X		X
Insufficient flow depth (excessive width / sedimentation)	X	X	X
Insufficient pool depth	X	X	X
Excessive flow velocity (Figure 1.2.4)		X	
Excessive turbulence		X	
Unnatural substrate			X
Excessive length	X	X	X
Darkness			X
Water quality (temp, DO)	X		X

AOP may be blocked if a culvert becomes perched through excessive velocity and scouring at the outlet (Figure 1.2.3), often a result of a culvert that is undersized or significantly constricts flow. AOP may also be impacted by culvert conditions that exceed organisms' swimming abilities in fast velocities or long stretches of culvert with no resting areas (Figure 1.2.4). Other aquatic life forms such as salamanders and crayfish can only tolerate lower velocities, and require streambed substrate for flow refugia.



Figure 1.2.3. Perched culvert on a tributary of Seven Mile Creek, Minnesota creating a physical barrier (C. Lenhart photo)



Figure 1.2.4. Excessive velocity over an extended length with no resting areas can impede fish and aquatic life movement both in culverts and adjacent channels creating a hydraulic barrier. This culvert also has shallow flow, another potential barrier to movement. Photo: Indian Camp Creek below TH61 in Cook County (P. Leete photo, 2015)

Inadequate water depth can also block AOP by creating physical and/or behavioral barriers. Particularly during low flow periods (typically in late summer to early fall in Minnesota and the upper Midwest) flow depths can become inadequate for fish movement (Figure 1.2.5.). Therefore, from an AOP standpoint one of the most basic considerations is whether the stream has perennial, intermittent, or ephemeral flow (USEPA archives 2017). Ephemeral streams only flow briefly after storms and are entirely dependent on rainfall and runoff for flow; i.e., there is no baseflow. Intermittent streams flow during wet times of the year while being fed by tributaries upstream and may have seasonal baseflow (groundwater discharge). Perennial streams flow all year long relying on surface water runoff and baseflow. In fact 60 percent of stream miles in the continental U.S are intermittent or ephemeral. As a result, it is very common for stream fishes and other forms of aquatic life to move on a seasonal basis to avoid drying streams. Invertebrates can avoid this to some extent by burrowing into the stream bed but fish and other vertebrate animals need to migrate.



Figure 1.2.5. In this mid-July 2017 photo there is no flow through this culvert on an intermittent tributary to Lawrence Creek, a designated trout stream in Chisago County (P. Leete photo).

Because culverts can create habitat conditions that are very different than the stream, behavioral barriers for fish and aquatic organisms may also impede their movement. Fish may look for a strong current to orient upstream, or may look for cover from predators, but cover is often not present within culvert barrels. There is some evidence that darkness within a culvert barrel may impede movement for some aquatic and semi-aquatic organisms (Woltz et al. 2008), but little evidence to indicate that light in larger culverts is an issue for some Minnesota fish species (Kozarek et al. 2017). Despite this, some parts of the country maintain requirements to address the lack of light by adding skylights or other light mitigation techniques (e.g. National Marine Fisheries Service recommendations and California).

Culvert designs that disrupt stream connectivity, namely the continuity of habitat, water flow, and sediment transport processes, can also interfere with AOP. When a culvert creates a flow constriction, both erosion and aggradation can be altered with deposition often occurring on the upstream end and scouring on the downstream end. Conversely, culverts that create a flow expansion can be subject to excessive sedimentation that can be enhanced by vegetation growth (Figure 1.2.6). Culvert designs that alter the upstream water surface slope can create upstream migrating headcuts that can not only create AOP issues, but can also destabilize streambeds and banks.

Unstable stream types, or streams in watersheds undergoing significant hydrologic changes (urbanizing, etc.) may be particularly problematic at culverts. Streams with high sediment load such as braided channels are more likely to create unpassable conditions within a culvert. On the opposite end of the sediment supply spectrum, streams with a very low sediment load may be particularly prone to scour as clear water is more erosive than sediment-laden water (Booth and Bledsoe 2009) leading to scour holes

at the culvert outlet. This is particularly problematic in urban streams where sediment supply has been greatly reduced.



Figure 1.2.6. Aggradation at low-flow due on an unnamed stream crossing under TH 23 (bridge number 8798), Pipestone County, MN. Note the culvert width is significantly wider than the channel width. (J. Kozarek photo).

Stream instability often has negative effects on road infrastructure aside from the AOP impacts. Unstable streams may undermine culverts and bridges, decrease capacity through excess aggradation or simply increase maintenance needs and costs. Streams or gullies with active headcutting may completely undermine culverts, ultimately leading to failure and the need for replacement. Similarly, high rates of lateral stream erosion may undermine the culvert from the sides or through the road berm itself. At high flows, overtopping is particularly likely to wash out or seriously undermine a culvert. Excess aggradation may require increased maintenance needs including clean-outs or dredging.

To overcome many of these issues, designing a culvert to maintain stream connectivity can accommodate a range of AOP, and may be expected to be more resilient to some perturbations within the system (Gillespie et al. 2014). Figure 1.2.7 shows an example of a geomorphic simulation project (US Forest Service Stream Simulation Working Group (FSSSWG) 2008). The culvert bottom is recessed and filled with bed material similar to the stream, and the culvert width is similar to the bankfull channel width.



Figure 1.2.7. Geomorphic simulation example from the USFS FSSWG 2008).

1.2.3 Connectivity at Watershed Scale: Cumulative Impacts of AOP Blockage

Numerous road crossings may have cumulative impacts on the distribution and diversity of aquatic life, and the sediment, habitat, and flow characteristics of a stream network. Many road crossings may not create complete barriers to AOP but impede certain species or life stages at certain times of the year, impacting organisms' ability to complete their life cycles. These temporary blockages can be significant if occurring during migration or other critical periods. From an aquatic resources planning standpoint all potential blockages in a watershed should be considered when accommodating AOP so that resources are spent the most effectively (Diebel et al. 2015). Barriers to AOP within a watershed, including dams and culverts, can have different owners (e.g., local government, private, state, etc.) and varying lifespans until repair or replacement. AOP improvements in these cases require cooperation between stakeholders and assessment of natural resources management values and goals in the watershed.

For example, dams and culverts in the Red River basin blocked access for the lake sturgeon (*Acipenser fulvescens*) totaling thousands of river miles. A coordinated effort amongst the Minnesota DNR and other state and local agencies was undertaken to remove and modify approximately 32 dams and culverts. The efforts restored the lake sturgeon to many hundreds of river miles where it was not found prior to the late 1990s (Aadland 2010). Natural blockages such as waterfalls can also limit fish movement. Waterfalls on the old lake ridge where tributary streams drop to Lake Superior may limit the

upstream migration of coaster brook trout (*Salvelinus fontinalis*). Passage efforts upstream of those blockages may be important to resident brook trout but may not benefit coaster trout.

Efforts to restore stream channels or stabilize banks are often undertaken by public agencies (such as watershed districts, USDA NRCS and USFS, MN DNR) and nonprofit groups to improve stream health, or to reduce excessive erosion and present opportunities for improved AOP. Coordination between culvert replacement design and nearby stream restoration efforts is likely to be more efficient and effective for both projects. One specific area of coordination that would be helpful is the collection of field data such as stream cross sections, expected flows, bed sediment information, etc. The Minnesota DNR Area Hydrologists are often aware of planned or completed stream restoration projects and may be able to facilitate project coordination helping to achieve greater overall benefits for aquatic ecosystems.

1.2.4 Case study: The Whitewater River in Southeastern Minnesota

The Whitewater River is a tributary of the Mississippi River in southeastern Minnesota near Winona. Much of the watershed has steep terrain as it lies in the unglaciated or Driftless area. There is also an abundance of culverts located at road crossings of streams (Figure 1.2.8). The Minnesota DNR conducted a watershed assessment and monitoring project there for nearly a decade (Minnesota DNR 2015) to characterize stream geomorphic properties, channel change and other stream attributes.

The Whitewater and tributaries support brook (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) in the middle reaches in the steeper parts of the watershed that receive groundwater discharge. Streams in the Driftless Area have been the subject of extensive restoration and management efforts over the past 30-40 years to improve trout fishing opportunities (Thorn et al. 1997). When considering the watershed context, trout stream areas and culvert locations, AOP practices to support trout populations would be most beneficial in the mid to upper watershed in 2nd – 4th order streams approximately < 50 square miles (129 km²) in drainage area. In these prime trout habitat reaches, strategies that allow for some channel adjustment and account for headcutting potential such as geomorphic simulation would be best suited for the unstable stream reaches concentrated in the middle watershed area (mostly in the area of the green, orange and red lines in Figure 1.2.9).

When considering AOP approaches, both the geomorphic context and aquatic communities need to be taken into account. The lower river supports some warm water fishes as the river is connected to the Mississippi River but has a fairly homogenous sand bed with little habitat structure and would thus require a different culvert design approach. Road crossings in the lower river of this area are also located in more unstable stream reaches with higher lateral erosion rates, depicted by the orange and red areas in Figure 1.2.9, creating potential problems for culvert maintenance and AOP. The lower main channel and intermittent tributaries lying above groundwater discharge zones to the far west and southwest of the watershed support few trout (Figure 1.2.9). Upstream of the steep drop zone, in the headwaters (1st – 2nd order streams) to the south and west, most of the culverts are located in farmland on stream reaches that do not have cool groundwater input and thus also do not support trout. Different approaches for accommodating target species and maintaining stream connectivity are discussed in Chapter 5.

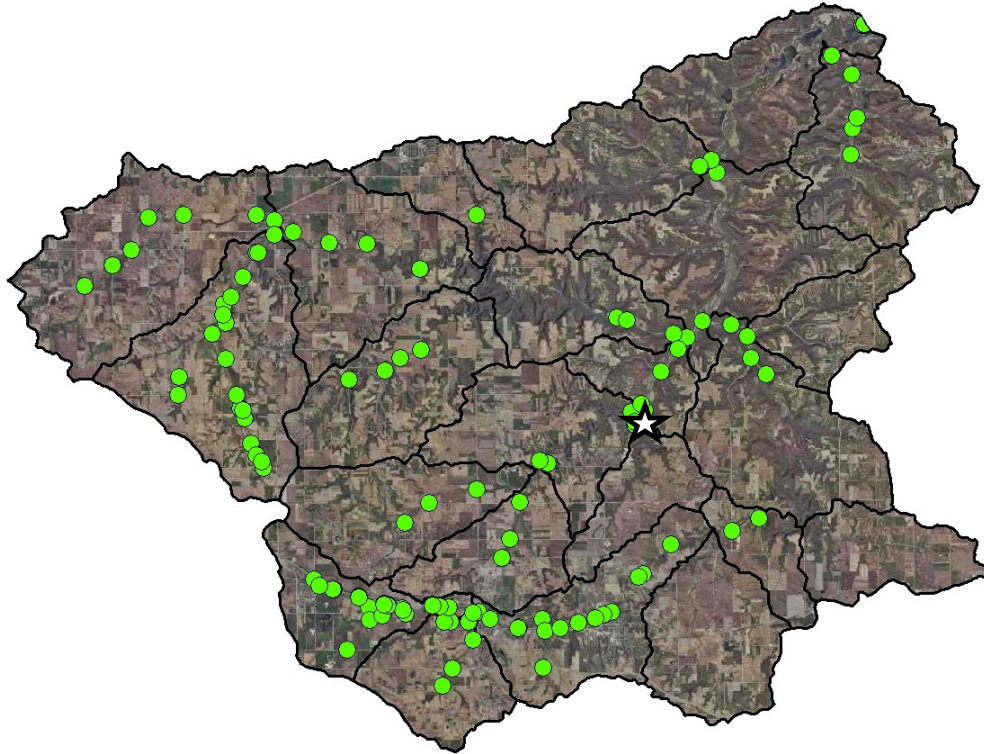


Figure 1.2.8. Whitewater River culverts located on perennial stream reaches (Minnesota DNR image).

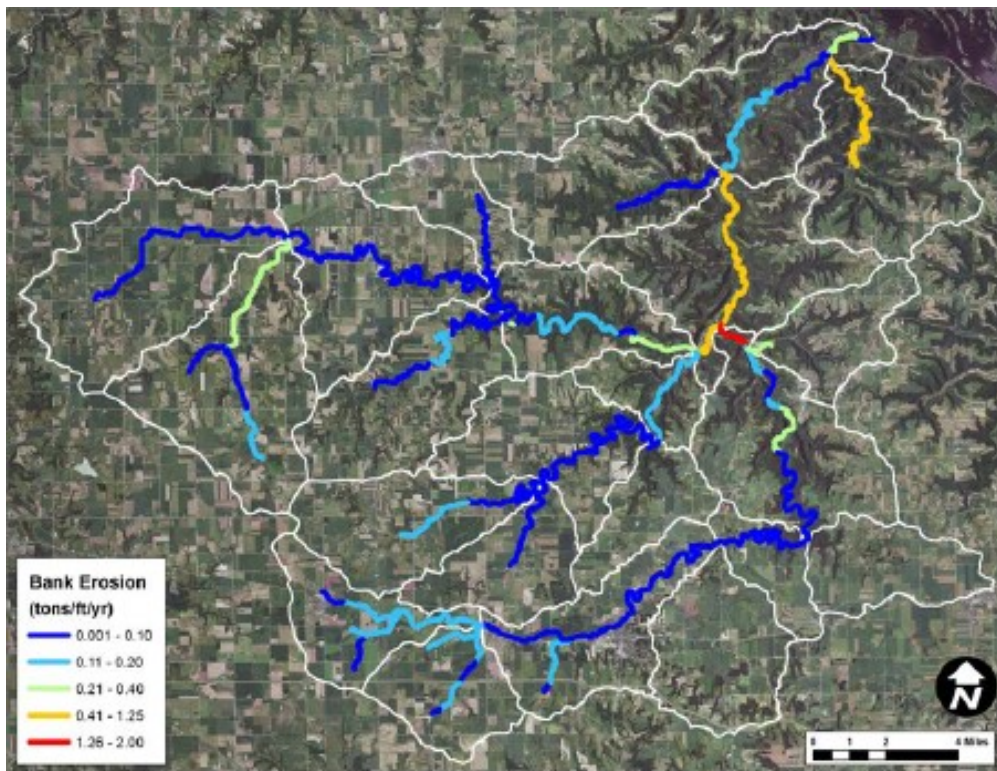


Figure 1.2.9. Whitewater River lateral erosion rates (MN DNR graphic). Whitewater State Park located at star.

1.3 REGULATORY AND PERMITTING PROCESS FOR CULVERTS IN MINNESOTA

1.3.1 Document Applicability

This document is intended to supplement culvert design in Minnesota provided by the MnDOT Bridge office including the MnDOT Drainage Manual (MnDOT 2000) for accommodating AOP and maintaining stream connectivity. It is not intended to replace guidance for culvert safety, structural, or geotechnical considerations, but provides additional technical information to supplement the MnDOT Public Waters Work General Permit guidance (Leete 2014). It is focused on public road crossings of Public Waters (defined below) in the state of Minnesota where a Public Waters Work Permit applies. The recommendations for AOP and stream connectivity may also be applied to other stream crossings in Minnesota as warranted. The guide is not intended to apply to culverts constructed strictly for roadway drainage.

1.3.2 Public Waters of Minnesota

Minnesota state statutes designate public waters to indicate which lakes, wetlands, and watercourses over which the Minnesota Department of Natural Resources (MN DNR) has regulatory jurisdiction. Public waters are shown on the Public Waters Inventory (PWI) maps, many of which may be accessed online via the MN DNR website. Refer to Appendix C, Web and GIS data links, for this and other links and GIS layers.

Although the PWI maps are definitive of public waters (except for some trout stream tributaries), two of the most important criteria generally identifying Minnesota public waters include: i) natural and altered watercourses with a total drainage area greater than two square miles; and ii) natural and altered watercourses designated by the DNR commissioner as trout streams. Public waters are fully defined in Subdivision 15 of Minnesota Statute 103G.005., Subd. 15. (<https://www.revisor.mn.gov/statutes/?id=103g.005>).

1.3.3 Permitting of Culvert Work in Public Waters

There are four situations, with respect to state permitting of in-stream work that affects public waters in Minnesota:

1. Public Waters General Permit (Section 1.3.3.1 below)
2. Individual Permit
3. No permit required or Exempt
4. Exception – replacement in-kind (Section 1.3.3.2 below)

Each of these four permitting situations is discussed briefly in Appendix D. Permitting information is provided in this document for context and preliminary guidance only; further explanation of the requirements is described on the MN DNR website:

http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/requirements.html

It is recommended to contact the MN DNR area hydrologist responsible for the region in which the project will take place with any permitting questions:

http://files.dnr.state.mn.us/waters/area_hydros.pdf

These situations are listed below, and described in more detail on the DNR website:

1.3.3.1 Public Waters General Permit

The Public Waters Work General Permit GP2004-0001, also known as the MnDOT GP, is the main regulatory document for Minnesota Department of Transportation (MnDOT) projects involving the repair or replacement of bridges, culverts, or stormwater outfalls at locations involving Public Waters state-wide. A link to the permit is below.

http://files.dnr.state.mn.us/waters/watermgmt_section/pwpermits/General_Permit_2004-0001.pdf

Similar, but not identical, General Permits pertain to in-stream work done at the county level in several individual counties, or groups of counties within DNR administrative regions.

To aid in application of the general permit DNR Transportation Hydrologist and liaison to MnDOT Peter Leete has assembled a document of Best Practices for Meeting DNR Public Waters Work Permit GP 2004-001 (Leete 2014). This document is referenced in the permit language, and may be found at the following website:

http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html

Version 4 (Leete 2014) is current as of publication of this document but expected to be updated in the near future. Note that the Best Practices document is referenced within the GP2004-0001 Public Waters General Work Permit, but also contains a wealth of information useful even in situations where the General Permit does not apply. Development of the current document, Minnesota Guide for Stream Connectivity and Aquatic Organism Passage through Culverts, is not to replace the Best Practices document, but rather to expand the design content and decision-making guidance, within the broader context of the Best Practices document.

1.3.3.2 In-Kind Replacement

Culvert replacement in-kind (replacement with a culvert of same size, elevation, and location) is exempted from permit coverage in certain situations (refer to Appendix D). This exemption does not apply to designated trout streams and their tributaries. Despite the legality of this exemption for in-kind replacement, the Minnesota DNR Culvert Permitting Fact Sheet advises that replacing culverts 'in-kind' (same size and elevations), "... may not be in the best interests of the environment or of the project proposer. Flood elevations, fish passage, ecological connectivity, lake and wetland control elevation, road safety and fiscal responsibility are all factors to consider when a crossing is to be replaced. The DNR encourages the correcting of ecological and hydraulic deficiencies of existing culverts to prevent

replicating poor design.” (DNR culvert permitting fact sheet September 8, 2015).

http://files.dnr.state.mn.us/waters/publications/culvert-permitting_fact-sheet_101615.pdf

1.3.4 Applicable Regulations for Culvert Projects

Regulations affecting culvert replacement operate at the local, state, and federal levels of government. Some federal regulatory authority is implemented by State agencies, while local entities including county, city, and township governments, joint county drainage authorities, and watershed districts may establish some of their own requirements, within the limits of state law. A local or federal permit or review process may be required, even if a State permit is not required, depending on the specific situation. Additional rules regulating floodplains, drainage ditches, and wetlands may also apply to culvert replacement projects. Selected information on regulations applicable to road-stream crossings in Minnesota may be found in Appendix D.

On the federal level, a Transportation Regional General Permit (RGP) is issued by the St. Paul District of the U.S. Army Corps of Engineers for Minnesota and Wisconsin. The current RGP (http://www.mvp.usace.army.mil/Portals/57/docs/regulatory/RGP/Transportation_RGP.pdf?ver=2018-02-22-093530-183) is dated February 21, 2018 and is valid until February 20, 2023. Culvert projects may fall under one of several project categories. Guidance should be obtained from the St. Paul District Corps of Engineers Regulatory Branch (<http://www.mvp.usace.army.mil/Missions/Regulatory/>).

Two of the most relevant sections (17 and 18) are listed below; refer to the full RGP for other important requirements:

17. Culverts and Crossings: Unless an RGP verification authorizes otherwise, replacement and installation of culverts or crossings authorized by an RGP are to follow (or be restored to) the natural alignment and profile of the tributary. The culverts or bridges must adequately pass low flow and bankfull events, bedload, sediment load, and provide site-appropriate fish and wildlife passage. Example design elements include recessing single culverts to accommodate natural bankfull width and adjusting additional culvert inverts at an elevation higher than the bankfull elevation.

18. Aquatic Life Movements: No regulated activity may substantially disrupt the necessary life cycle movements of those species of aquatic life indigenous to the waterbody, including those species that normally migrate through the area, unless the activity's primary purpose is to impound water

1.3.5 Protected species

The US Fish and Wildlife Service (USFWS) oversees work involving federally endangered species, including Topeka Shiner (*Notropis topeka*). Topeka Shiner are the only federally endangered fish in Minnesota (although they are only state-listed as a species of Special Concern by the Minnesota DNR). Figure 1.3.1 shows counties that have designated critical Topeka Shiner habitat. It is illegal to take (i.e., kill, harm, harass, capture, etc.) Topeka Shiner, even incidentally, such as during a construction project.

Similarly, there are five species of freshwater mussel listed as federally endangered (Table 1.3.1.) and 28 of 50 Minnesota mussel species are state listed as threatened or endangered (<https://www.dnr.state.mn.us/ets/index.html>).

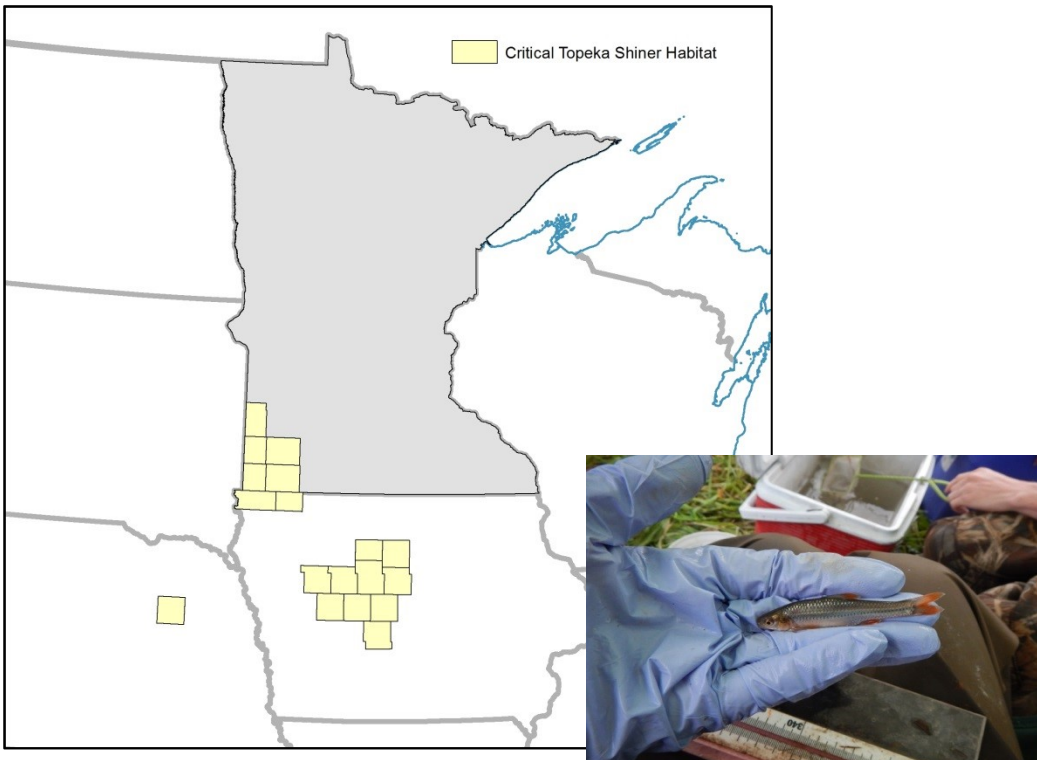


Figure 1.3.1. Map showing Final Critical Habitat for the Topeka Shiner (*Notropis topeka*) designated July 2004. Topeka Shiner are widespread in the Big Sioux and Rock River watersheds. Note that Topeka Shiner have been found outside of these designated areas. Map J. Kozarek with [USFWS data](#). Photo B. Mosey (2016)

Table 1.3.1. Summary of federally endangered freshwater mussel species in Minnesota (as of December 2017). Nineteen additional species are listed as threatened or endangered within Minnesota (see https://files.dnr.state.mn.us/natural_resources/ets/endlist.pdf)

Species	Federal Status	Counties	Habitat
Higgins eye pearlymussel (<i>Lampsilis higginsii</i>)	Endangered	Chisago, Dakota, Goodhue, Hennepin, Houston, Ramsey, Wabasha, Washington, Winona	Mississippi and St. Croix Rivers
Sheepnose (<i>Plethobasus cyphus</i>)	Endangered	Wabasha and Winona	Mississippi River in Wabasha and Winona counties, St. Croix River in Washington county
Snuffbox (<i>Epioblasma triquetra</i>)	Endangered	Chisago, Hennepin, Ramsey, Washington	Mississippi River in Hennepin and Ramsey counties; St. Croix River in Chisago and Washington counties

Spectaclecase (<i>Cumberlandia monodonta</i>)	Endangered	Chisago, Pine, Wabasha, Washington	St. Croix River and Mississippi River
Winged mapleleaf (<i>Quadrula fragosa</i>)	Endangered	Chisago, Ramsey, Washington	St. Croix River and Mississippi River (Upper Pool 2)

Four fish species are state-listed endangered species in Minnesota: Skipjack Herring, Crystal Darter, Pallid Shiner, and Slender Madtom and another five are threatened. Of the endangered species, all are found in medium to large rivers, except for the Slender Madtom, which prefers medium sized permanent spring-fed creeks, but has only been found in a tributary to the Cedar River in Minnesota. Other state-listed rare species may be affected by culvert work as well. For a full list of aquatic species that are classified as threatened, endangered, or special concern at the state level, refer to the Minnesota DNR website for rare species: <http://www.dnr.state.mn.us/ets/index.html>. A search by county, watershed, habitat, or other variables is available at: http://www.dnr.state.mn.us/rsg/filter_search.html.

Officially-designated trout streams are Public Waters in Minnesota and are considered a high-value resource and thus afforded a higher level of regulatory protection than other streams. A list of officially designated trout streams may be found at the following website: <https://www.revisor.mn.gov/rules/?id=6264.0050>

Trout stream maps are also available: http://www.dnr.state.mn.us/fishing/trout_streams/index.html

CHAPTER 2: CULVERT DESIGN FOR AQUATIC ORGANISM PASSAGE AND STREAM CONNECTIVITY

This chapter begins with the definition of a culvert (2.1), then describes culvert design for hydraulic conveyance including possible environmental consequences (2.2). A survey of approaches to AOP and stream connectivity (2.3.1) is followed by brief notes about the suitability of these approaches (2.3.2). Drawing on available research and experience, seven best practices for culvert design are presented in Section 2.4 . Each of these practices is explored in more detail in subsections of 2.4 . Site data, analysis tools, and design methods are developed in subsequent chapters.

2.1 CULVERT DEFINITION

The MnDOT Drainage Manual (MnDOT 2000) defines a culvert in Chapter 5 as, “a structure sized hydraulically to convey surface water runoff under a highway, railroad, or other embankment.” Culverts come in many shapes (Figure 2.1.1) and sizes, and may be fully enclosed (e.g. pipe or box) or more rarely open-bottom, also called three-sided bridge structures or three sided culverts.

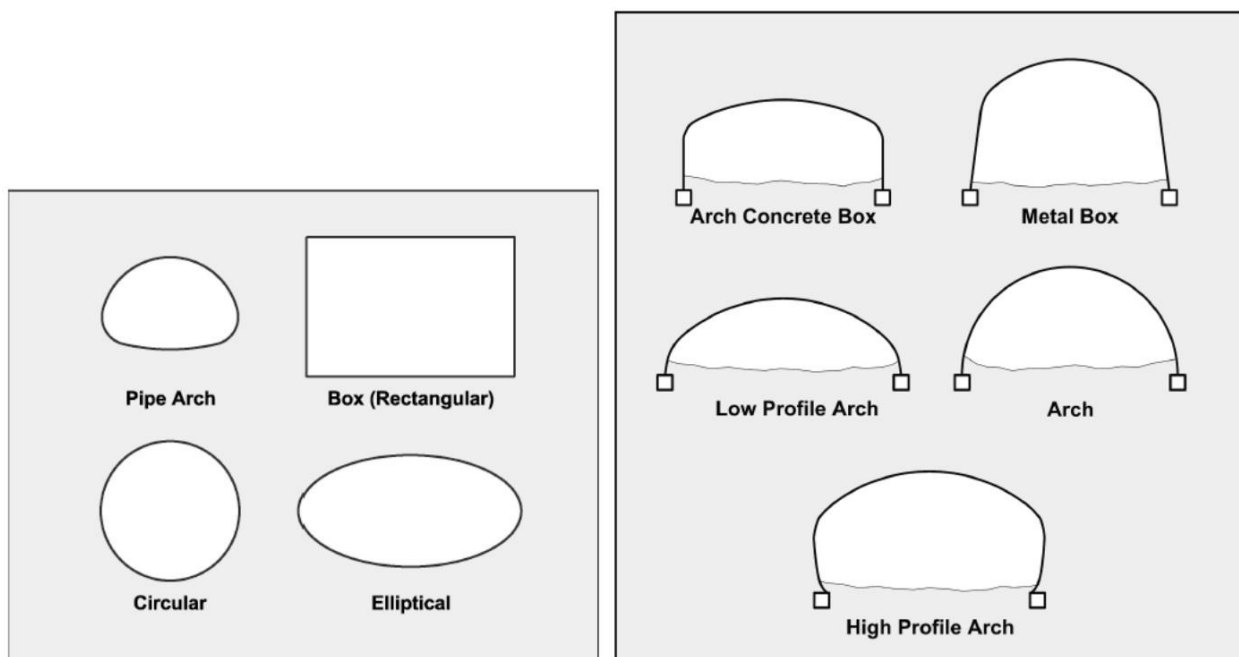


Figure 2.1.1. A selection of culvert opening shapes. Typical fully enclosed shapes are at left, open-bottom shapes at right, which are also called three-sided bridge structures. (from Figure 1.5, FHWA HDS 5 (Schall et al. 2012))

While culverts and bridges have similar functions, this document is focused on stream crossings of a size where culverts or multiple culverts may be used to convey flows, and the term ‘culvert’ is used to designate these crossings. In Minnesota, culverts are *classified* as a bridge when the horizontal opening width is 10 feet or greater measured perpendicular to the roadway centerline; however, the structure is analyzed using procedures for culverts. As indicated, in this case ‘bridge’ is a Minnesota regulatory

classification relating to how the structure is inspected and catalogued. The federal regulatory definition of 'bridge' includes structures greater than 20 feet, including the added spans of multiple barrel culverts (23 Code of Federal Regulations, Sec. 650.305).

The MnDOT drainage manual states that culverts are distinguished from bridges by being covered with an embankment and generally composed of a structural material around the entire perimeter (with some exceptions, such as open bottomed culverts). In some cases, using a three-sided bridge structure or abutment-supported bridge to span the stream banks and allow the natural streambed to continue through the structure may advance the goals of AOP and stream connectivity - this option is discussed in more detail in Section 5.2 . Regardless of the choice of structure type, the design variables related to hydraulics, stream connectivity, and AOP are similar.

2.2 DESIGN FOR HYDRAULIC CONVEYANCE

Many resources exist for hydraulic design of culverts and this guide is designed to complement existing manuals, e.g. the MnDOT Drainage Manual, compiled by MnDOT's Office of Bridges and Structures (MnDOT 2000). For MnDOT projects, Chapter 5 of the Drainage Manual sets the standards for culvert design, allowable roadway overtopping frequency, and other parameters. The manual includes design procedures for minor (48 inches and less) and major (>48 inches) culverts. Other entities may have different guidelines, for example, the MN State Aid Bridge hydraulic guidance, (<http://www.dot.state.mn.us/stateaid/bridge/docs/7.pdf>). Nationally, Hydraulic Design Series Number 5, Hydraulic Design of Highway Culverts, 3rd Edition (HDS 5) is a guidance document published by the Federal Highway Administration in 2012 (Schall et al. 2012). HDS 5 is a primary document for standard culvert design and also includes a chapter (Chapter 4) on design for AOP. When culvert design for AOP and stream connectivity is conducted, it is important that hydraulic design requirements or choices, such as the design flood return period or permissibility of pressure flow, are consistent with the chosen AOP design methodology. For instance, the US Forest Service Stream Simulation Design (FSSSWG 2008) is based on a Q100 design flow and a headwater to depth (HW/D) ratio of 0.8 or less. Refer to Chapter 5 for information regarding design methods.

Traditional hydraulic conveyance culvert design often attempts to pass water through the smallest pipe or multi-pipe structure with an acceptable risk level as determined by flood probabilities, road classification, and traffic volume due to less upfront cost. Hydraulic conveyance designs may not take into account other materials (debris, sediment) or organisms travelling in streams, which can lead to barriers to AOP (Section 1.2.2), and to stream morphology changes which have the potential to affect the stream crossing (culvert and roadway) and long-term landscape stability. A more complete definition of a culvert that addresses stream connectivity and AOP would be ***a structure comprehensively sized to convey surface water, sediment, debris, and resident aquatic organisms under a highway, railroad, or other embankment.***

Figure 2.2.1 illustrates unintended but common conditions associated with hydraulic conveyance culvert design, including aggradation, inlet contraction, outlet drop, and a scour pool – features which are symptomatic of poor stream connectivity and possible barriers to AOP. Figure 2.2.2 illustrates a culvert

recessed below the streambed and filled with a natural sediment bed (e.g. embedded). The second case (Figure 2.2.2) lacks some features of the first (aggraded material upstream, scour pool), and more closely resembles an unimpeded stream reach.

Additional definitions for culvert-related terms may be found in Section 5.1.2 of the MnDOT Drainage Manual (MnDOT 2000). The comprehensive glossary of FHWA HDS 5 (Schall et al. 2012) is also a useful reference.

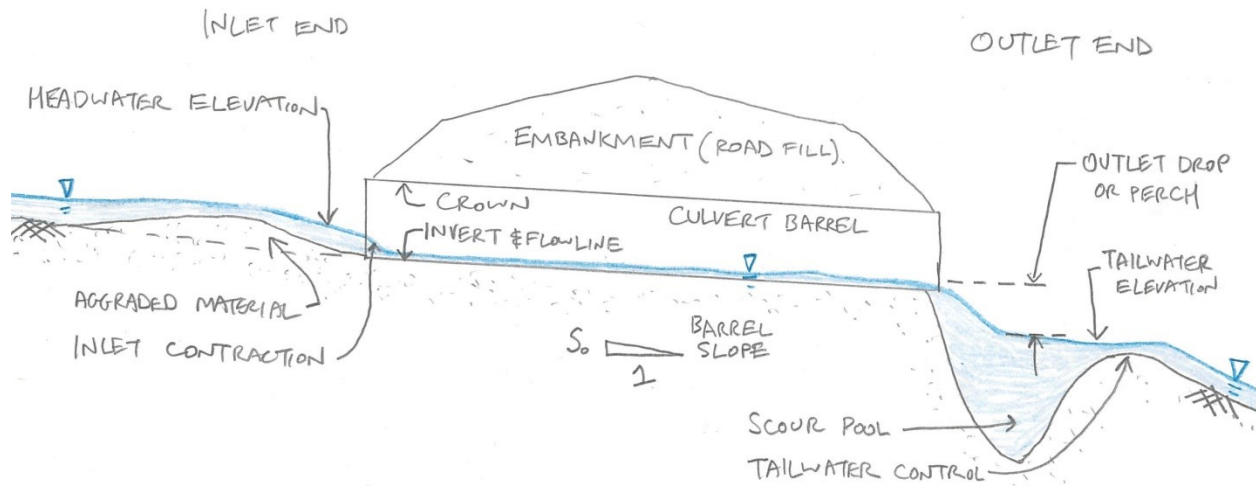


Figure 2.2.1. Longitudinal profile of conditions that may be associated with a culvert designed for hydraulic conveyance only (M. Hernick sketch)

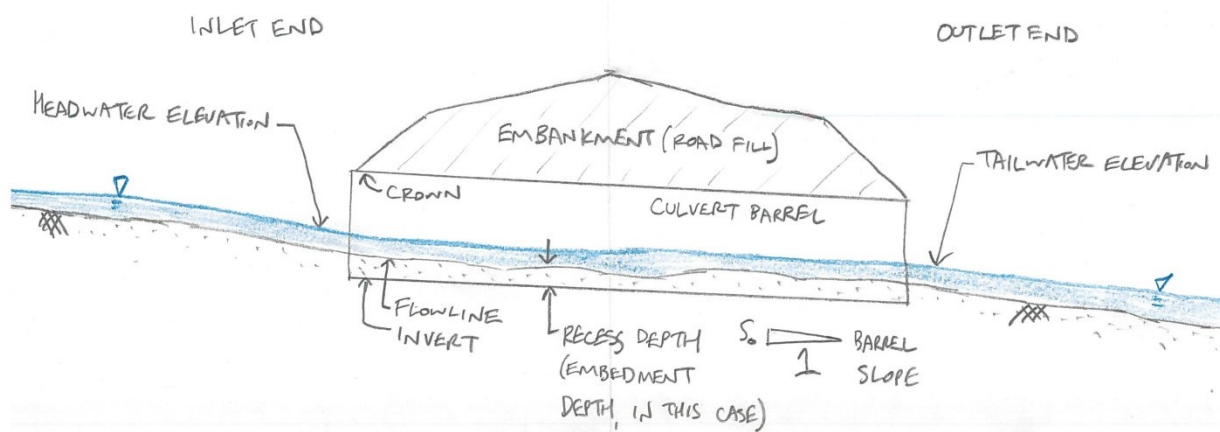


Figure 2.2.2. Longitudinal profile of a recessed and filled (embedded) culvert (M. Hernick sketch)

2.3 AOP AND STREAM CONNECTIVITY CULVERT DESIGN APPROACHES

2.3.1 Summary of Approaches

A number of practices for maintaining or reestablishing AOP and geomorphic stream connectivity at road-stream crossings have been developed and used nationally and in Minnesota. These practices may be generally categorized as Geomorphic Simulation, Hydraulic Simulation, or Hydraulic Design, as noted in Table 2.3.1 (Hotchkiss & Frei 2007). The categories in this table are useful to differentiate between characteristics of AOP design approaches; more detail is needed to implement an approach.

One of the purposes of this guide is to help identify which methods are most likely to be successful in meeting goals for AOP and stream connectivity at a specific site; it should also be recognized that not all methods are appropriate in all situations. Suitability of general approaches is discussed in Section 2.3.2 .

Table 2.3.1. Categories of AOP and stream connectivity design approaches. (Adapted from Table 6.1, pg. 6-16 in Hotchkiss and Frei 2007).

Category	Description	Relative Width	Biological Characteristics	Geomorphic Characteristics	Hydraulic Characteristics
Unaltered	No Impedance	≥ Q100 floodplain	Pass all fish and aquatic organisms	Unchanged	Q100 unconfined
1	Geomorphic Simulation	≥bankfull	Pass all fish and aquatic organisms	Natural substrate; Mobile bed; Stability of substrate usually not checked	Unaltered for Q slightly above bankfull; Check Q100
2	Hydraulic Simulation	≤bankfull	Reported to pass all fish and aquatic organisms	Oversized substrate; Stationary bed; Stability of bed usually checked	Similar for Q slightly less than bankfull; Check Q100
3	Hydraulic Design	variable; usually <bankfull	Pass target species at target life stage	Artificial channel	Must meet target species and life stage requirements; Check Q100

The paragraphs below list a number of design practices or methods promoting AOP and stream connectivity, including features of the method, potential drawbacks, and general category from Table 2.3.1. The list is provided for reference, not as recommendation. Some of these practices are complete design procedures while other practices take the form of a recommendation related to only certain aspects of the culvert, to be integrated into the existing design process. Several of these methods are explained in greater detail in sections 5.1 through 5.6. This guide focuses on culvert design to accommodate AOP and stream connectivity issues (Section 1.3.1); designers must rely on other references (e.g. drainage manual) for other aspects of the hydraulic structure design.

Bridge or bottomless culvert (3-sided box or long arch)

Features: Allows natural streambed (and associated natural roughness and processes) to continue through the crossing structure.

Potential drawbacks: May be costly, foundation construction may be difficult, and there is high potential for scour.

Category (Table 2.3.1, following Hotchkiss & Frei 2007): Unaltered – 1

Recessed culvert (the culvert bottom or invert is placed below stream grade with no streambed material placed during construction)

Features: Assumes that streambed material will partly fill culvert to form a natural bed, likely greater water depth than non-recessed culverts, depending on channel and culvert shape.

Potential drawbacks: Culvert may not fill depending on bed material and site characteristics (e.g. slope). May allow upstream propagation of headcuts. Design steps not fully defined.

References: Kozarek and Mielke 2015, Hansen et al. 2009; 2011, Leete 2014

Category (Table 2.3.1): 1 - 2

Embedded culvert (invert below stream grade, with streambed material placed inside)

Features: Bed material placed in culvert simulates natural bed; additional structures (steps, pools, etc.) are placed in high gradient culverts

Potential drawbacks: Placed material may be scoured out or be inappropriately large if design based on sediment stability/mobility is inaccurate. Design steps not fully defined.

References: Kozarek and Mielke 2015, Hansen et al. 2009; 2011

Category (Table 2.3.1): 1 - 2

No Slope method

Features: Culvert set at 0% slope. It is sometimes assumed that streambed material will fill in to form a natural bed at a natural slope.

Potential drawbacks: Not appropriate for higher slopes (See also recessed culvert)

References: WA, KS, and ME state guidance documents (Barnard et al. 2013; KLTAP 2015; MaineDOT 2008)

Category (Table 2.3.1): 1 - 2

USFS Stream Simulation (FSSWG 2008)

Features: Attempts to re-create a stream reach including bed structures based on physical measurements of actual stream reaches, and then fit a structure around it. Full design procedure, including sediment transport calculations.

Potential drawbacks: Requires experience to design and implement, may have a higher construction cost.

References: FSSSWG 2008, Barnard et al. 2013

Category (Table 2.3.1): 1

FHWA HEC 26 (Kilgore et al. 2010)

Features: Attempts to provide depths and velocities similar to upstream and downstream reaches.

Full design procedure, including sediment transport calculations.

Potential drawbacks: Does not account for bed structures or banks, could lead to designs that work numerically but not natural for stream.

References: Kilgore et al. 2010

Category (Table 2.3.1): 1 - 2

MESBOAC method

Features: Principles outlined in the acronym (Match, Extend, Set, Bury, Offset, Align, Check) attempt to provide conditions (e.g. width, depth, slope, and alignment) similar to a natural stream.

Potential drawbacks: Method lacks detail on design specifics and is not used statewide

References: Section 5.5.7, documented in appendix of Version 4 of Best Practices for Meeting DNR General Public Waters Work Permit GP2004-0001, (Leete 2014), Hansen et al. 2011

Category (Table 2.3.1): 1 - 2

Maximum velocity requirements (e.g. maintain ≤ 2 ft per second at 2-year peak flow)

Features: Velocity limited to be within the swimming range of some fish for most passable flows.

Potential drawbacks: Blanket velocity requirement may not be representative of actual stream conditions, does not account for natural sediment movement, or range of fish swimming abilities.

References: Former requirement in Minnesota General Permit GP 2004-0001

Category (Table 2.3.1): 3

Species-specific hydraulic design method

Features: Structural measures designed to create depths, velocities, and turbulence amenable to a target aquatic organism and life stage.

Potential drawbacks: Need species-specific information which is not available for most species.

Culverts designed for one species (and flow regime) may not work for another. Baffles can catch debris.

References: National Engineering Handbook (NEH), Part 654, TS 14N (NRCS 2007)

Category (Table 2.3.1): 3

2.3.2 Suitability of AOP and Stream Connectivity Culvert Design Approaches

From the standpoint of ecological connectivity, the best stream crossing would be indistinguishable from the adjacent upstream and downstream reaches of the stream – the No Impedance or Unaltered category in Table 2.3.1. In this case, there would be no need to consider the behaviors of individual aquatic species, since any aquatic organisms able to live and pass through the adjacent stream reaches would be equally able to pass through the crossing. Similarly the entire reach including the crossing would respond to sediment, debris, and flood flows in the same manner, thus there would be no need for channel maintenance or infrastructure armoring. This is difficult to achieve, with the potential exception of a channel-spanning bridge in the right situation.

In practice, conditions imposed by the natural and built environment limit the choices which designers can make. The challenge of designing culverts for stream crossings to account for AOP and stream connectivity is to achieve project design goals based on societal needs (efficient transportation, short- and long-term cost effectiveness, water level and flood control) while limiting disruption to the natural stream processes to an acceptable level. What constitutes an acceptable level of disruption is a function of the stream and landscape properties, environmental regulations, land management priorities, and expectations of society in general.

Geomorphic Simulation (category 1 in Table 2.3.1) is second to No Impedance in terms of minimal impact to AOP and connectivity. This concept is comprehensively put into action via Stream Simulation Design (FSSSWG 2008). In Stream Simulation, a stream channel replicating a nearby reference reach is designed, including bed, banks, and vertical adjustment potential, and a conveyance structure (culvert or bridge) is designed around it. The emphasis is on channel design with the expectation of structure accommodation (fitting a structure around the stream) is philosophically different than other stream crossing design methods which start with structure (culvert) design and expect accommodation by the stream channel (fitting a stream through a structure), which has been the traditional mode of design. Analysis of fish passage flows is typically not needed because the channel conditions have been matched (Hotchkiss and Frei 2007); however movement of organisms and sediment is considered in the design.

Hydraulic Simulation (category 2) may be appropriate where Geomorphic Simulation is not achievable to provide some aspects of a stream-like channel through the culvert such that hydraulic conditions and hydraulic diversity is not identical to the stream channel but is similar. Typically this involves a sediment bed through the culvert, possibly including natural rock as roughness elements (Hotchkiss and Frei 2007).

Hydraulic design (category 3) may only account for the needs of a single target (fish) species, life stage, and period of movement. Structures in the culvert including baffles, weirs, or oversized substrate (rocks) are designed to create hydraulic conditions acceptable to passage at the target criteria (Hotchkiss and Frei 2007). These designs are not intended to account for the needs of aquatic organisms other than the target organism, and do not account for sediment and debris moving through the stream.

2.4 BEST PRACTICES FOR AOP AND STREAM CONNECTIVITY

Seven best practices that have been compiled for use in Minnesota are listed in Table 2.4.1. These best practices are preferred for all Minnesota culverts addressing AOP and geomorphic stream connectivity in the design. Each of these best practices is described in sections 2.4.1 to 2.4.7 below.

Table 2.4.1. Best practices for AOP and stream connectivity.

1. Design the culvert slope to match stream channel slope
2. Place the culvert to best match stream alignment
3. Design the culvert opening to bankfull channel width or slightly greater
4. Provide culvert flow depth comparable to channel flow depth for aquatic organism passage (not over-wide and too shallow)
5. Provide a continuous sediment bed with roughness similar to the channel
6. Maintain continuity of sediment transport and debris passage, similar to adjoining reaches
7. Design for safety to the general public, longevity, and resilience

Regardless of the design approach selected or tools used, the best practices included in this guide incorporate elements that make habitat within and near the culvert more stream-like with elements which accommodate as much of the natural stream function as possible. In other words, if the stream is passable to aquatic organisms, the culvert will be also.

The purpose of this way of thinking is to develop infrastructure that is efficient, sustainable, and resilient over the long term. In the case of culvert replacements, increasing the stream-like characteristics of a new culvert is likely to yield ecological benefits including increased AOP, as well as engineering benefits such as improved debris passage. Most of these design elements are common to the specific design methods referenced in Chapter 5. In some situations, existing constraints may limit the possibility of implementing all of the listed design elements.

2.4.1 Design culvert slope to match stream slope

Channel slope is closely related to how energy is dissipated in a stream, including the depth and velocity of flow, and how sediment moves. Abrupt changes in slope can lead to a disconnection in stream characteristics such as an imbalance in the flow of water and sediment and an AOP barrier or disconnection, with an extreme example being a perched culvert. Maintaining the stream's natural slope helps to promote continuity. The design streambed slope through the culvert should be within the range of slopes encountered in the longitudinal profile of the stream reach nearby, i.e. reference reach. (Refer to Section 3.4 for further discussion). As a practical matter in very low slope systems, the culvert may be constructed with zero slope provided adequate depth of bed sediment (Section 2.4.5) is maintained.

In some cases, matching slope may require additional measures such as stream grade controls (Section 6.3), or other design measures. Following Bates et al. (2003), the USFS Stream Simulation procedure advises that a culvert slope of up to 25% steeper than the slopes encountered in a reference reach

(upstream or downstream) may be acceptable, provided that a bed mobility analysis (see Section 4.3) is completed (p6-26, FSSSWG 2008), particularly in streams with fine sediment.

2.4.2 Place the Culvert to Best Match Stream Alignment

Assessment of the stream alignment viewed from the planform (refer to Section 3.3), and then designing a culvert to fit within that alignment is hydraulically efficient, helps to avoid scour of the streambed, erosion of road embankment, and debris problems that are associated with sharp bends at culvert entrances or exits. Proper alignment is needed to prevent erosion of the culvert, reduce risk of headcutting and channel cutoff and to reduce velocity to maximize AOP success. Alignment should follow the natural pattern of the stream and work with stream tendencies, such as meander locations, rather than simply being placed perpendicular to the road, and should account for both flood flows and low flows. Alignment at flood flow should be considered since large woody debris that could clog the culvert and cause considerable damage is generally transported at higher flows. Consultation with Minnesota DNR is required when considering changes to stream alignment. When considering alignment, designers should balance considerations of stream alignment, culvert length and cost, and roadway safety considerations, while being aware that changes in channel length affect the stream slope (Section 3.3) and thus may alter flow velocity and sediment transport characteristics.

To reduce stream impacts (i.e. improve AOP and connectivity) and reduce maintenance needs such as frequent debris removal from a sharp entrance bend, culvert replacement can be an opportunity to correct poor alignment. Deficient alignment may be due to previous installation practices or significant stream movement since the previous installation. Re-grading of a short length of channel may be necessary to complete the alignment correction. Stability of side slopes and stream banks, including reconstructed or armored banks, should be considered in light of high flows as well as alignment alterations. Guide banks can help maintain the channel shape up to (and through) the culvert, correcting the over-wide inlet pool condition common at many existing culverts. Refer to Section 5.2.5 of the MnDOT Drainage Manual (MnDOT 2000) for inlet and outlet design problems, and Section 6.1.1.4 of the USFS Stream Simulation Manual (FSSSWG 2008) for guide bank information. Angled wingwalls may be desirable to direct flow and debris into the culvert barrel in non-perpendicular crossings and areas where an actively moving channel is expected.

2.4.3 Design the Culvert Opening to Bankfull Channel Width or Slightly Greater

The width of the culvert should generally match or exceed the natural stable bankfull width of the stream channel to allow for similar flow conditions in the stream and the culvert, up to the bankfull discharge, generally approximated as the 1.5 year recurrence interval flow (Q1.5). Accommodating the bankfull channel width at a crossing does not excessively constrict channel flow and allows for natural sediment and debris movement critical to maintaining AOP and connectivity. Refer to Section 3.5 for further discussion of bankfull determination methods.

The Minnesota DNR's *Stream Crossing Inventory and Ranking Guidelines* (Hillman 2015) uses the ratio of culvert width to bankfull channel width as an indicator of a possible barrier to AOP. If a culvert width to

bankfull width ratio was less than 0.8 Hillman (2015) ranked it as a significant AOP barrier (constricted flow leading to high velocity and scour). If a culvert width was greater than twice bankfull, it was ranked as a partial or seasonal barrier (likely very wide, shallow flow at some times). Over-wide culverts can contribute to an AOP barrier and disruption in continuity of sediment transport. There is no specific guidance available on what constitutes an over-wide culvert; designers should check low flow depths and widths for appropriateness (Section 2.4.4).

Rounding the bankfull width to the nearest standard structure size is acceptable since culverts are typically only available in 6 inch to 1 foot increments. If banks or channel boundaries are to be constructed within the culvert, the structure width will be the total of the bankfull channel width and constructed banks. As width increases, bridges become more feasible and economically viable. An economic analysis of a culvert versus a bridge or span structure when the width exceeds 16 feet is recommended in the New Hampshire Stream Crossing Guidelines, for example (UNH 2009).

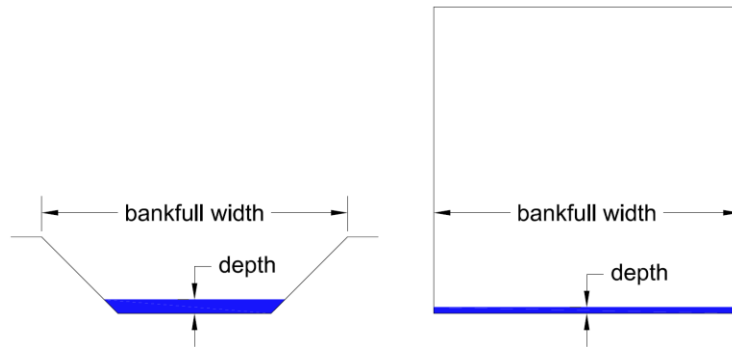
In the case of multiple culverts in the stream channel, the sum of culvert spans should be equal or greater than the bankfull width, with one or more barrels designed to be preferential at lower flows. Refer to Section 6.1 for discussion of multiple barrel culverts.

2.4.4 Provide Culvert Flow Depth Comparable to Channel Flow Depth

Very shallow, sheet-like flow in the bottom of a culvert is a likely barrier to many aquatic organisms that need a minimum depth for swimming or cover. If culverts are substantially wider than is needed to transport bed materials, aggradation may occur, creating insufficient water depth at low flows for AOP. This often occurs at multiple barrel culverts for example (see Section 6.1 ; Verry 2000a).

An essential component to provide adequate depth in culverts that are bankfull width or wider is to create a low flow or guide channel to concentrate low flow through the culvert. In multiple barrel culverts, recessing one barrel below the streambed helps to mitigate the AOP issues caused by a cross section that is too shallow for successful navigation by aquatic species. When developing a low flow channel, a good starting point is to simplify an appropriate surveyed reference cross section (Section 3.5) to mimic a similar flow area at corresponding depths, provided the slope and energy dissipation are similar to the reference reach.

Figure 2.4.1 illustrates an example where shallow flow and increased velocity develop in a non-recessed, flat bottom culvert that matches both slope and bankfull width of the stream channel. In some cases, banks may need to be constructed through culverts, typically from immobile stone, because vegetation that normally holds bank lines and controls stream width will not grow inside the structure.



	natural channel	rectangular culvert	as % of channel
Slope (ft/ft)	0.005	0.005	100%
n	0.03	0.015	50%
depth (ft)	0.45	0.20	44%
bottom width (ft)	5	10	200%
top width (ft)	5.9	10	169%
WP (ft)	6.3	10.4	165%
R hyd radius (ft)	0.39	0.19	49%
Area (SF)	2.5	2	81%
V (ft/s)	1.9	2.3	124%
Q (CFS)	4.7	4.7	100%

1. Channel assumed as trapezoid w/1:1 slopes
2. Culvert assumed as rectangular box, square corners

3. Manning equation
$$Q = VA = \frac{1.49}{n} AR$$

Figure 2.4.1. Example analysis comparing flow depth and velocity in an idealized natural channel versus a rectangular culvert for the same flow and slope.

In the MN DNR report, *Stream Crossing Inventory and Barrier Ranking Guidelines*, Hillman (2015) selected a flow depth less than 0.2 feet as a general threshold depth limiting fish passage. Actual minimum depths required for passage will depend on the species, organism life stage, and time of year. It is recommended to confer with a DNR area hydrologist to determine an appropriate low passage flow. As a starting point for preliminary analysis, see Section 5.4.3 .

2.4.5 Provide a Continuous Sediment Bed with Roughness Similar to the Channel

A continuous sediment bed through the culvert is preferred in most cases, and provides three primary advantages in AOP and stream continuity culvert design:

1. Higher surface roughness (often estimated by Manning’s n), hence lower near-bed velocity, than most culvert materials. Lower near-bed velocity helps smaller organisms to navigate upstream.
2. Decreased effects of a behavioral barrier to passage, such as may occur at the transition between a natural and artificial channel bottom.

3. Better continuity of sediment movement, helping to avoid excessive aggradation and erosion.

Wherever possible, the distribution of sediment sizes (i.e. gravel, cobble, sand, etc.) present in the culvert should be similar to that of the stream channel, so that habitat characteristics and the scale of roughness and energy dissipation through turbulence (see Section 4.1) inside the barrel are compatible with those found in the surrounding stream channel. Constructing stream-similar features such as banks, rock clusters, or persistent bedforms in the culvert barrel may be important to maintain continuous bed sediment and roughness for the design life of the culvert. In some cases culverts are recessed below the streambed but left unfilled with the assumption that they will later fill in with bed material, though this has been shown to not always be effective (refer to Section 5.5 on recessed and embedded culverts in Kozarek and Mielke 2015). When a sediment bed is placed in a culvert at construction, a well graded sediment mixture should be used with enough fine material to fill in the spaces between coarse materials so that the stream flows above, and not through, the bed. The Fuller and Thompson (1907) method of developing a dense sediment mixture is suggested by both the USFS (FSSWG 2008) and FHWA HEC 26 (Kilgore et al 2010). Likewise, when immobile bed materials such as large riprap are placed to stabilize the sediment bed through the culvert, these materials should be covered or incorporated with native-like material to match the upstream and downstream bed in consistency and elevation.

2.4.6 Maintain Continuity of Sediment Transport and Debris Passage, Similar to Adjoining Reaches

Facilitating the free movement of sediment through the culvert such that the sediment bed is in equilibrium with the stream builds on the best practices noted in the preceding sections such as providing adequate width and appropriate alignment for stream processes to continue through the culvert, without excessive aggradation or degradation. This favors long-term stream connectivity and AOP as well as minimizing external maintenance needs.

An understanding of how and when sediment (sand, gravel, etc.) is likely to move in a particular stream will help a designer to avoid creating a sediment transport disconnection and possible barrier at a culvert. Depending on the shear stress applied by the flowing water, bed particles of various sizes (Section 3.6) will either be stationary or mobile (able to be moved) at any particular flow, such as the Q1.5 or Q100. Stability / mobility calculations are specified in several design methods, USFS Stream Simulation for example, and briefly summarized in Section 4.3 .

Woody debris such as branches and logs are important in streams as habitat and roughness, but can create major issues when caught at culvert entrances. Allowing debris to pass through the culvert reduces the inlet debris jam possibility and associated maintenance as well as benefiting stream health. Since most woody debris and ice floats, freeboard above the water surface is an important design consideration, especially where high prevalence of debris is expected (Section 3.8).

Culvert designs that significantly raise the headwater (HW) at a culvert inlet may be susceptible to disrupted transport, with aggradation as sediment drops out of suspension in the headwater pool,

followed by (clear water) scour due to flow concentration at the inlet. Although not achievable in all situations, some design methods such as Stream Simulation recommend maintaining open channel, or free surface, non-pressurized flow conditions to allow for debris passage as well as more stream-like sediment transport. In terms of culvert design, this corresponds to a partially full, outlet-controlled flow condition. One free-flow criterion is $HW/Depth \leq 0.8$ at design flow (Q100, in this case; FSSSWG 2008). The design HW/D ratio could vary based on debris prevalence, ice likelihood and whether a fully mobilized bed which can easily scour and re-fill is expected.

2.4.7 Design for Safety to the General Public, Longevity and Resilience

The intent of a stream-like culvert is that it should be a largely self-maintaining channel, within the dynamic equilibrium of the stream, so that maintenance needs are minimized. Important aspects of design for longevity are selection of appropriate materials, designing for potential vertical and horizontal stream adjustments or flow changes, and selecting an appropriate design flow return period. For example road crossings at major state or interstate highways will be designed to last longer than smaller county roads. (see MnDOT Drainage manual (MnDOT 2000) for flood frequency guidance.) As a starting point, the AASHTO LRFD Bridge design manual is based on an assumed 75 year service life (AASHTO 2012, 2013).

A resilient design is one for which an event beyond the design flow would not cause a catastrophic failure, but rather cause minimal, repairable damage, to both the roadway and the stream. Resilience is often improved in culverts designed for AOP. Gillespie et al. (2014) found that culverts designed for AOP and stream connectivity have survived large floods while standard culverts were washed out. Katopodis (1993) describes successful organism passage through geomorphic simulation culverts built in the late 1970s on the Liard Highway in remote Northwest Territories, Canada. These culverts remain in service after ~40 years, while traditional hydraulic design culverts in a similar situation (Makenzie Highway) washed out in less than 20 years (C. Katopodis, pers. Comm. May 2018); see Section 6.7.2 for a discussion of culvert lifecycle cost and benefit analysis.

CHAPTER 3: SITE ASSESSMENT

This chapter includes summaries of several basic physical and biological stream parameters used as input for decision making and analysis to maintain stream connectivity through culverts. It also includes information on how these parameters can be used in stream crossing designs that promote AOP and stream connectivity. The level of site assessment and data collection needed to inform a successful AOP and stream connectivity culvert design will vary depending on stream type, size, level of risk, and resource value. References to more comprehensive resources for assessment are included in many sections of this chapter. Stream crossing design is an interdisciplinary exercise that should include engineers, planners, fishery biologists and fluvial geomorphologists if possible. Therefore, input from knowledgeable practitioners can be extremely helpful in understanding the current and probable future state of a stream at a crossing site. Gathering quality data in the site assessment phase is essential to successful design.

Office and field: Some assessment data, such as LiDAR topography and peak flow estimates, can be obtained remotely or from previous studies. Other parameters, such as streambed particle sizes and water depths, need to be verified during a site visit, often as part of a geomorphic assessment or survey. Regardless of the source of site assessment data, to be useful for design, physical and biological data must be representative and reliable.

Reference reach: Assessment for AOP and stream connectivity at culverts requires information about the culvert and the stream reach on which the culvert will be built. A reference reach provides key information about the channel dimensions (width, depth, slope, etc.), bed material, and the presence, pattern, and spacing of bedforms, which can inform sediment stability assessments and geomorphic simulation. Ideally, a reference reach should be a relatively stable reach of stream under the current climate, landuse and hydrologic conditions (Harrelson et al. 1994, Rosgen 1996) but outside of the impact of any current road stream crossing. Reference reaches could be found either upstream or downstream from the culvert site or if needed, on a nearby stream that is similar in watershed size and physical stream characteristics. In addition to providing numerical data about a stream, examining a reference reach builds a designer's intuition about a site, which in turn informs their engineering judgement in the design process.

Site assessment resources: Many resources, such as forms and checklists, exist to aid in assessing stream crossings and stream characteristics in general. Three resources are listed below:

1. Stream Stability at Highway Structures (FHWA HEC 20) by Lagasse et al. (2012) includes information on geomorphic assessment and stream stability, including a three-level stability assessment tool. Appendices contain stream reconnaissance record sheets for data collection.
2. MnDOT has developed a survey requirement form for bridge crossings which may also be used for culverts. This form is located in Appendix G.
3. The Minnesota DNR has created a Geomorphic Assessment at Road/River Intersections form that could be used to summarize stream and landscape conditions at the crossing site based on modeling, for use in supplementing or comparing to field data. The form and accompanying

documentation are available at:

<http://www.dnr.state.mn.us/eco/streamhab/geomorphology/index.html>.

3.1 HYDROLOGY

In the context of culvert design, hydrology is important to determine the probable peak stream flows for various flood frequencies (i.e. Q100, Q25, Q1.5) at a particular site. An understanding of a stream's hydrologic regime is critical for sizing culverts appropriately and understanding potential sediment transport, flooding and scouring issues. Culverts are typically designed based on peak flows to pass a certain design flow event, such as a 50-year flood (Q50). Appropriate design flows are listed in the MnDOT Drainage Manual (MnDOT 2000), see also Section 2.2 . FHWA's Highway Hydrology, HDS 2 (McCuen et al. 2002) is another source of hydrologic design information. For consideration of AOP, base flows, and seasonal low flows are also important, as is the hydrologic regime (Section 3.1.1).

A number of methods are available for estimating peak stream flows, including rainfall-runoff models, such as NRCS TR-20 and TR-55, SWMM, HEC-HMS, and estimates based on extrapolation of stream gauge data, such as the free online USGS Streamstats tool, which is covered in Section 3.1.2 . Comparison of multiple methods in developing design flows is encouraged. For Minnesota, NOAA Atlas 14, Volume 8 (<https://hdsc.nws.noaa.gov/hdsc/pfds/>) is the appropriate rainfall data source for rainfall-runoff hydrologic modeling. Links to NOAA Atlas 14 data and descriptions of how the data should be used in Minnesota are available through the Atlas 14 section of MnDOT's hydraulics web page, <https://www.dot.state.mn.us/bridge/hydraulics/atlas14.html>.

3.1.1 Hydrologic Regime Assessment

Minnesota is a headwaters state. Runoff from Minnesota landscapes travels to the Mississippi, Missouri, or Red Rivers, or Lake Superior drainage basins. Variation in hydrologic response is observed between and within the various major basins; a unique hydrologic analysis is required for each culvert site. Simply put, what works in one region of the state may be inappropriate or even detrimental to AOP in a region with very different characteristics.

A characterization of the flow regime is necessary to improve AOP at culverts. As can be seen in Figure 3.1.1, average annual precipitation and evapotranspiration varies greatly across the state. Due to less available excess runoff and reduced baseflow, intermittent and ephemeral channels are increasingly common moving from eastern Minnesota toward the Dakotas as precipitation decreases and baseflow decreases.

Intermittency has an enormous impact on the movement of aquatic life, sediment transport, culvert design and maintenance. Even if water is not flowing in the streambed all year long, the ability of aquatic life to pass through culverts when flow is available is important to the species that inhabit these streams. AOP is more easily blocked at streams with only intermittent and temporary flow since passage is limited seasonally and by flow levels. Sediment transport is also more transient and episodic in these

streams (Schumm 1961) creating periods of sediment mobilization followed by deposition which can block movement and AOP at low flows and create culvert maintenance issues. The North Carolina Division of Water Quality (2010) lists geomorphic, hydrologic and biological characteristics to distinguish ephemeral streams from intermittent to perennial streams.

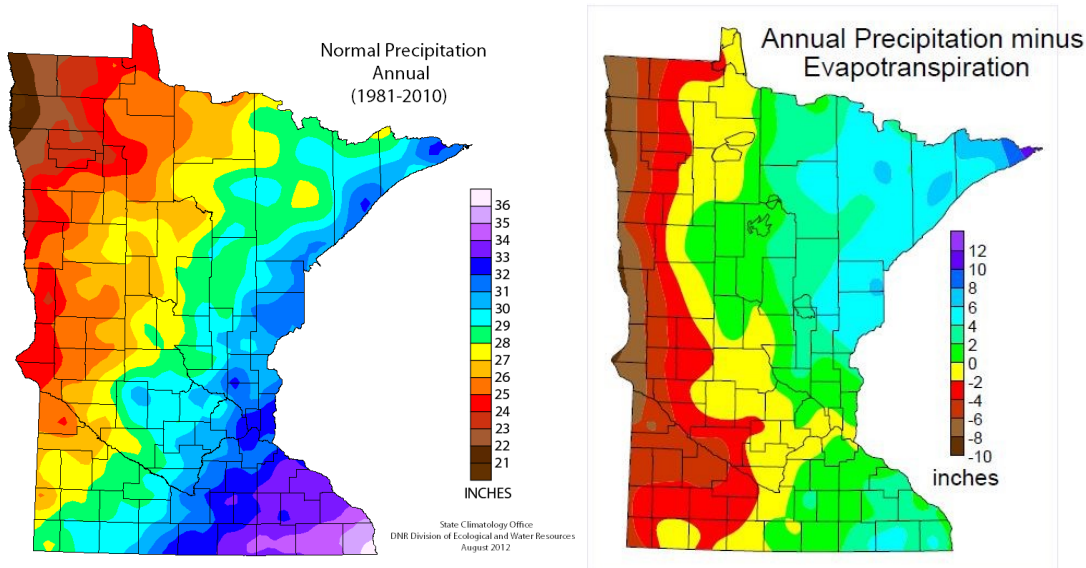


Figure 3.1.1. Annual mean precipitation 1981-2010 and precipitation minus evapotranspiration (from http://www.dnr.state.mn.us/climate/summaries_and_publications/normalsportal.html; <https://www.extension.umn.edu/agriculture/soils/soil-properties/five-factors-soil-formation/>)

3.1.2 Streamstats Tool for Assessment of Peak Flow at Ungauged Streams

Stream gauge data is critical for assessment of hydrologic regime yet it is unavailable in the majority of small streams. The StreamStats program was designed to predict peak flows at un-gauged streams and baseflow at some streams to help address the lack of data in these areas. StreamStats is a free online tool (<https://streamstats.usgs.gov/ss/>) developed by the US Geological Survey (USGS) that delineates a drainage basin based on a clickable map and calculates basin characteristics and predicted peak flows using a GIS-based hydrology analysis. This tool provides rapid streamflow estimates at ungauged sites.

Peak flow predictions for the 1.5-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year recurrence intervals are calculated based on regression equations for each of six hydrologic regions in Minnesota (Figure 3.1.2), which were developed based on expert grouping of hydrologic landscape units. The regression equations were developed by Lorenz et al. (2010) by analysis of data from 330 streamflow gauges in Minnesota and nearby portions of Iowa and South Dakota. Flow-duration and low-flow frequency statistics are also available in StreamStats (Ziegweid et al. 2015) This webpage explains the current version of StreamStats in Minnesota and contains links to the references used in development: <https://water.usgs.gov/osw/streamstats/minnesota.html>

StreamStats also reports estimates of standard errors (SE) as percentages, and in some cases 90-percent prediction intervals. This information is helpful to check the sensitivity of a given culvert design to

variation in discharge, which is important in assessing resiliency. The developers of the regression equations caution that the regression equations were developed and apply to stream locations, “...where flows are not substantially affected by regulation, diversion, or urbanization” (Ziegeweid et al. 2015). If the culvert site is judged to be substantially affected by these factors, another method of hydrologic analysis should be used. All streamflow predictions have associated uncertainties; it is prudent to perform several hydrologic analyses using different approaches to cross-check results.

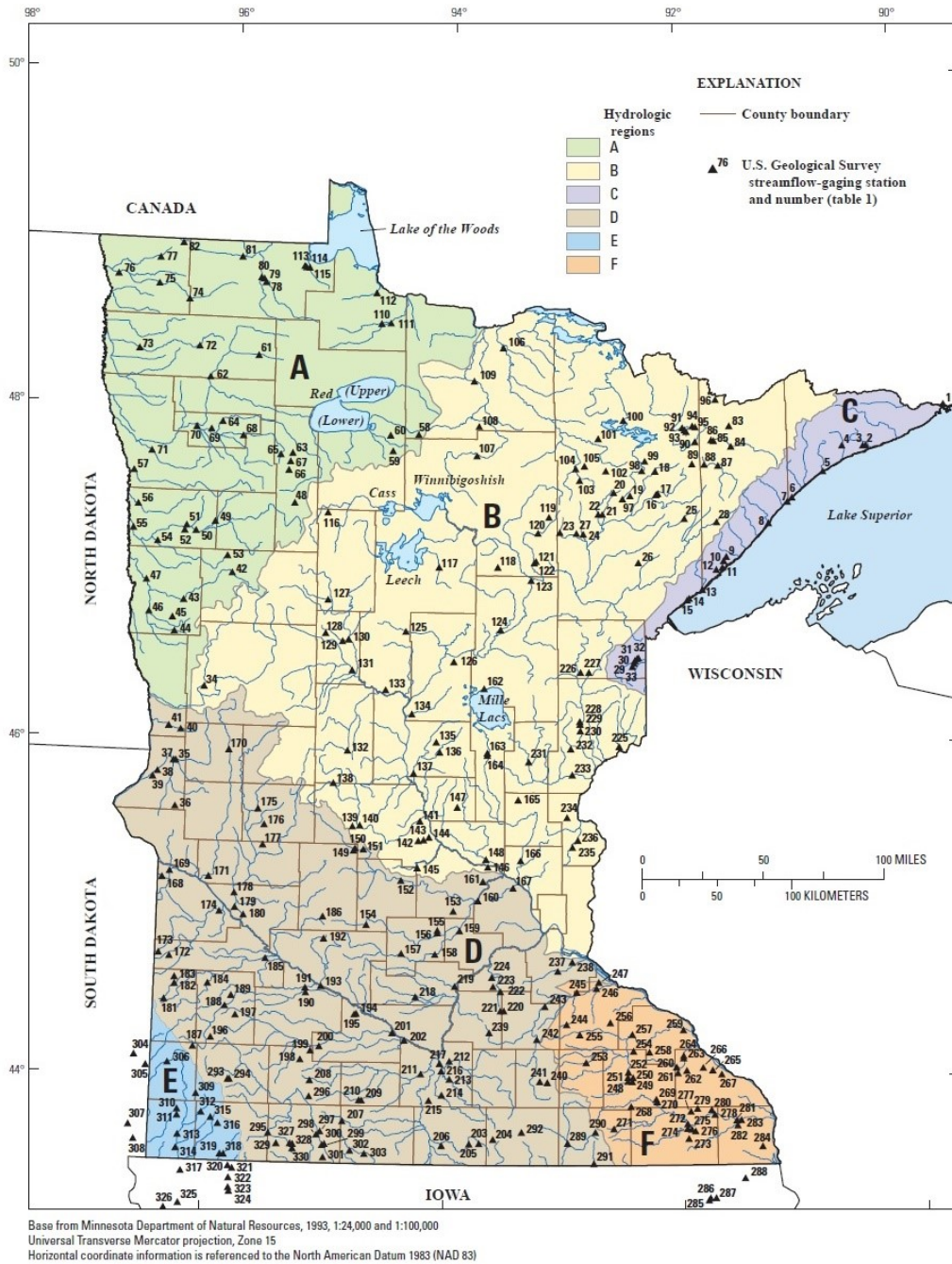


Figure 3.1.2. Peak-flow hydrologic regions and streamflow gaging stations used in development of peak flow regressions deployed in USGS StreamStats (from Figure 1, Lorenz et al. 2010)

3.2 CHANNEL AND BANK STABILITY

3.2.1 Importance, Definition, and Time Scale of Stream Stability

Channel stability is important for the success of culvert installations and long-term sustainability. Constructing a culvert on an unstable stream reach without consideration of the source or probable results of the existing instability is likely to be a poor investment and be detrimental to AOP. For example headcutting caused by poor culvert design is likely to lead to aquatic life blockages and/or create the need for costly repairs.

A stable channel is considered to be one that is not excessively aggrading or degrading, but has a balance between the two processes such that channel dimensions, including base level, do not change rapidly over time. This can be difficult to account for in the design of in-stream structures; see Heede (1986) for a discussion of the issues. The concept of dynamic equilibrium between discharge, slope, and sediment transport is described by (Rapp and Abbe 2003) and was briefly summarized in the form of Lane's equation:

$$Q_s d_s \propto Q_w S_o \quad (\text{Equation 3-1})$$

where Q_s = sediment discharge, d_s = sediment diameter, Q_w = water discharge, S_o = stream slope.

Stability may be considered over different time scales. Short-term adjustments occur in response to more recent flow changes or disturbances to the watershed or near-channel areas. Longer-term changes may take place over many years and are often a result of past landuse and/or climatic changes that can on a decadal or longer time scale. Short-term or more transient sediment movement may include processes like bank collapse from saturation and re-stabilization, where time averaged channel dimensions do not change substantially.

Example of longer-term changes include responses to watershed land cover change or re-meandering of channelized streams. Historically, many streams in Minnesota were more connected to their floodplains or only slightly entrenched (see Section 3.7 ; Verry 2000b). Years of human alteration from activities such as ditching and dredging for ditch maintenance lowered channel elevations and created berms alongside the channel and promoted bed degradation from increased slope. Other processes, such as increased streamflow have caused bed degradation in many rivers. As a consequence, many of these streams are now more highly entrenched due to direct channel modification and altered hydrologic conditions (Lenhart et al. 2012). This has important implications for culvert design as well as overall stream stability.

In the context of culverts, long-term stability refers to the stability of the stream relative to the expected design life of the crossing structure expected life. Stream crossings intended for AOP and stream connectivity are often designed for a service life exceeding 50 years, which, although short in geologic time, is significant in terms of a human lifetime. Typically streams in Minnesota migrate laterally in the

range of 0 to 1 feet per year although some may exceed that rate (Oknich 2017). Lateral migration may be controlled at the culvert location in the short term but is likely to affect the culvert lifespan over decades.

3.2.2 Assessment of Stream Stability

The cause(s) of any instability should be investigated and diagnosed so they can be managed to the extent possible within the limitations of the project. The two most important questions related to stability and the culvert design processes are: 1) is the stream reach stable in its current state? and 2) is the stream reach likely to remain stable through the design life of the culvert? Since streams evolve and change over time in response to changing streamflow, climate, and landuse it is critical for culvert sustainability and maintenance to assess the potential for rapid channel movement, both vertically (to determine if its aggrading or degrading) and laterally (to assess lateral movement in plan form). If watershed and climate factors are relatively stable the stream is less likely to change its average dimensions within the culvert lifespan.

There are a number of tools for assessing channel stability ranging from semi-quantitative indices to more numerical modeling approaches. Short-term stability issues may include bank erosion, bed erosion and/or aggradation. Indices of bank stability include the Bank Erosion Hazard Index (BEHI), a part of an empirical model called BANCS which is used to assess the probability of bank collapse at a cross section (Rosgen 2006, Sass and Keane 2012), Pfankuch Stability Index (Pfankuch 1975), and others. More simply, the bank height ratio can be an indicator of stability. The bank height ratio is the ratio of the overall bank height to the bankfull elevation (the elevation of the channel-forming flow). In addition, Johnson et al. (1999) present a method for Rapid Assessment of Channel Stability in the Vicinity of a Road Crossing for gravel-bed streams based on 13 stability indicators: 1) bank soil texture and coherence, 2) average bank slope angle, 3) vegetative bank protection, 4) bank cutting, 5) mass wasting or bank failure, 6) bar development, 7) debris jam potential, 8) obstructions, flow deflectors, and sediment traps, 9) channel bed material consolidation and armoring, 10) shear stress ratio, 11) high flow angle of approach to bridge or culvert, 12) bridge or culvert distance from meander impact point, and 13) percentage of channel constriction (by the structure). This method draws on observations, measurements, and simple calculations to rate stream stability in the vicinity of a road crossing. Each of the 13 indicators is assigned a relative weight; the ratio of applied to critical shear stress (see Section 4.3) is given the highest weight.

Headcut potential should also be assessed by examining the longitudinal profile of the stream and elevation differences between upstream and downstream ends of the culvert. If there is a perched culvert with a large jump from the streambed to the existing culvert outlet, the stream is at risk for headcutting. If the culvert bed is lowered to match the downstream scoured bed, a headcut may be initiated upstream.

More quantitative assessment of stream bank erosion can be done by measuring lateral migration rates from historic aerial photos and/or measurements of channel width change using GIS; see Lauer et al. (2017) for example. This will help to assess potential for future channel change as well. If a river is

getting wider, this is most likely an indicator of imbalance between erosion and deposition within those stream reaches. Some channels may migrate laterally substantially over time without necessarily getting wider, particularly alluvial channels that are comprised of very erodible and/or sandy material.

Assessment of shear and bed erosion potential can be completed with numerical modeling tools such as HEC-RAS or other analysis tools (Section 4.3.1). Typically, shear forces are calculated for a given channel geometry at different flow levels. Shear force is compared to the shear strength of the bed materials to determine if the bed materials will be mobilized during high flow events. In AOP projects that simulate the natural sediment movement of streams, bed material is expected to be both transported and deposited in balance with mobilization during the hydrograph rise and deposition as flow levels recede. Typically the largest size classes of bed material will remain on the bed.

3.3 STREAM ALIGNMENT AND SINUOSITY

Stream alignment refers to the horizontal planform of the stream including the angles and direction of curves and bends. In the context of a road crossing, the compatibility between the road alignment and stream alignment is a determining factor in how the culvert will perform hydraulically and of its susceptibility to clogging or damage by trees, woody debris, and sediment. As a general rule, it is best to locate a crossing on a straight section of the stream with the culvert aligned with the stream channel to promote stability of the stream and reduce long-term risk to the roadway embankment. This is not always the minimum culvert length, however, and designers typically face limited choices in culvert replacements making compromises between inlet and outlet angles and culvert length necessary.

A high skew angle between the stream approach and the culvert increases the likelihood of debris plugging and embankment erosion, and thus should be avoided (Figure 3.3.1). A stream reach with radius of curvature of an upstream bend at least five times the bankfull width is considered to have similar capacity for sediment and debris transport as a straight reach. There is a substantially increased risk of negatively affecting debris and sediment transport on a bend where the radius of curvature is less than two times the bankfull width (FSSSWG 2008).

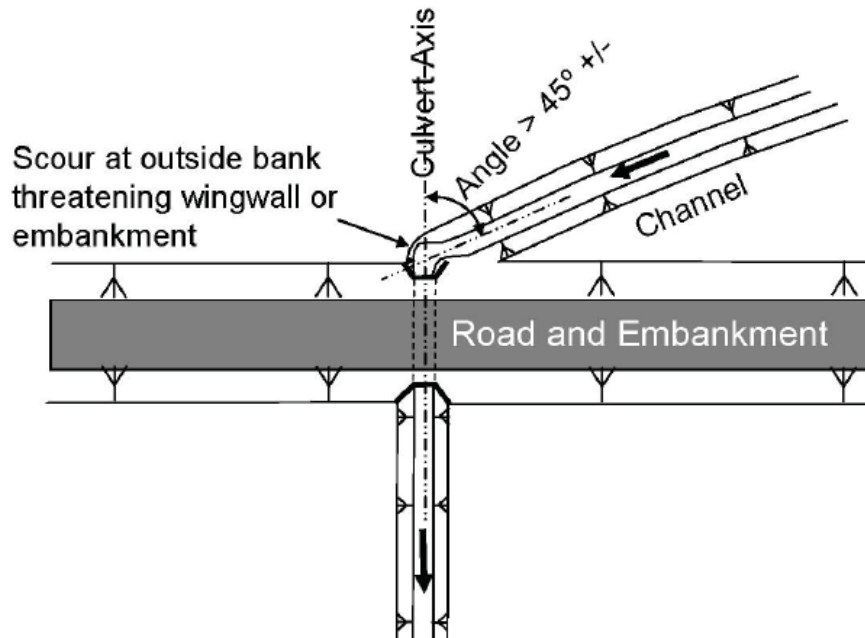


Figure 3.3.1. Poor culvert to channel alignment. (From Hunt et al. (FHWA) 2010)

Historical alignment changes

Many Minnesota streams have been straightened or moved since the beginning of European settlement to accommodate agriculture, roadways and development, or increase drainage efficiency (Lenhart et al. 2012). At road crossings, this often involved forcing a stream through a pipe perpendicular to the road or cutting off meander bends, thereby increasing the slope in the affected reach. These measures were an advantage in the short term (such as shorter, less expensive culverts) but can have de-stabilizing effects on the stream, leading to unintended consequences as a stream shifts to regain equilibrium (Section 3.2). Depending on characteristics, streams respond differently to disturbances. Lower gradient streams with finer bed material are typically more sinuous than those with coarser bed materials, and also more susceptible to erosion and rapid channel movement.

Sinuosity

Sinuosity refers to the degree of meandering of the stream channel and is calculated by dividing the stream length by the valley distance. Thus a straight ditch section where the channel length is equal to the valley length will have a sinuosity of 1.0, while a highly meandering channel will have a sinuosity of 1.5 or greater. As a result, the channel slope of a meandering stream is less than the valley slope. The valley slope can be estimated by interpolating valley cross sections and with a field survey of depositional flats along the channel (Zytkovicz and Murtada 2017).

Figure 3.3.2 shows an example of a stream converted to a ditch. Taking the red dashed line as the valley length (2,500 ft), the top photo from 1955 shows a stream before straightening (4,270 ft), while the bottom photo from 2015 shows the shortening of the channel to 2,615 feet after straightening (Figure 3.3.2). The calculation of the channel and valley slopes for the pre-straightened and straightened

reaches is shown below. When the stream alignment was shortened, the channel slope also changed, increasing by 63% in the example below, corresponding with a 63% increase in applied bed shear stress (Section 4.3.1). This is an important consideration when re-designing a channel alignment in the vicinity of a culvert, as channel slope is closely linked to sediment transport and energy dissipation in the channel.

Table 3.3.1. Sinuosity and channel slope estimates for the stream in Figure 3.3.2.

1955	2015
sinuosity = 4,270 ft / 2,500 ft = 1.71	sinuosity = 2,615 ft / 2,500 ft = 1.05
slope = 1.1 ft / 4,270 ft = 0.026%	slope = 1.1 ft / 2,615 ft = 0.042%
change in slope (% change)	(0.042-0.026)/0.026 = 63%

Number of active channels

Multiple channels or braided streams tend to be fairly mobile with frequently changing boundaries. While there may be a few multiple-channel or braided-channel streams in Minnesota the majority have a single thread or main channel. Further investigation is recommended if a multiple-channel or braided stream is suspected, as this may be an indicator of an aggrading floodplain and a spanning bridge may be warranted. However, designs for crossings on multiple-channel streams are not considered in this guide.



Figure 3.3.2. Example of sinuosity and river straightening near Clara City, Minnesota. Top photo is from 1955 (MN Historical Aerial Photographs Online, <https://www.lib.umn.edu/apps/mhapo/>, accessed 11/2/2017), Bottom photo is from 2015 (Google Earth Pro, accessed 11/2/2017)

3.4 VERTICAL PROFILE

3.4.1 Channel Slope

The channel bed slope, also referred to as the stream gradient, is defined as the vertical change in elevation with respect to the horizontal distance within the channel (Kilgore et al. 2010). Channel slope is one of the most important parameters in understanding how a stream functions, specifically how kinetic energy developed by water flowing under the influence of gravity is dissipated in the stream (see Section 4.1). It is also critical for culvert design. Accurate estimates of bed and water surface slope can only be obtained through a field survey since even small elevation differences can greatly increase stream shear forces that lead to bed erosion and undermining of culverts or loss of infill material.

In a uniform channel and normal flow regime, the water surface and energy grade line (EGL) approximate the channel bed slope. Natural streams are more complex, with slope influenced locally by changes in width and cross section, bedforms, and even individual rocks or logs. The bed slope, or series of slope segments, is constructed by a longitudinal profile, or long profile, measured with survey points along the deepest points, or thalweg, of the stream. An example of a longitudinal profile survey is shown in Figure 3.4.1.

The longitudinal profile survey is a variation of topographic survey specifically targeting features within the stream and banks, such as bed features, grade breaks, pools, etc. Water surface elevations should be collected at these points as well. Care should be taken to choose survey points that best represent the stream features, such as locating the thalweg (deepest point in the channel) and not just a generic center of channel. This requires more attention to the structure and details of the stream and landscape than, for instance, a typical topographic survey used to generate earthwork quantities.

The longitudinal profile should generally extend 20-30 channel widths upstream and downstream of the crossing (FSSSWG 2008). Surveying a reach long enough to determine an equilibrium slope, or range of slopes, is important. In a replacement situation, the influence of the existing culvert on stream profile is likely to extend about five bankfull widths upstream and downstream, possibly more in low gradient streams (Gubernick, Higgins, and Gran 2017). Note that for many streams, especially in low-gradient regions, water surface elevation may be controlled by factors relatively far downstream, such as channel constrictions or downstream tailwater. Identifying and assessing these water surface controls is important for correct hydraulic analysis (Section 4.2) and culvert design.

The USFS Stream Simulation manual emphasizes the importance of the longitudinal profile for geomorphic simulation culvert designs. The longitudinal profile provides information on the "...channel gradient, the local gradient variability, the features controlling channel gradient, the depth and variability of scour, the length and spacing of channel units, such as pools, riffles, and steps, the length and depth of any accumulated sediment upstream from the culvert (channel aggradation), and the length and depth of channel scour downstream from the culvert (channel degradation). The longitudinal profile is necessary for determining the appropriate channel elevation and design gradient through the crossing, identifying a reference reach with a similar gradient, and determining the range of potential

vertical streambed adjustment (vertical adjustment potential)” (FSSSWG 2008). Refer to Section 5.3.3 for a list of steps used in the USFS Stream Simulation longitudinal profile assessment, and an example profile.

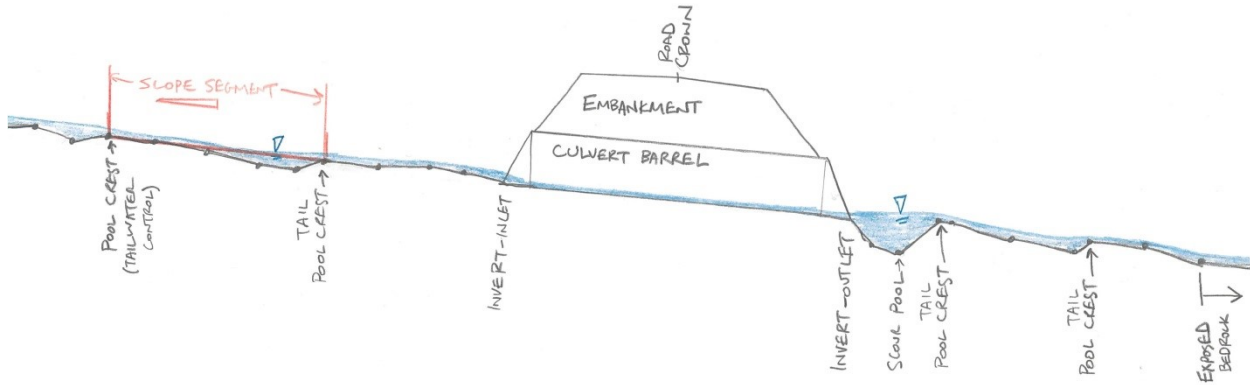


Figure 3.4.1. Longitudinal profile, showing survey points along the thalweg. Important controlling points, such as pool tailwater controls, inverts, deepest pools, and exposed bedrock are noted, and an example slope segment is shown.

Additional references for longitudinal profile surveys include:

- Section 5.1.3 of the USFS Stream Simulation manual (FSSSWG 2008)
- Appendix of Best Practices for Meeting DNR General Public Waters Work Permit GP2004-0001, Version 4 (Leete 2014).
- Appendix E of National Inventory and Assessment Procedure - For Identifying Barriers to Aquatic Organism Passage at Road-Stream Crossings (Clarkin et al. 2005)
- Stream channel reference sites: an illustrated guide to field technique (Harrelson et al. 1994)
- Chapter 5 of Applied River Morphology, (Rosgen 1996)

Once the longitudinal profile survey is plotted, bed slope segments are typically measured between similar features, such as riffle to riffle. Streambeds are often highly variable alternating between bed features such as riffles, runs and pools. The water surface slope and EGL are typically more continuous. However, sometimes the longitudinal profile reveals a non-uniform channel slope, which may occur if the stream crossing is located at a slope transition. Figure 3.4.2 illustrates some possible longitudinal profile shapes. Extra care and geomorphic analysis is warranted when dealing with non-uniform profiles due to the possibility of higher rates of erosion or sedimentation. The slope of the valley can be assessed from topographic or LiDAR data over a long distance.

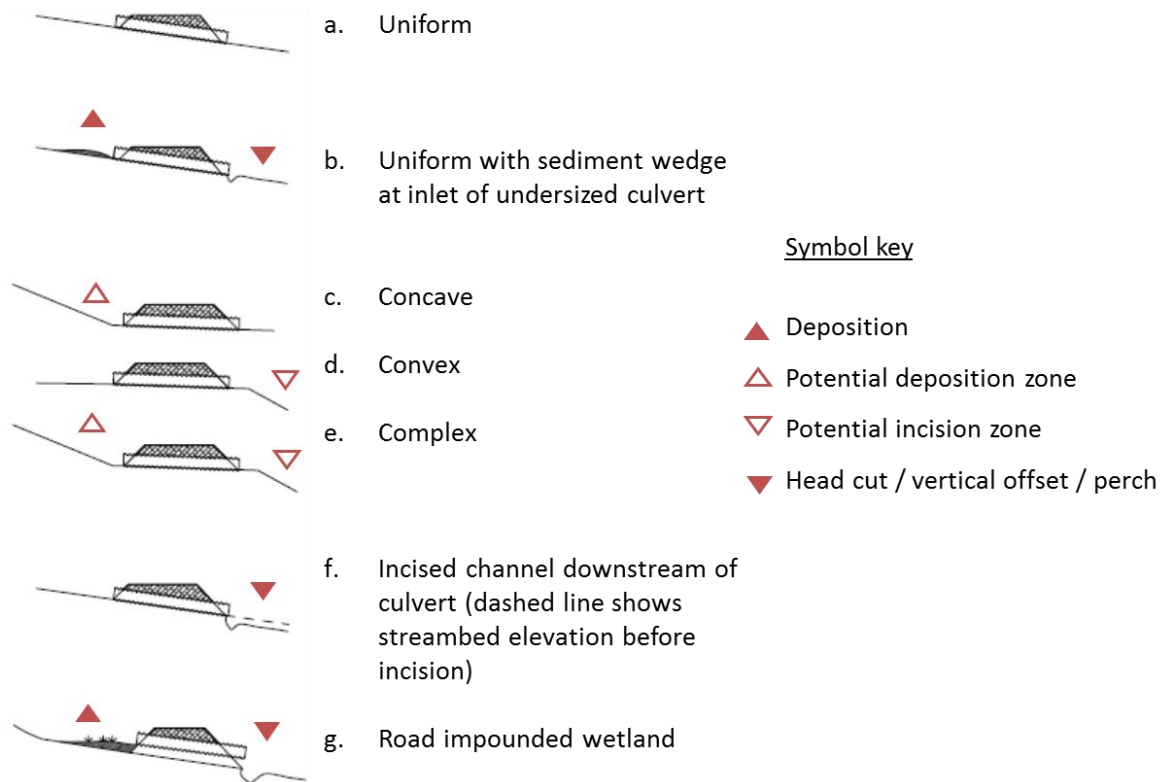


Figure 3.4.2. Some possible longitudinal profile shapes (adapted from Figure 5.12, FSSSWG 2008 and Gubernick, Higgins, and Gran 2017)

In a free surface, or open channel flow, the hydraulic grade line coincides with the free water surface. The energy grade line, EGL, also called the friction slope, represents the total energy of the flow, including the velocity ($V^2/2g$) term where g = acceleration of gravity. In a uniform channel and normal flow regime, the water surface and energy grade line (EGL) are approximated by the bed slope measured over similar features (i.e. riffle to riffle), because they are parallel to the channel bed slope. This is not the case where flow is rapidly changing such as at contractions, drops, hydraulic jumps, etc. Many tools (Section 4.2) are available to perform hydraulic calculations, including construction of water surface profiles and EGL gradients.

3.4.2 Vertical Discontinuity (Perch)

A perched culvert is the classic and most readily recognizable break in stream continuity and barrier to AOP, although other significant barriers exist (Section 1.2.1). A vertical discontinuity, or perch, is a vertical drop from the invert of a culvert to the water surface below. This commonly occurs due to erosion downstream of the culvert outlet, often taking the form of a scour pool. During normal low flows, many aquatic species cannot jump the vertical distance from the pool into the culvert. Organisms that may manage to navigate the perch are immediately exposed to shallow, fast-moving flow along the bottom of the culvert near the free fall that can act as a compounding barrier to passage. Figure 3.4.3 illustrates a culvert with a relatively large perch and very shallow flow in the barrel. This culvert is a

significant barrier to most aquatic organisms in Minnesota. Figure 1.2.3 is another example of a perched culvert in Minnesota.



Figure 3.4.3. Perched cast in place box culvert exhibiting very shallow flow depth. Indian Camp Creek under TH61, Cook County. (P. Leete photo, 2013)

In a stream crossing inventory of the Root River watershed in southeastern Minnesota, Hillman (2015) considered a perch of 0.5 feet to 2.0 feet to be a significant barrier, and a perch greater 2.0 feet to be a complete barrier. Like other potential barriers, the effect of a perch on AOP is dependent on species and life stage. For smaller fish, even a 0.5 foot perch may be impassable. A vertical discontinuity can also lead to undermining of the culvert outlet or flared end, increasing stress in the structure or ties and increasing the possibility of a culvert failure due to soil piping.

When a culvert is replaced, a vertical discontinuity should be eliminated whenever possible. To this end, the presence of a perch should be identified early in the culvert design process and measured as part of the longitudinal profile (Section 3.4.1). Eliminating a perch may involve setting the culvert invert lower (Section 5.5), increasing culvert slope within tolerable limits (refer to Section 3.4.1), employing grade controls upstream, downstream, or within the culvert (Section 6.3), or a combination of these methods. These methods to eliminate a vertical discontinuity should be employed with caution; if applied improperly, destabilization of the stream channel with a corresponding reduction of AOP could result.

3.5 CHANNEL WIDTH AND DEPTH

The physical dimensions of a stream channel, including average width, depth, and cross sectional area, are important in understanding how a stream works, and what type of crossing may be appropriate. An important and widely recognized channel metric is the bankfull width, associated with the bankfull elevation, which the USFS defines as “... the point where water fills the channel just before beginning to spill onto the flood plain” (FSSSWG 2008). The bankfull flow is “...widely recognized as a good estimator of the channel-forming flow in stable alluvial rivers...” (FSSSWG 2008).

However, in incised systems, the bankfull elevation can be difficult to determine from field indicators alone. Since incised channels are disconnected from their floodplains, bankfull width in these cases often does not correspond with the highest top of bank slope break. This can be confusing and may easily lead to discrepancies in reported bankfull width. For consistency in this document, the term bankfull is used as an indicator of channel forming discharge. There is considerable discussion on this topic and the related channel-forming discharge by Copeland et al (2000).

The return period for bankfull flows is often estimated as 1.5 years (Q1.5), though the statistical return period may vary between watersheds. In drier environments the bankfull or channel-forming flow is typically less frequent, often greater than a two- year return period (Powell 2009). In other regions, especially in agricultural areas with abundant surface ditches and sub-surface drainage, the return period may be closer to one year (Powell et al. 2006a). Annable et al. (2011) found the return period of bankfull events in urban streams in southern Ontario to be less than one year.

Width: Bankfull width refers to the unaltered top width of the bankfull channel. Many of the culvert design procedures for maintaining stream connectivity recommend a culvert width of 1.0 to 1.2 times the bankfull width, thus, determining an appropriate measure of bankfull width is critical to avoid creating barriers due to culverts being too narrow (resulting in high velocity, excessive scour) or too wide (resulting in very shallow flow, excessive aggradation).

Depth: Mean bankfull depth is the average of channel depth measurements (bed elevation to bankfull elevation) in a cross section, and may be calculated as the cross sectional area at bankfull divided by the bankfull width. Maximum bankfull depth is the vertical distance between the elevation of the bankfull width and the lowest point, or thalweg, of the stream in a riffle section, and is used in calculation of entrenchment ratio (see Section 3.7).

Identifying bankfull dimensions: There are many references used to help identify representative bankfull dimensions, and if available, several should be used together to validate the estimate, with the geomorphic field survey of primary importance. Appendix E of MN DNR’s Stream Crossing Inventory and Ranking Guidelines (Hillman 2015) lists three methods of determining bankfull dimensions, and a fourth is added based on expected return periods for bankfull flow.

1. *Field measurement directly from bankfull indicators.* Field measurement of bankfull dimensions is the preferred method. This method is most reliable in alluvial channels that are not incised. The USFS has produced several video presentations to assist in identifying bankfull indicators, available

online at <https://www.fs.fed.us/biology/nsaec/products-videoswebinars.html>. The references below by Verry (2005) and Wolman et al. (2003) are most applicable to bankfull determination in Minnesota.

- a. Identifying Bankfull Stage in Forested Streams in the Eastern United States (2003), by M. Gordon Wolman, William W. Emmett, Elon S. Verry, Daniel A. Marion, Lloyd W. Swift Jr., Gary B. Kappesser.
- b. A Guide to Identification of Bankfull Stage in the Northeastern United States (2005-1), by Elon S. Verry
- c. A Guide for Field Identification of Bankfull Stage in the Western United States (1995) by Luna B. Leopold, William W. Emmett, Hilton L. Silvey, David L. Rosgen.

While a simple concept for unaltered channels which regularly access their floodplains (not incised), determining the bankfull width for a stream requires some skill in identifying bankfull flow indicators which define the bankfull elevation, and thus the bankfull width. Bankfull width is measured as the horizontal distance perpendicular to (bankfull) flow from one bankfull indicator to the same elevation on the other side of the channel. Indicators include:

- elevation of the active floodplain immediately adjacent to the channel;
- elevation of a break in bank slope;
- changes in vegetation;
- elevation of the highest depositional feature (such as a point sand or gravel bar).

There can be significant challenges in determining bankfull width. For incised, confined, or non-alluvial channels there may not be a bankfull channel in the strict sense and one must use channel width indicators to determine this (Barnard et al. 2015). In watersheds undergoing hydrologic change, (e.g. urbanizing), field indicators have not yet reached an equilibrium with flow, and may indicate channel dimensions that are not stable. Because bankfull width and depth can be difficult to determine, especially in disturbed, unstable, or incised streams where there is no discernible flood plain, possible bankfull indicators in these situations must be checked against multiple data sources.

The recommendations about an appropriate reference reach in the beginning of this section apply. For instance, measuring the width of an over-widened plunge pool downstream of a small culvert would not be representative of the normal bankfull width. Bankfull measurements may be taken as part of a geomorphic cross section, for example, as in Figure 3.5.1. Taking an average of several (3 to 5 or more) bankfull measurements and noting the level of confidence in the field measurement is recommended. For a stream that is not rapidly changing, the bankfull elevation should on average parallel the water surface elevation. Surveying probable bankfull indicators, and thus the estimated bankfull elevation, is a good practice as a part of the longitudinal profile (Section 3.4).

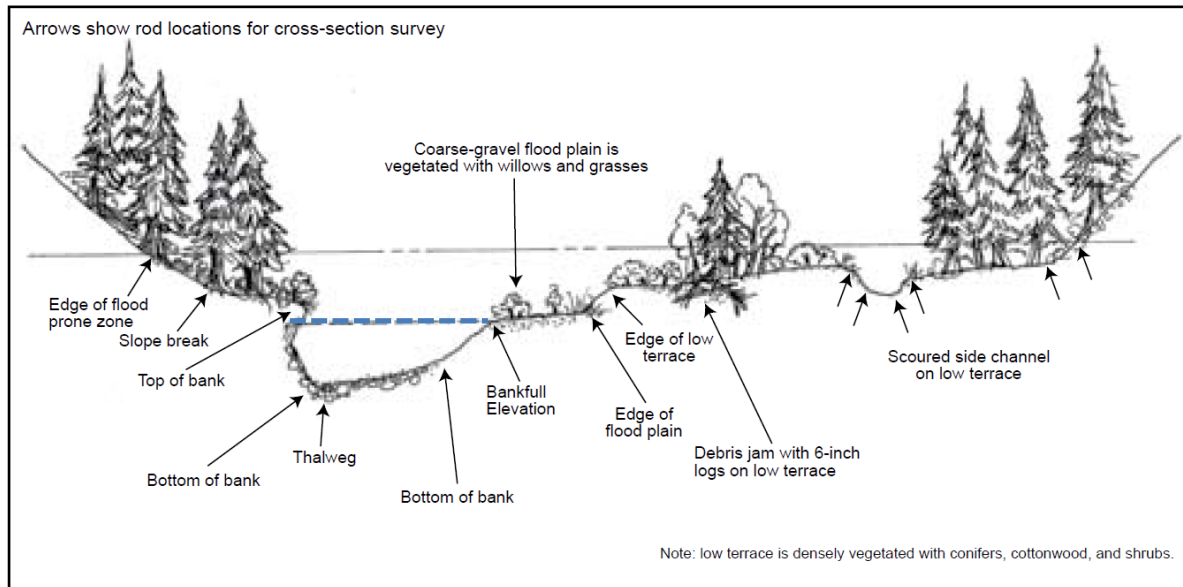


Figure 3.5.1. Survey points in a cross section. The dashed line denotes the bankfull elevation. (Fig. 5.4 from FSSSWG 2008)

2. *Estimate of bankfull dimensions based on the cross-sectional area.* This involves a basic tape and level rod survey of a cross section (outside the influence of the existing crossing). Regional hydraulic geometry curves for Eastern and Western Minnesota have been developed by the Minnesota DNR to estimate bankfull width, mean depth, and cross sectional area based on watershed drainage area in square miles. The regional hydraulic geometry curves are shown in Appendix E, and available online at: <http://www.dnr.state.mn.us/eco/streamhab/geomorphology/index.html>. Use Western MN curves for the Red River, Minnesota River and Missouri River basin streams, and Eastern MN curves for Rainy River, Great Lakes, St. Croix River and Mississippi River basins (Hillman 2015). The DNR may be updating these regressions in the near future (pers. Comm., K. Zytkovicz, August 2017). USGS StreamStats (Section 3.1.2) may be used to obtain a rapid estimate of drainage area.

The regional curves may be helpful for initial bankfull estimates or to assist in identifying the likely location of bankfull indicators in the field. For instance, in Figure 3.5.2, width, depth, and cross section data from regional hydraulic geometry curves could help differentiate bankfull features (A) from terrace features (B and C). However, as may be observed from the plots in Appendix E, there can be considerable variation in bankfull metrics; regional curve data should not be used as a substitute for field observations and measurements, since the geometry of each stream is unique.

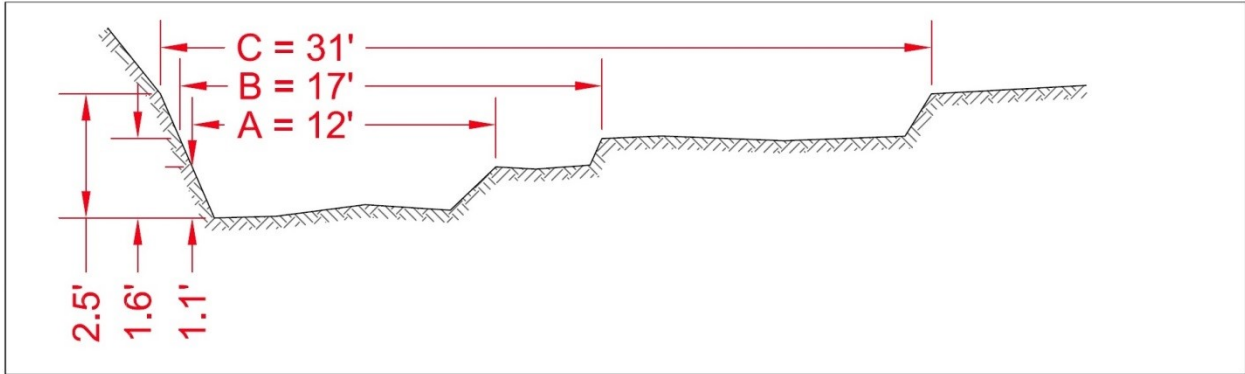


Figure 3.5.2. A hypothetical stream cross section with multiple potential bankfull indicators. Regional curves or other indicators may help to identify likely location of bankfull indicators in the field.

3. *Use of remote sensing data, typically aerial photos or aerial LiDAR.* Wide-area topographic data, typically obtained from aerial LiDAR measurements, are helpful for creation of preliminary stream cross sections including a preliminary bankfull width estimate, and may be useful for classification efforts. Aerial photos may also be helpful to identify the general shape of the channel and stream alignment. However, a geomorphic field survey is recommended to collect channel data for design purposes. LiDAR-generated topography should not be relied upon as the only data source for the following reasons. 1. Most LiDAR beams do not penetrate water, thus the streambed below water line will not be represented; 2. Steep or overhanging banks and areas of dense vegetation are likely to be poorly represented in the LiDAR data; 3. Elevation points are collected at random without reference to observable features such as top of bank or slope breaks which would be represented by breaklines in a traditional survey, and; 4. LiDAR and other remote topo surveys have no way to visually distinguish bankfull indicators, such as depositional features, or other important features like logs or sediment sizes. One source of statewide LiDAR data is the DNR's MN TOPO: <http://www.dnr.state.mn.us/maps/mntopo/index.html>. Figure 3.5.3 shows an example of MN TOPO data.



Figure 3.5.3. Example of MnTOPO LiDAR data. The elevation profile (stream cross-section along the red line) is helpful in showing the general shape of the stream and valley, however, a field survey is necessary to adequately capture the streambed.

4. Use of stream flow data (if available) to correlate flows at expected bankfull return periods ($Q_{1.5} - Q_2$) with features on the stream cross section. Figure 3.5.4 illustrates the concept of bankfull as a breakpoint in the stage vs discharge curve. Note that this method only works in non-incised streams.

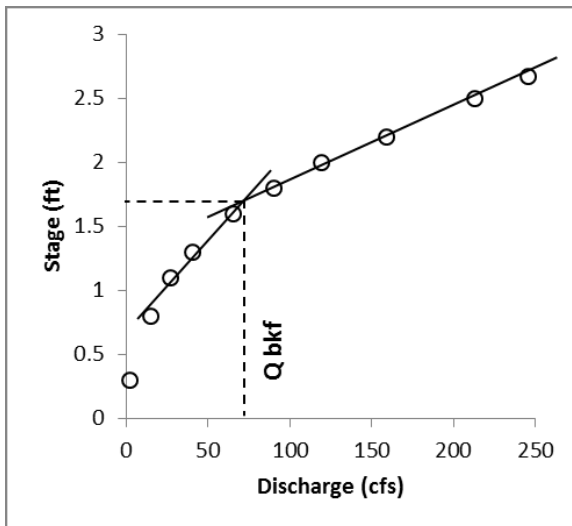


Figure 3.5.4 Stage discharge curve illustrating a break in slope corresponding to the bankfull characteristics in a non-incised stream.

3.6 BED MATERIAL ASSESSMENT

Bed material size is important for choosing an appropriate AOP culvert design strategy because it affects sediment transport processes, depth of scour and in-stream habitat. However, a 2017 survey of practitioners involved in culvert design in Minnesota revealed 45% of respondents did not use the grain size distribution of streambed material in culvert design and review. Only 20% said they used the grain size distribution often.

For preliminary design, bed material size distribution can often be estimated by a visual assessment. Table 3.6.1 gives five basic particle size categories. Other descriptors for bed material may include cohesive soil such as firm clay, and bedrock.

Table 3.6.1. Streambed material classification (following Table 1.1, Bunte and Abt 2001)

Streambed material	Range of median streambed material particle size							
Silt/Clay	<	0.063	mm	<	0.00021	ft		
Sand	0.063	-	2	mm	0.00021	-	0.0066	ft
Gravel	2	-	64	mm	0.0066	-	0.210	ft
Cobble	64	-	256	mm	0.210	-	0.84	ft
Boulder	256	-	4096	mm	0.84	-	13.4	ft

A Wolman Pebble count will provide more detailed data (Bunte and Abt 2001) when most particle sizes are fine gravel (2 mm) or larger. MnDOT has forms for collecting bed material data at road crossings using the Wolman Pebble count (see Appendix G). Various other analyses are applicable, including use of a size template (Figure 3.6.1) in the field, or sieve analysis of samples.

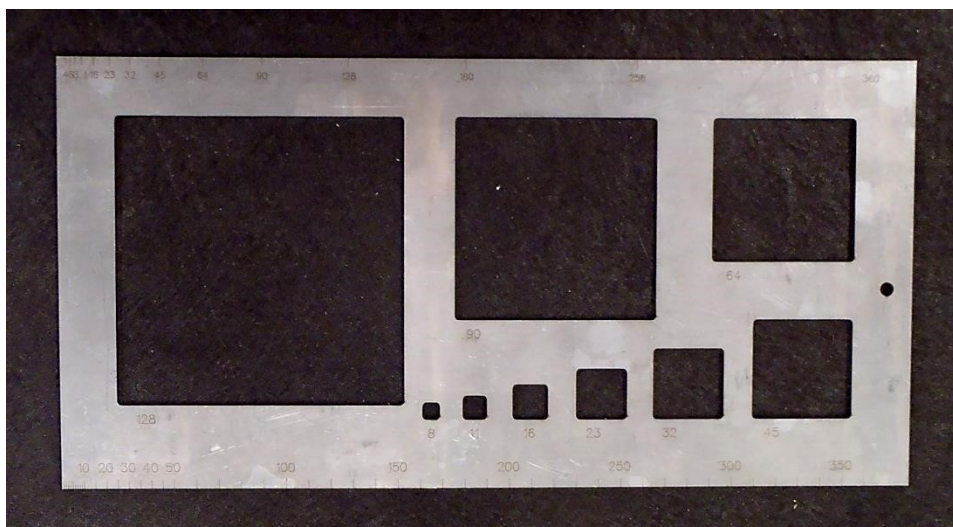


Figure 3.6.1. Particle size template for field use. (Photo M. Hernick)

Streambeds with a variety of particle sizes are often armored, meaning that the finer particles on the surface of the streambed have been washed away, leaving only the coarser particles in the top layers, as

shown in Figure 3.6.2. In this case, it is important to find the particle size below the armor layer, since these smaller materials will move if the armor layer is disturbed in high flows. It is helpful to note if bank material is different than bed material; often times the bed material is armored on the surface and therefore coarser than stream banks.

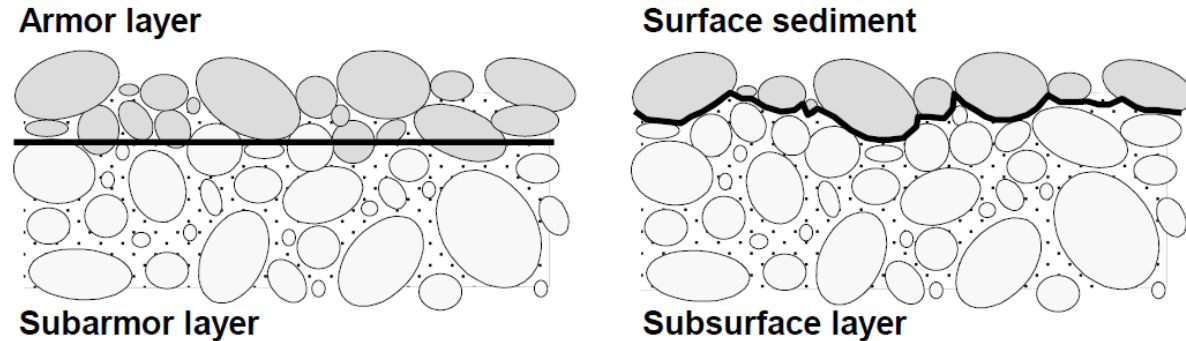


Figure 3.6.2. Armor, subarmor, surface, and subsurface sediment layers. Precise definitions vary, but the depth of the armor layer is often approximated by the size or protrusion of the largest particle. From Figure 4.1 (Bunte and Abt 2001).

Bedforms are a naturally-formed ordering of streambed sediments, often in a repeating pattern, and are important in controlling the stability and roughness characteristics of streambeds in which bedforms occur. If bedforms (e.g. boulder steps, riffles, ribs, etc.) are present in the stream, material sizes of these elements should be collected and noted, in addition to a whole bed survey. The type and pattern of bedforms should be documented for use in culvert channel design. Refer to the example in Section 3.11.1 .

3.7 FLOODPLAINS

Within this document, the floodplain of a stream refers to the area prone to flooding beyond the bankfull elevation. The horizontal extent of the floodplain beyond the channel may be negligible for entrenched or incised channels (discussed below) or very large, depending on the stream type and history of stream alterations. Connection to the floodplain is important in consideration of the design of the channel culvert opening as well as floodplain culverts, if applicable.

When used in a regulatory sense, the term floodplain typically refers to the area corresponding to the base flood, also called the 1 % annual chance or 100-year flood. If a project is located within a designated floodplain as mapped by the Federal Emergency Management Agency (FEMA), certain federal and state regulations apply, primarily with the aim of limiting increases to flood elevations. Refer to Section 4.4 for more information on regulatory floodplains and links to maps, etc. FEMA maps and flood studies can be a good source of hydraulics and hydrology data if a culvert project falls within a mapped floodplain.

The entrenchment ratio (ER) is a measure of the width of the floodplain in relation to the width of the bankfull channel. Entrenchment ratio is calculated as:

$$ER = (\text{valley width at } 2 \times \text{maximum bankfull depth}) / \text{bankfull width (Equation 3-2)}$$

Note that maximum bankfull depth is the vertical distance from the thalweg to the bankfull elevation. The Rosgen stream classification method recognizes three entrenchment ranges, $ER < 1.4$: entrenched, $1.4 < ER < 2.2$; moderately entrenched, and $ER > 2.2$; slightly entrenched (Rosgen 1996). In an entrenched channel, most flood flows are contained within the channel banks, so the channel is effectively disconnected from its floodplain even for most moderate flood events. A slightly entrenched channel typically is well connected to the floodplain, and flows above bankfull stage ($Q_{1.5} - Q_2$) spill onto the floodplain. An example of entrenched and slightly entrenched streams is shown in Figure 3.7.1.

This metric is relevant to the design of the culvert opening size as well as the usefulness of additional culverts placed in the floodplain to pass flood flows more effectively with less contraction (see floodplain culverts, Section 6.2). If flood flows for a slightly entrenched stream with a wide floodplain are forced through a channel-width culvert opening, the likely result is contraction scour at the culvert entrance as well as scour of sediment (if any) in the culvert barrel. The valley width at twice the maximum bankfull depth is sometimes referred to as the flood prone area width. Another way to visualize the entrenchment ratio is the number of bankfull channel widths which would fit into the flood prone area width – fewer bankfull channel widths indicates a more highly entrenched stream.

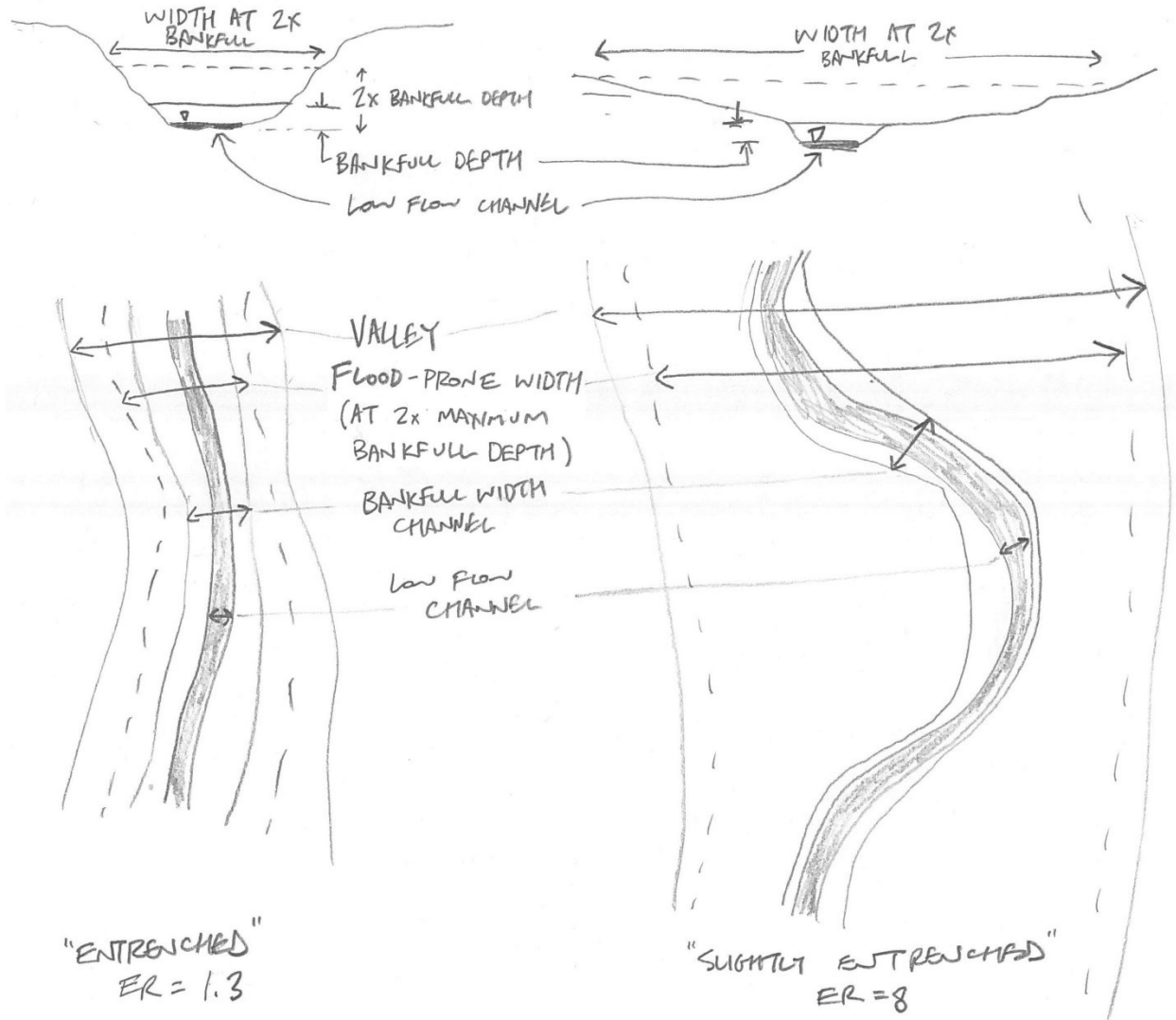


Figure 3.7.1. Conceptual section and plan of streams with different entrenchment.

The Washington Department of Fish and Wildlife (WDFW) Water Crossing Design Guidelines labels the ER as floodplain utilization ratio (FUR), and recommends streams appropriate for geomorphic simulation, and culverts in general, have an ER (FUR) less than approximately 3 (Barnard et al. 2013). USFS recommends that a backwater and bed mobility/stability analysis be conducted when the ER is 6 or greater in forested floodplains, and at a lesser threshold for smoother floodplains with high conveyance (FSSSWG 2008, pg. 6-75).

3.8 DEBRIS AND ICE

In this document, debris refers primarily to logs, branches, roots, and other vegetation transported by a stream. Man-made debris such as trash, scrap lumber, etc. may also be present. It should be noted that wood pieces are sometimes used in engineering structures for bank erosion and grade control (see

Section 6.3) although these should be carefully placed and secured so that they do not lead to future culvert blockages.

Many culvert failures can be attributed to plugging due to accumulations of debris and /or ice. The level of risk at a specific location depends on several factors, including:

1. Physical parameters of the culvert and site such as the presence of a sharp bend at the culvert entrance;
2. Debris load and type from the watershed, generally based on landuse, i.e. cropland, forest, urban, etc., and;
3. Climate at the site, including the orientation of the culvert to sunlight and prevailing winds, which are important in ice formation, melt and re-freezing.

The designer's experience with local conditions combined with observations of the site and other stream crossings in the watershed are important in determining the risks due to debris and ice, and to mitigate those risks. Typically, the designer has no influence on the debris load and climatatic factors, but does have control over at least some of the culvert and site parameters. FHWA's HEC-9, *Debris Control Structures, Evaluation and Countermeasures* (Bradley et al. 2005) and Section 5.2 of FHWA HEC-20, *Stream Stability at Highway Structures* (Lagasse et al. 2012) contain resources for characterizing potential debris and estimating debris quantities. Below is a list of possible strategies to deal with debris and ice, many of which are also best practices for culverts designed for AOP and stream connectivity:

- Carefully align the culvert to the stream (Section 3.3)
- Match the culvert channel width to the stream bankfull width (Section 3.5). Accumulation of woody debris and sediment is increased in wide pools which sometimes form at the inlet end of culverts (Furniss et al. 1998). Wood transported in the channel is often bankfull width or less (Merten et al. 2010) with larger pieces forming jams or deposited on the floodplain. If the culvert is similar in width to the rest of the stream, in winter it is more likely that concentrated base flow will continue, rather than freezing in a ponded or over-wide section.
- Increase culvert height. Providing freeboard (for instance, $HW/D < 0.8$ at design flow) should help versus designs with $HW/D > 1.0$.
- Avoid multiple barrels when significant debris is expected.
- Where there is a large elevation difference between the roadway and culvert crown, provide relief openings higher up on slope, especially for ice-prone streams. Floodplain culverts (Section 6.2) can also serve as relief openings. Vertical risers may also be an option, but are not preferred for stream crossings incorporating AOP.
- In a low cover situation and where allowable, plan for road overtopping (including debris) with a road dip.
- Provide a sloping, non-flared end section flush with embankment that will allow some debris to ride up the slope out of flow (MnDOT Drainage Manual 2000).
- Construct a bridge with high clearance.

Finally, attempting to retain debris or ice upstream of a culvert with some type of debris control structure is often unreliable, greatly increases maintenance and is not recommended for AOP.

3.9 GEOTECHNICAL CONSIDERATIONS

Culverts designed for AOP and stream connectivity, may be larger, set deeper, or constructed differently than traditional culverts designed solely for hydraulic conveyance and thus potentially carry a higher level of geotechnical risk in the construction phase. Post construction, culverts designed for AOP and stream connectivity are likely to be more stable in the long term (Gillespie et al. 2014). Consideration of subsurface soil or rock conditions is very important when choosing a structure type as well as selection of construction methods. Changing a foundation, structure type, or installation method mid-project is likely to be costly, and decreases the likelihood of positive project outcomes. The assistance of a geotechnical engineer, and/or a geomorphologist may be beneficial.

Some type of geotechnical investigation is recommended to characterize subsurface conditions at a stream crossing site. The scope and level of detail depends on what is known about the site already as well as the level of risk from culvert failure. For decision guidance on the need for geotechnical assessment see the U.S. Department of Transportation's culvert assessment and decision-making manual (Hunt et al. 2010). They suggest two levels of investigation with a Level 2 assessment being triggered by embankment piping, channel degradation, headcutting, embankment slope instability, sediment blockage and channel aggradation, and channels designed for AOP, among other indicators.

3.10 AQUATIC ORGANISM DATA

Site assessment must include collection of data available for fish, mussels, and other forms of aquatic life likely to be present and whose passage may be impacted by culverts. In general, the most information is available on gamefish such as bass, walleye or trout. Less information is typically available for mussels and other invertebrates. Occasionally there are state threatened and endangered species, including fish, turtles, mussels, and other aquatic life forms that may be impacted by a culvert project. Those potentially in the stream or watershed need to be documented and thought given as to whether improvements to culvert design could improve their passage. For a summary of aquatic organism and passage issues at culverts see Section 1.2 . For more species-specific information see Appendix B.

Specific categories of organisms or stream types that support protected fish, mussels or other aquatic life may require special consideration (see Applicable Regulations for Culvert Projects in Appendix D). For example, the Minnesota DNR list of designated trout streams should be consulted if working in the southeast or northern to northeastern Minnesota (<http://www.dnr.state.mn.us/troutstreams/designations.html>). Another category of importance is streams supporting Federally Endangered fish in Minnesota, of which the Topeka Shiner (*Notropis Topeka*) is the only one. It occurs in the southwestern part of the state in small streams and oxbow lakes (https://www.fws.gov/midwest/endangered/fishes/TopekaShiner/tosh_mn.html).

3.11 SITE ASSESSMENT EXAMPLES

Two examples of site data are listed in the subsections that follow. Woods Creek (Section 3.11.1) is a high-gradient (3%) stream located near Grand Marais, Minnesota characterized by persistent bedforms (steps and pools) and large bed material (cobbles and boulders). Le Sueur Creek (Section 3.11.2) is a meandering, gravel bed stream with a 0.2% gradient in the Minnesota River basin. An abbreviated listing of site assessment data for Moody Creek, a very low-gradient (0.05%) sand bed stream located near Grand Rapids, is part of the recessed/embedded culvert design example in Section 5.5.6 .

The methods and data presented are meant to be illustrative of data collection efforts, not a comprehensive culvert design. Designers assessing a culvert site can choose from numerous field data forms and analysis methods to document their observations and measurements. The goal of site assessment is not only to complete a data form, but rather to understand stream dynamics well enough to complete a culvert design that allows for AOP and improves stream connectivity.

Site assessment examples in literature may be found in FSSSWG 2008, FHWA HEC-20 (Lagasse et al. 2012), FHWA HEC 26 (Kilgore et al. 2010), and in many other references.

3.11.1 Woods Creek

Woods Creek was used as a steep (3%) reference reach to set up laboratory experiments at the University of Minnesota in Kozarek and Mielke 2015. Woods Creek is a tributary to the Devil Track River, which empties into Lake Superior about three miles northeast of Grand Marais. This site was visited in 2013. Streambed roughness was found to be dominated by structures such as ribs, riffles, steps, pools, cascades, and boulders (Figure 3.11.1). To adequately represent this complexity, a detailed longitudinal survey was conducted to calculate the slope and mark the location of roughness elements (Figure 3.11.2). Structures were identified and described with input from USFS geomorphologist, Bob Gubernick. For each element, element size and the protrusion out of the bed was recorded (Table 3.11.1). Grain size distributions were measured by a pebble count (n=400) and subsurface grain size distributions were measured by sieving. Armoring was significant. The surface median grain size, D50 was 76 mm while the subsurface D50 was 13 mm (Figure 3.11.3).

The detailed field survey was used to 1) develop an appropriate grain size mixture for within the model culvert that adequately represented the fine fraction of the bed material and 2) create appropriate roughness within the culvert barrel that consisted of steps, boulders, and ribs at similar spacing to the reference reach. In these laboratory experiments, the placement of structures within the culvert barrel in a steep stream stabilized the sediment both within the barrel and within the stream channel up- and downstream of the culvert (see Kozarek and Mielke 2015) for more details.



Figure 3.11.1. Woods Creek reference reach. J. Kozarek photo, 2013.

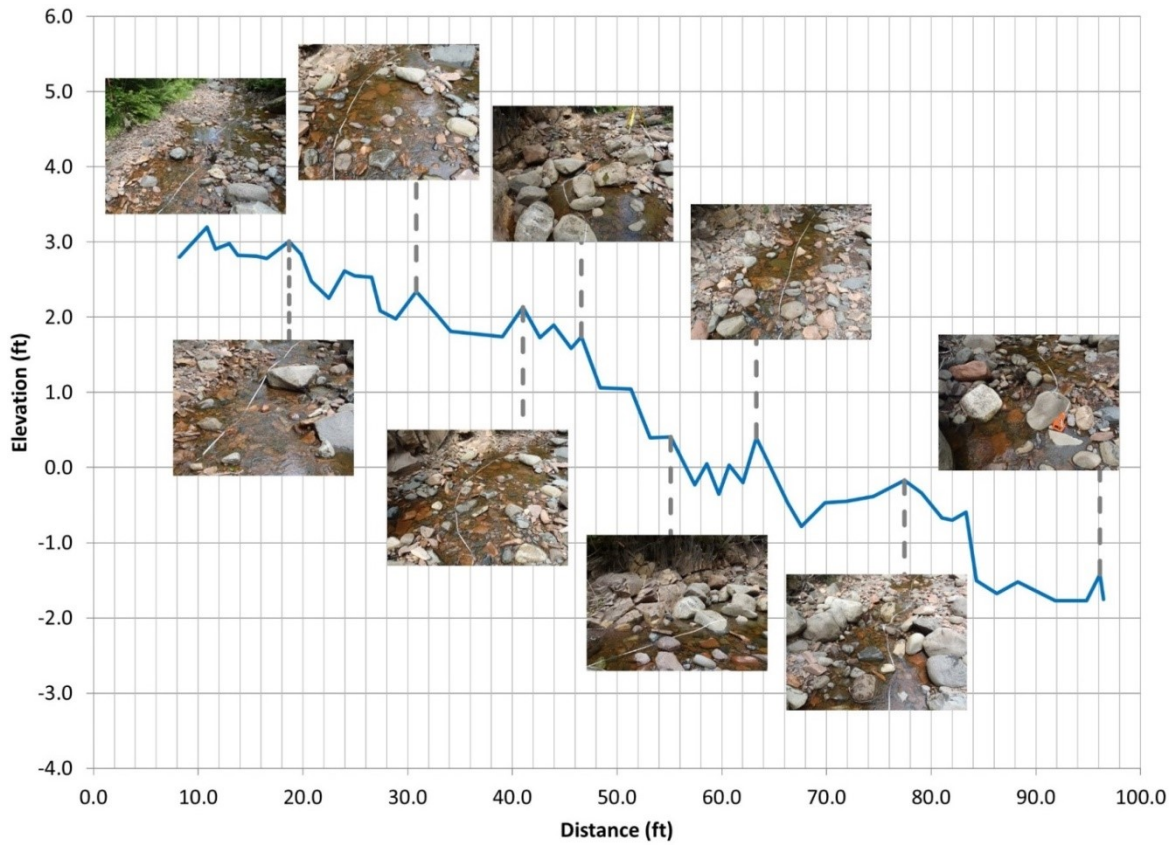


Figure 3.11.2. Longitudinal profile with images of bed structure in the Woods Creek reference reach.

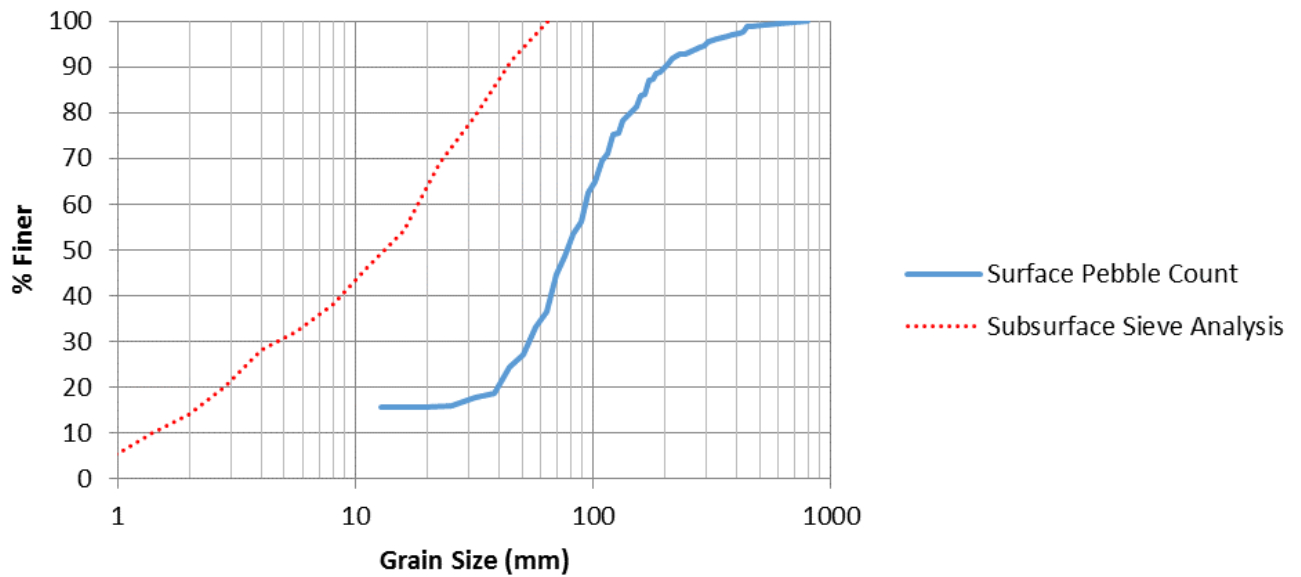


Figure 3.11.3. Surface pebble count and subsurface sieve analysis for Woods Creek reference reach.

Table 3.11.1. Location and description of roughness elements in Woods Creek reference reach.

Location (ft)	Description	Element Size (in)				Protrusion (ft)	Location Notes
19.7	rib	1	10	14	10.5		
		2	6	8.5	11.5		
		3	5.5	20	20.5	0.7 average	
26.9	rib	1	16	24	11.5		
		2	27.5	37	7.5		
		3	11	18	7	0.5 average	
34.8	roughness element	1	10.5	22	13	1.3	7 from RB
		2	bedrock				2.7 from LB
41.0	riffle	1	9	11	5		
		2	6	3.5	8		
		3	10	10.5	10		
		4	8.5	14	6.5		
		5	16	5	6.5		
		6	7.5	105	8	0.8 average	
47.6	cascade	1	19	25	11.5		
		2	18	15	9.5		
		3	23	35	17.5		
		4	34	32	14		
		5	11.5	20	22		
		6	18	36	7.5	2.0 average	
60.0	roughness element	1	BEDROCK				3 from LB
		2	19	27.5	15	1.4	5 from RB
		3	2	20	8	0.8	6.5 from RB
69.9	roughness element	1	19.5	21	11	1.3	2.5 from LB
		2	14.5	20	8	1.0	6 from LB
		3	13	21	8	0.8	5 from RB
77.4	cascade	1	10	13	6.5		
		2	13	19	8		
		3	22	20	13.5		
		4	18	26	11		
83.3	step		33	15.5	13		
			18.8	17	9.5		
			16.5	22	19		
92.8	roughness element	1	12	15	13	1.5	1.8 from LB
		2	18	10.5	13.5	1.2	3.6 from LB
		3	27	21	12	1.7	3 from RB
96.1	rib	1	10	12.5	8.5		
		2	9.5	12	10		
		3	10.5	16	7	0.6 average	

3.11.2 Le Sueur Creek

This example of a hypothetical culvert replacement starts with site assessment in this section, following the section headings of Chapter 3, Site Assessment. The example continues with design of a recessed or embedded culvert in Section 5.5.5, following the flow chart in Figure 5.5.1 to Figure 5.5.4. Data presented in the example is taken primarily from field observations gathered by Brad Hansen and Sara Mielke in November 2010 as part of their work published as Hansen et al. (2011). Existing data has been supplemented by field observations of the present authors in 2018. Note that if this were an actual design situation, changes over the intervening 8 years would mean the previous data should be validated or more likely collected anew.

An aerial photo figure of Le Sueur Creek and road intersection is shown in Figure 3.11.4.

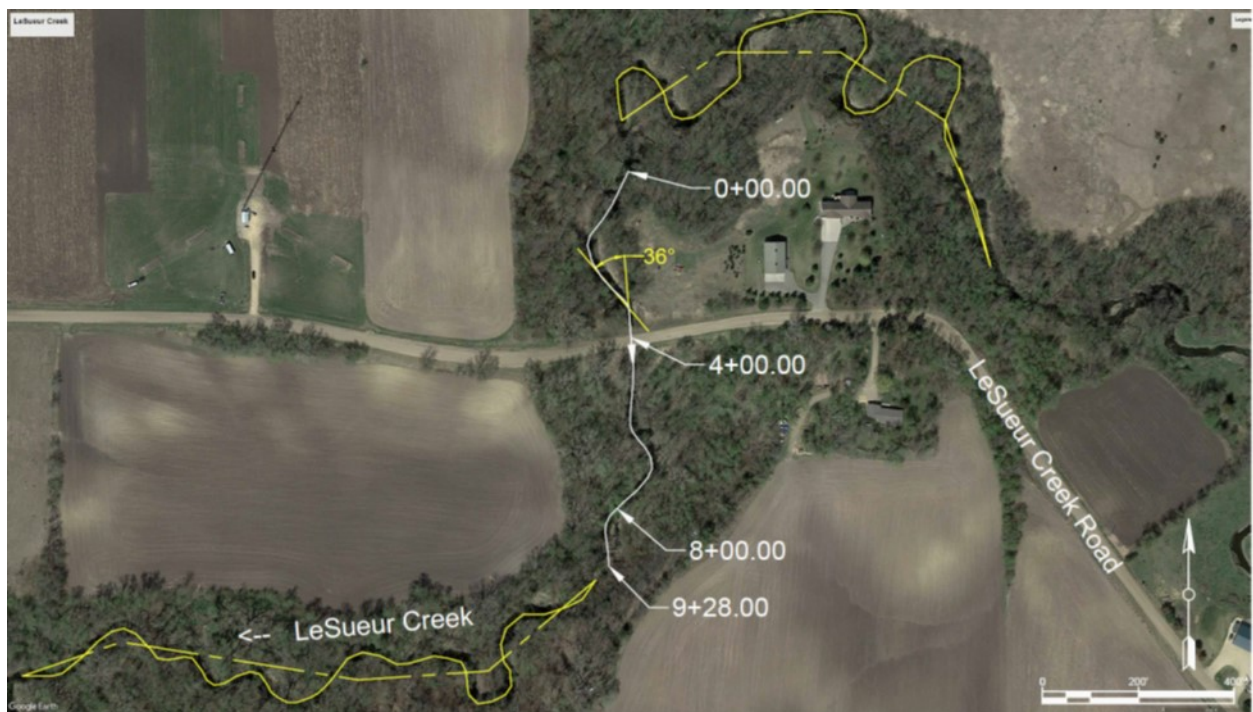


Figure 3.11.4. Aerial photo of Le Sueur Creek site example, Le Sueur County, Minnesota. Flow is from right to left. (Google Earth aerial photo, 2018)

Hydrology

- Estimate Design Flows – using USGS Streamstats (<https://streamstats.usgs.gov/ss/>)
 - Drainage area is 38.25 square miles
 - Q100 for design (1,570 cfs). Note that the prediction interval is 610 – 3,110 cfs.
 - Q1.5 as representative of bankfull (176 cfs).
 - For a low passage flow, assume 95% duration exceedance (1.3 cfs)
- For an actual design, comparison with other flow estimates is recommended.

Channel and Bank Stability

- Banks are generally steep and loamy, with exposed roots (Figure 3.11.5). The bank tops are vegetated with trees mostly intact, although some have fallen in the channel.
- The stream was classified under the Rosgen system as C4, explained in (Rosgen 1996) as, “slightly entrenched, meandering, gravel-dominated, riffle/pool channel with a well-developed floodplain”.
- Assessments of channel and bank stability were undertaken:
 - Pfankuch Stability Index (Pfankuch 1975) as modified by (Rosgen 1996) = 119 (poor) downstream, 123 (poor) upstream.
 - Bank Erosion Hazard Index (BEHI) = 39 (High susceptibility to erosion)
- Foreseeable adjustments: Channel sediment is significantly coarser than bank sediment; lateral adjustments are possible. If bank trees were removed due to a change in landuse, significant erosion would be likely because the tree roots are holding the bank lines. The debris jams, especially downstream of the culvert, are important in maintaining the channel grade and if removed the channel may be more susceptible to downcutting. Further discussion of this topic is located in the continuation of the example in Section 5.5.5 .

Stream Alignment and Sinuosity

- Figure 3.11.4 is an aerial photo of the site. Stationing corresponding with the vertical profile (next item) is shown on the figure.
- Stream alignment to the culvert: The culvert is located on an outside bend, with approximately a 36 degree angle at the inlet (Figure 3.11.4). There is some riprap on the outer bank at the bend. At the outlet there is a slight bend, and also riprap at the outer bank. It would be logical to reduce the inlet angle by rotating the replacement culvert a few degrees counterclockwise. If this is considered, possible downstream effects should be examined including whether directing more flow toward the downstream outside bank is likely to cause instability. Indeed, there is more evidence of scour at the outlet than at the inlet, so keeping the current alignment may be reasonable. If the amount of sediment in the west barrel (inside of bend) were reduced, high flow may be more evenly distributed, reducing outlet scour on the eastern bank (outside of bend).
- Sinuosity is defined by channel distance divided by valley distance. Picking one upstream and one downstream reach, shown in yellow in Figure 3.11.4:
 - Downstream: $1,623 \text{ ft} / 1,287 \text{ ft} = 1.26$, moderately meandering
 - Upstream: $1,736 \text{ ft} / 1,081 \text{ ft} = 1.6$ highly meandering
 - The degree of sinuosity varies; the immediate culvert vicinity is less sinuous than upstream and downstream.



Figure 3.11.5. Riffle and far bank on Le Sueur Creek. (M. Hernick photo August 2018)

Vertical Profile

- A vertical profile (longitudinal profile) of Le Sueur Creek is shown in Figure 3.11.6. The elevation data was taken with a laser level (3 setups) and tape measure and captures the vicinity of the culvert. A sampling of field notes identifying features has been imposed on the profile.
- Ideally, the survey would be longer to encompass a reference reach outside the influence of the existing culvert, or reference reach data could be taken in a discontinuous but nearby reach.
- Slope: Assuming the water surface slope is approximately equal to the EGL, the slope is 0.0019 ft/ft or 0.19%. The slope is fairly uniform both upstream and downstream of the existing culvert but there may be a slight break in slope between 8+00 and 9+00 – more survey data in this area would be helpful to gauge if this is a stable feature or may be a small head cut that could move up stream.
- Features: The channel has a riffle and pool sequence with fairly deep pools especially at bends. A significant amount of tree trunks and branches is present in the channel due to the forested banks, and debris jams appear to add to the stability of the stream. There is a partial riprap weir just upstream of the culvert and some mid-channel aggradation in the vicinity.

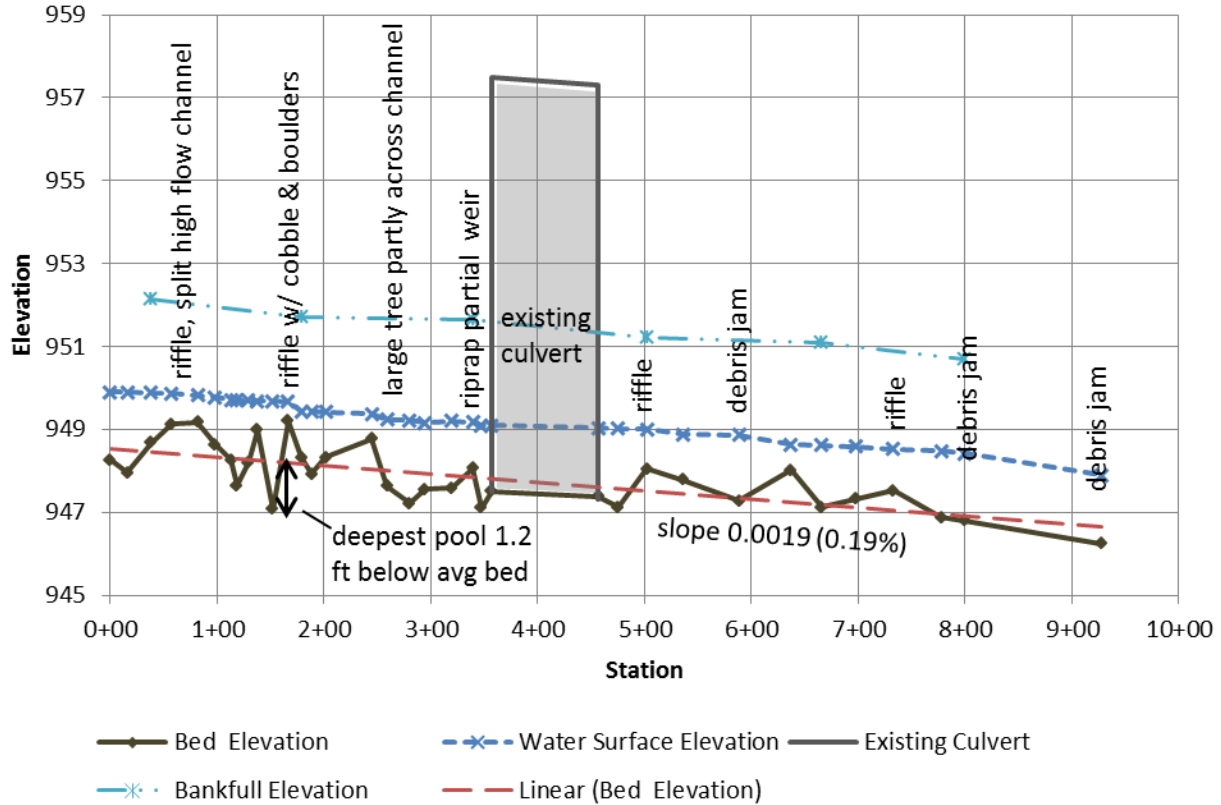


Figure 3.11.6. Vertical profile of Le Sueur Creek example. Station and elevation in feet.

Channel Width and Depth

Channel width and depth was measured in the field (Figure 3.11.7). A cross section is shown in Figure 3.11.8. The bankfull width was determined in the field to be 28 feet, with a maximum bankfull depth of 3.3 ft. The cross sectional area at bankfull is 69 ft², yielding an average bankfull depth of 2.4 ft.

Bankfull measurements were taken in several other locations outside of the influence of the culvert and summarized in Table 3.11.2 below. Three of the four measurements are in close agreement. The outlier (34 ft) was already marked as questionable in field notes, so is not likely a representative section.



Figure 3.11.7. Measurement of bankfull width for Le Sueur Creek example. Deposition of very fine sand just above a slope break was found as a bankfull indicator at the end of the tape measure. The sediment appeared to be deposited this season and subsequently colonized by the fast growing grasses visible in the photo. (M. Hernick photo August 2018)

Table 3.11.2. Bankfull width and depth measurements including bankfull indicators identified, Le Sueur Creek.

Bankfull Width (ft)	Max Depth (ft)	Notes / Indicators
27 ft	3.7	Fine sediment deposition, point bar top elevation
34 ft	4.0	Fine sed., moss transition on bank, pool. Unsure if good spot?
28 ft	3.33	Fine sed. deposition inner bank, outer bank at valley wall, straight section (Figure 3.11.8)
29 ft	3.1	Sediment & vegetation transition line

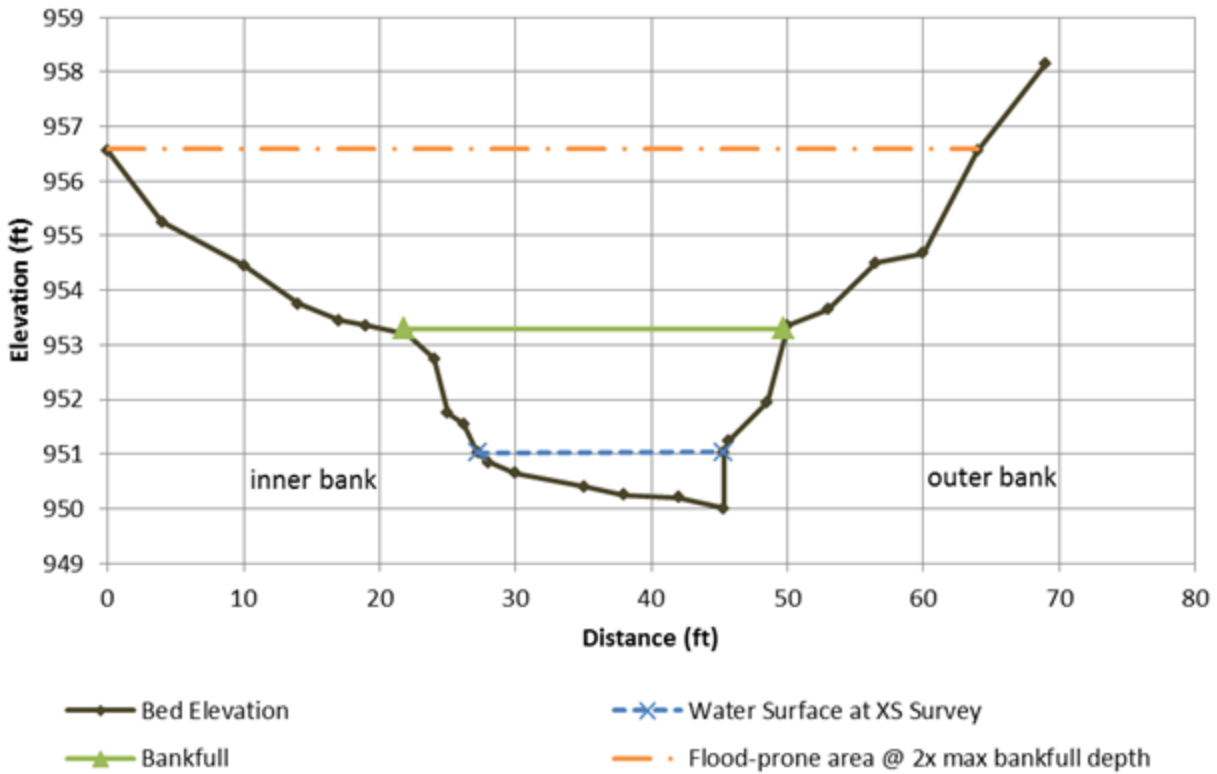


Figure 3.11.8. Example cross section of Le Sueur Creek, taken at a riffle, looking downstream.

For comparison, Table 3.11.3 shows data from regional curves (Appendix E). Le Sueur Creek is in the Lower Minnesota River watershed, which is at the eastern boundary of the Western region. The field bankfull width estimate of 28 ft is within the range of the predicted bankfull width for the Western region (23.7 ft) and within the scatter of data points used to construct the regional curve, indicating bankfull indicators chosen in the field were sufficient.

Table 3.11.3. Bankfull parameter estimates from regional curves for Le Sueur Creek example.

Drainage Area (sq. mi) =	38.25		
	Eastern	Western	
w_{bkf} (ft) =	34.6	23.7	Bankfull width
d_{bkf} (ft) =	2.0	1.8	Bankfull depth (average)
XS Area (ft ²) =	69.4	43.9	Cross-sectional Area

Bed material assessment

A pebble count was done in a riffle section upstream of the culvert. The summary is shown in Figure 3.11.9.

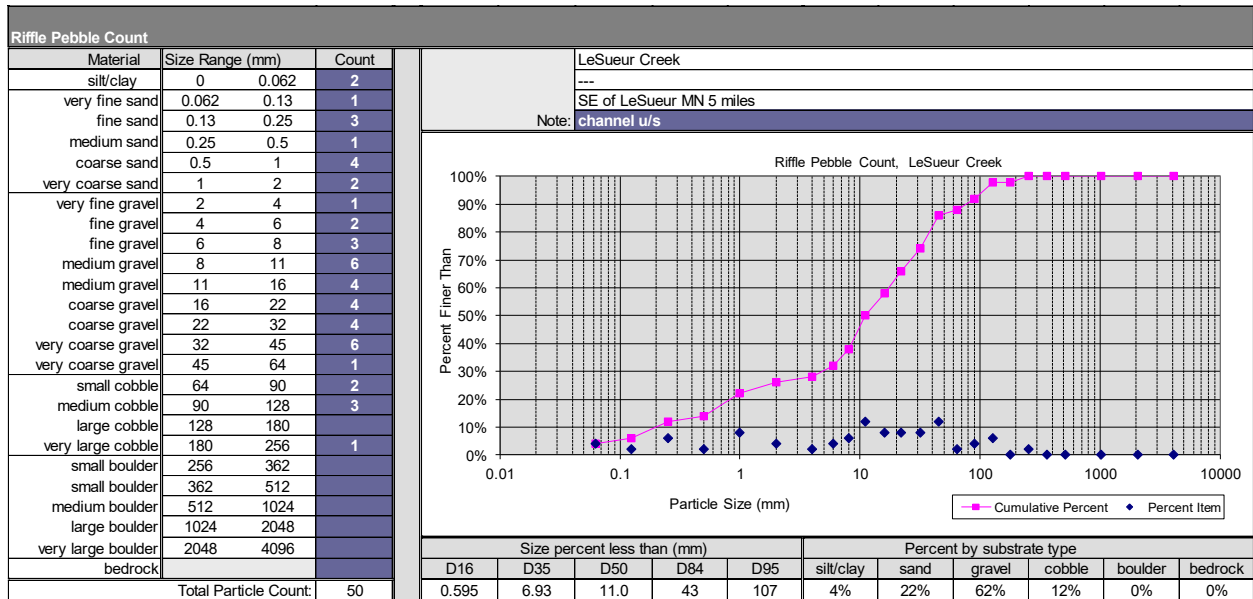


Figure 3.11.9. Riffle particle count for Le Sueur Creek example. The Reference Reach Spreadsheet form used by Hansen et al. (2011) was created by Mecklenburg (1999); see also Powell et al. (2006b).

- Bed material particle size distribution (see Figure 3.11.9)
 - D_{84} is 43mm (very coarse gravel), D_{50} is 11mm (medium gravel)
 - Sediment along banks and settled in pools is finer – sand to silt range.
 - The bed appears to be partially armored with coarser particles evident in riffles and fine sediment deposits in lower velocity areas.
- Bed features, bedforms, roughness
 - Riffle-pool pattern as previously noted. Some riffles include boulders and cobble while others are primarily large to small gravel and thus possibly more mobile.
 - Isolated small to medium boulders and some large cobbles are present but not captured in the count.
- As previously noted, trunks and wood jams are present and contribute to roughness and energy dissipation. Sinuosity and bends also contribute to dissipating energy.
- Just upstream of the culvert is a line of riprap that partially spans the channel (Figure 3.11.10). A mid-channel bar of sand and small gravel has formed upstream of this partial weir. The top of the vegetated sediment in the west barrel is 3 to 4 feet above the east barrel invert, which forces all flow through the east barrel up to that water surface elevation. It is likely the mid channel bar has aggraded due to ponding upstream of this flow constriction.



Figure 3.11.10. View of culvert inlet for Le Sueur Creek example, looking south (downstream). The east barrel on the outside of the bend conveys lower flows. The west barrel is almost hidden by vegetation growing on accumulated sediment. A mid channel bar has aggraded just upstream of a partial line of riprap.

Floodplains

- The crossing is shown in Zone A, Special Flood Hazard Areas Inundated by 100-year Flood, No Base Elevation Shown, on FEMA FIRM panel 27079C0140D, Le Sueur County Unincorporated Areas. Therefore, floodplain regulations apply to the site. A digital FIRM is not available. Checking the MN DNR FEMA Hydraulic Model Download website (link in Section 4.4), a hydraulic model is also not available.
- Entrenchment ratio: referencing the cross section in Figure 3.11.8, the width of the flood-prone area (valley width at two times the maximum bankfull depth) is 64 ft. The entrenchment ratio is 64 ft flood prone area width / 28 ft bankfull width = 2.3, classified as slightly entrenched (Section 3.7).

Debris and Ice

- The surrounding forest is dominated by mature maple trees
- Woody debris is present in the stream, including large trees. The largest trunks in the stream appear to be relatively stable while medium diameter (6 to 12 inch) logs look like they may be mobile at high flows. An example of a wood jam is shown in Figure 3.11.11.
- The existing two barrel culvert could be susceptible to catching woody debris; the sloped end sections may help floating wood to ride up the slope at high flows.
- Ice buildup at the culvert is not expected to exceed normal ice conditions for the region.



Figure 3.11.11. Example of wood jam on Le Sueur Creek, located at station 6+40 on the longitudinal profile. (M. Hernick photo, August 2018).

Geotechnical Considerations

A geotechnical investigation has not been undertaken at the site; subsurface conditions are unknown. There is no visible evidence of bedrock.

Aquatic Organism Data

No site-specific aquatic organism data is known. Le Sueur Creek is not a designated trout stream.

CHAPTER 4: ANALYSIS AND TOOLS

This chapter is a collection of tools aimed at helping to understand and analyze aspects of a stream that were not often considered in traditional culvert design but become important for AOP and stream connectivity designs. The process of energy dissipation into turbulence is discussed in the initial section (Section 4.1), including the scale and mechanisms of flow resistance in several types of streams, as well as the importance of the scale of roughness in facilitating AOP. Hydraulic analysis is covered next (Section 4.2), focusing on software that accounts for sediment beds through culverts, as well as methods for estimating roughness 'n' coefficients for natural materials. Sediment transport, specifically the application of critical versus applied shear stress to the determination of the stability or movement of channel materials, is discussed in Section 4.3 . Resources on regulatory floodplains (Section 4.4) and structural and geotechnical design (Section 4.5) are noted. The final Section (4.6) notes suggested items to document as part of the design process to assist in future culvert maintenance and assessment of whether the culvert is functioning as intended for stream connectivity and AOP.

4.1 ENERGY DISSIPATION

As water flows through a stream channel, the available potential (gravitational) energy due to the difference in elevation between an upstream and downstream point on the water surface, and kinetic energy due to velocity, is continuously being dissipated through friction. As the water interacts with the bed, banks, and material in the flow, eddies are created and there is a cascade of energy to diminishing sizes of turbulence, until the mechanical energy of the flowing water is dissipated into heat and sound. Throughout the process, energy is conserved.

In a culvert designed for AOP and stream connectivity, energy should be ideally dissipated in a stream-like manner – that is, at a similar rate (slope of EGL), and if possible with similar mechanisms or roughness elements as the natural stream channel. The concept of energy grade line or EGL is covered in most hydraulics texts, and Section 3.4.1 . Equation 4-1 and Figure 4.1.1 illustrate the energy grade line. Variables are defined in the paragraph below the figure.

$$y_1 + z_1 + \frac{V_1^2}{2g} = y_2 + z_2 + \frac{V_2^2}{2g} + h_L \quad (\text{Equation 4-1})$$

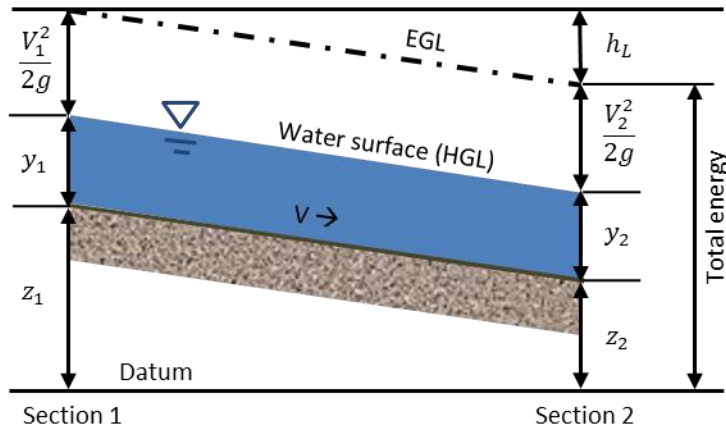


Figure 4.1.1. Sketch of energy grade line concept for open channel flow. Adapted from FHWA HDS 4, (Schall et. al. 2008).

At any point the elevation of the EGL is the sum of the potential and kinetic energy. Potential energy is represented for free surface or open channel flow by the sum of the depth of flow (y_1 and y_2) plus the distance to a datum (z_1 and z_2). Kinetic energy or velocity head of the flow, represented by the $(V^2/2g)$ term where V = velocity and g =acceleration of gravity. The term h_f represents friction loss between sections 1 and 2. In subcritical flow conditions typical of natural streams, acceleration of the water flow such as in a contraction or bend increases velocity head while reducing depth (potential energy). At a deceleration of flow such as at an expansion in cross section, depth increases and the velocity head is reduced.

The slope of the EGL is a measure of how quickly energy is being dissipated. A sharp drop in EGL indicates that significant energy is being dissipated, typically in a region of high turbulence. For design of a culvert which incorporates elements to promote natural stream function (Section 2.4), patterns and rates of energy dissipation should be similar to those found in a natural stream. Part A.3.6 of Appendix A of the US Forest Service Stream Simulation guide (FSSSWG 2008) lists three components of flow resistance at work in streams: boundary resistance, channel resistance, and free-surface resistance. *Boundary resistance*, or surface resistance, is made up of grain roughness of individual particles, which is dependent on particle size and how far particles project into the flow, form roughness associated with channel bedforms, and vegetation roughness, which varies with the type, density, height, and rigidity of vegetation. *Channel resistance*, has to do with the shape of the channel, including bends, bank non-uniformity, cross-section shape, and variability in slope such as in a series of drops and pools. Energy losses associated with surface waves, hydraulic jumps, and plunges can be categorized as *free surface resistance*. A portion of the energy from the flowing water may be transferred to the bed and banks. If the shear force on a particle is greater than the forces resisting movement, the particle will become entrained in the flow. Moving sediment also dissipates stream energy (see Section 4.3 on sediment mobility).

The relative significance of any component of resistance depends on the composition of the channel as well as flow characteristics such as depth and velocity. Table 4.1.1 lists typical contributing roughness for

several channel types. Boundary roughness is often the most significant factor, especially in cobble and gravel bed channels, where individual particles influence energy loss. In sand bed channels, form roughness, associated with bedforms such as ripples and dunes is more significant than individual particles in dissipating energy (Figure 4.1.2). Vegetation often plays a significant role in energy dissipation, especially in low gradient streams, both along the banks and on the floodplain. Channel bends (sinuosity) and associated features such as point bars also dissipate energy.

For the purposes of hydraulic analysis, the various components of flow resistance are often lumped into one roughness factor, typically 'n' in the Manning equation. Since resistance varies, it is appropriate to estimate different 'n' values in different conditions, such as low flow and flood flows. Refer to Section 4.2.2 for discussion of selecting 'n' values.

Table 4.1.1. Contributing roughness elements by bed material. (From Table 6.5, FSSSWG 2008)

Bed material	Dominant roughness elements	Sediment	Reference stream characteristics
Silt to clay	Sinuosity, banks, bed irregularities	Fine sediment moves over immobile bed at moderate flows depending on size. May be thin layer of alluvium over immobile bed.	Channel in cohesive material
Sand to medium gravel	Sinuosity, mobile bedforms, banks. Small debris may provide structure.	Live bed, significant sediment transport at most flows	Dune-ripple
Fine to coarse gravel	Bars, pools, grains, sinuosity, banks.	Bed is often armored; usually mobilizes near bankfull.	Pool-riffle (mobile)
Coarse gravel to cobble	Bars, pools, grains, sinuosity, banks.	Finer sediment moves over immobile armor at flows near bankfull. Armor layer mobilizes at higher flow	Pool-riffle (intermediate mobility)
Gravel to cobble, usually armored	Grains, banks	Mobility may vary, see pool-riffle descriptions.	Plane-bed
Cobble to boulder	Steps, pools, banks. Debris may add significant structure.	Fine material moves over armor at frequent flows. Bed-forming rocks may move at higher flows >Q30	Step-pool
Boulder	Grains, banks	Smaller bed material moves in floods higher than bankfull. Large rocks immobile in flows <Q50.	Cascade
Bedrock	Bed, banks	Bedload movement depends on size. Wood can strongly affect sediment mobility.	Rock surface, may be thin layer of alluvium

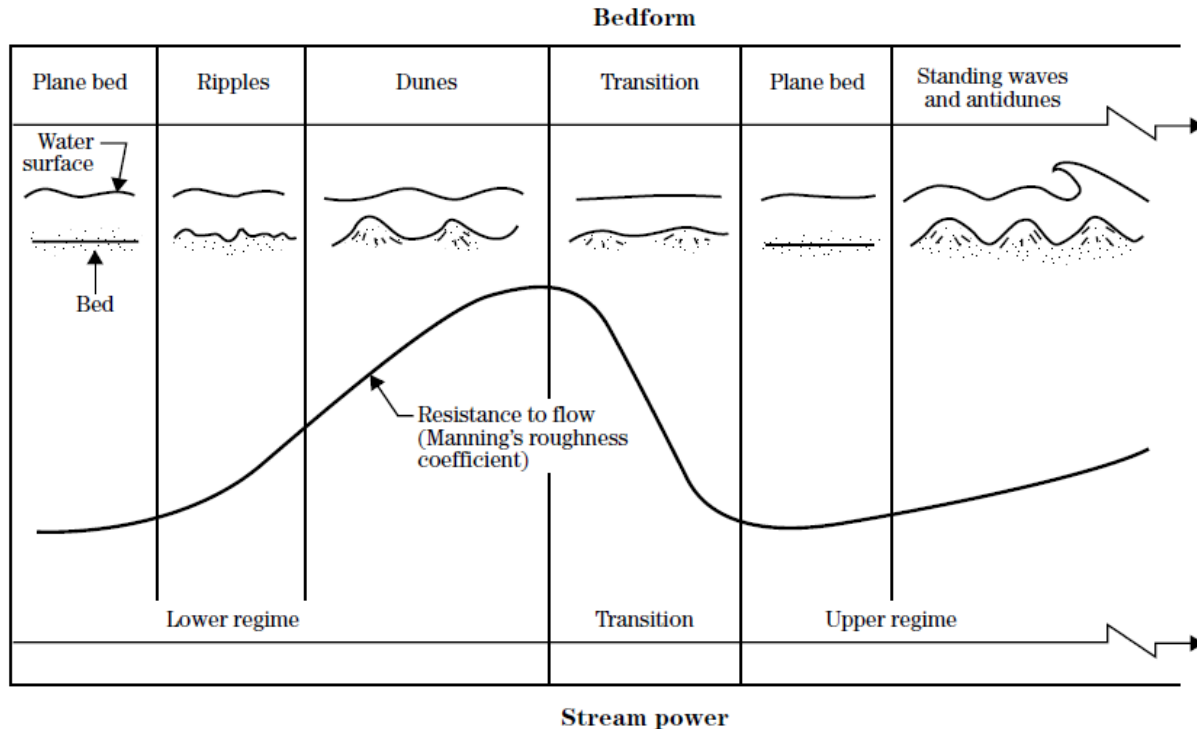


Figure 4.1.2. Bedforms for sand bed streams. (From Figure 6-10, NRCS NEH Part 654 (NRCS 2007))

One of the elements of traditional culvert design for hydraulic efficiency is a goal of minimizing the conduit (pipe) size per unit of flow, primarily by minimizing the flow resistance of the culvert. As an example, if the culvert is operating under outlet control on account of the barrel, the barrel roughness may possibly be reduced by choice of a smoother material, or the slope may be increased, and if the culvert is operating under inlet control, the inlet can be designed to minimize entrance losses, represented by lower entrance coefficient k_e . The result is that the energy of the flow at the culvert outlet is usually greater than can be absorbed by the stream channel, with the common result of the creation of a scour hole, which deepens until an energy balance is achieved. In some cases the plunging flow of the scour hole itself dissipates enough energy to avoid structural damage or undermining of the culvert, but in others the excess energy must be dissipated at the culvert outlet, commonly with a riprap apron as outlet protection.

The top of Figure 4.1.3 illustrates an example of a common energy grade line situation. Far upstream of the culvert, the EGL is parallel to the streambed slope; energy is dissipated relatively continuously. Just upstream of the culvert in the ponded headwater the slope of the EGL is less than the average slope of the stream reach. Sediment may be deposited in this region, leading to aggradation. At the culvert entrance, the EGL drops sharply due to contraction of flow. This is a zone of high velocity and high turbulence. If bed material is present in the culvert, this is a primary area of scour. In the culvert barrel, normal flow is established; in this case, the depth is below the critical depth, so the flow is supercritical. Velocity is high due to the relatively smooth culvert barrel, approximate Manning's $n=0.013$, versus an approximate $n=0.028$ for a stream channel at the same discharge, and much less energy is dissipated in the barrel than would be in a stream channel of the same length. At the end of the culvert, this excess

energy is dissipated in part by a hydraulic jump and in part by a scour pool, with a corresponding rapid drop in EGL. Downstream of the scour pool the slope of the EGL may again be parallel with the bed slope as the rate of energy dissipation is again relatively continuous.

Of course, within a stream there may be significant local variation in rates of energy dissipation, even within one cross-section of the stream. A variety of velocity and turbulence is important in providing areas for organisms to swim and rest. Some culvert designs attempting to provide AOP rely on roughness elements such as baffles or boulders to reduce velocities by dissipating energy into turbulence, sometimes called a roughened channel design. This principle should be applied carefully; it is possible to convert a velocity barrier into a turbulence barrier to AOP. Recognizing this, Washington Department of Fish and Wildlife specifies a maximum Energy Dissipation Factor (EDF) in ft-lbs per cfs for design of roughened channels and baffles (Barnard et al. 2013). The scale of turbulence created by roughness elements is also important. In a 2010 study on the swimming behavior of creek chub, Tritico and Cotel (2010) found that the stability of the swimming fish was affected by eddy diameters approaching fish lengths.

The top culvert example in Figure 4.1.4 would likely present several barriers to AOP that may be understood in terms of the rate at which energy is dissipated. High head losses (energy dissipation) at the entrance and exit are likely to result in a barrier of high velocity and excessive turbulence. Low relative head loss in the smooth barrel is likely to result in excess velocity with corresponding insufficient depth barriers. Shallow depth, high velocity, and high turbulence are three of the most common barriers to organism passage. All three of these conditions may exist in rapidly changing flow where a large amount of kinetic energy is being converted to turbulence such as at a hydraulic jump. Sediment transport rates will also be disconnected from the stream as mentioned in the example.

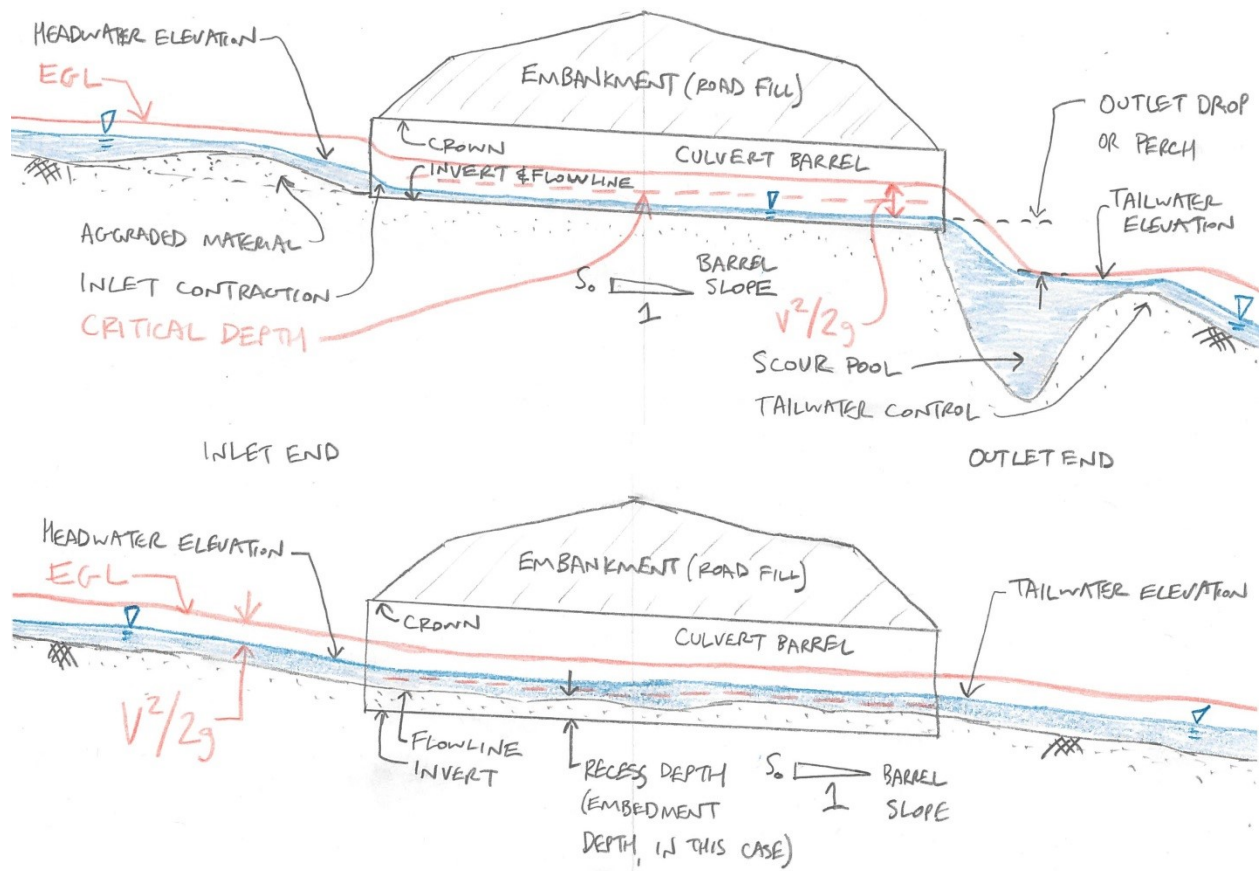


Figure 4.1.3. Comparison of EGL profiles in idealized culverts. A hydraulic conveyance design is shown above, with large EGL changes at the entrance and exit and supercritical barrel flow. Below, the slope of the EGL is relatively continuous from upstream to downstream, which is advantageous for AOP and stream connectivity.

4.2 HYDRAULIC Analysis

Analysis of hydraulics is of central importance in culvert design strategies that emphasize AOP. Traditional techniques such as nomographs, which are generally set up for full pipe or inlet control, are not well suited to assessing questions of AOP suitability and sediment transport at bankfull flows or lower flows. Culvert designs to address AOP and sediment issues often fall in the roughness (barrel) controlled open channel flow regime, which can require much iteration with hand calculations. However, most hydraulic design is now done using computer software, which performs complex calculations quickly, provided the designer has specified accurate input data. Typical output that can be used directly or indirectly are: EGL slope, depths, velocities (usually average velocities), and shear stress.

Several software programs are listed in the following subsection (4.2.1), including brief information on capabilities related to calculations for AOP and sediment transport. A reasonable estimation of roughness or flow resistance (Manning's n) is especially important in culverts that incorporate natural channel materials or are expected to fill in with sediments. Several resources are listed in Section 4.2.2.

Several good practices when working with hydraulic models include:

- Use reliable input data. Keep notes of interpolation or assumptions made to get the program to run.
- Use the same analysis technique or program for analysis of an existing culvert (or channel) and the design condition. In this way, the methods of calculation and built-in assumptions will be the same before and after.
- Use a simpler model that is well understood by the user rather than a more complicated program with uncertain inputs. In many situations, more than one model or method can be used together, or as a check.
- Do a sensitivity analysis. In most hydraulics programs it is easy to run multiple scenarios in order to better understand how a proposed culvert is likely to respond to difference in flow estimates or other parameters such as 'n'. For example, if the bankfull flow is 60 cfs with an estimated uncertainty of 30%, how does the culvert respond at $60 \times 1.3 = 78$ cfs and $60 \times 0.7 = 42$ cfs?

4.2.1 Hydraulic Analysis Software

The list of programs below is provided for reference and does not represent an endorsement of any particular software. The list is not comprehensive, but covers some that are typically used. Some programs such as HY-8 analyze only the culvert, while others such as HEC-RAS require a sufficient stream reach downstream and upstream to make calculations at and through a culvert. The level of detail in required input data varies, as does the level of detail of the output. Matching the complexity of the site to the complexity of the model is good practice, for instance, streams with wide floodplains or multiple channels can benefit from 2D analysis. Table 4-1 in Hydraulic Design of Safe Bridges, FHWA HDS 7, (Zevenbergen et al. 2012) suggests whether 1D or 2D modeling is appropriate for a number of hydraulic conditions encountered at bridge crossings. The recommendations may be useful to guide model selection at culverts as well.

HY-8 – Federal Highway Administration (FHWA).

(<https://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/>)

- Culvert analysis for one or more stream crossings (may include multiple culverts). Check to be sure that all inflow is accounted for between the multiple culverts.
- Supports embedded culverts with different resistance factors (Manning's n) for bed material and culvert structure, provides a calculation of 'n' from particle size distribution.
- Low flow (minimum 1 cfs) and AOP calculations are included.
- AOP routine requires input of upstream and downstream cross sections.
- The low flow hydraulics routine includes inputs for minimum threshold depth and maximum threshold velocity, potentially useful for species-specific or hydraulic design methods.

HEC-RAS – US Army Corps of Engineers (<http://www.hec.usace.army.mil/software/hecras/downloads.aspx>)

- One- dimensional step-backwater river model, latest versions also have a 2-d component.

- Often used as standard for regulated floodplains (FEMA). Hydraulic models used to develop FEMA models are available for some Minnesota streams, refer to Section 4.4 .
- Used to model stream reaches, as well as culverts and bridges.
- Has procedures for steady and unsteady flow, sediment analysis, and bridge scour. (Note that the scour routine within HEC-RAS is not recommended for use by MnDOT Bridge Office.)
- Generates detailed output data. Substantial cross section data is required.
- Powerful and widely used software, care is needed in selecting appropriate cross section locations, ineffective flow areas, and calculation options.

SRH-2D, Sedimentation and River Hydraulics – US Bureau of Reclamation (USBR)

(<https://www.usbr.gov/tsc/techreferences/computer%20software/models/srh2d/index.html>)

- Two-dimensional river and floodplain model also used by FHWA and available to state DOTs.
- Uses Surface-water Modeling System (SMS) software. Can perform extensive topographic and cross section data and processing.
- Two-dimensional modeling may be important for wide floodplains and crossing where 1-d flow is not representative.
- Powerful but has a learning curve.

WinXS Pro – USDA Forest Service (<https://www.fs.fed.us/biology/nsaec/products-tools.html>)

- Tool to analyze cross section data for hydraulic and sediment transport analysis.
- Designed for slopes greater than 1%.

FishXing – USDA Forest Service (<https://www.fs.fed.us/biology/nsaec/fishxing/>)

- Calculates depths, velocities and water surface profiles for a culvert at high and low fish passage flows (not peak design flows).
- Allows embedded culverts with different roughness for bottom versus sides.
- Results are directly compared to literature-based or user-defined fish swim speeds to estimate whether a particular design and flow is passable for a particular species or life stage.
- Minimum required slope of 0.3%

HydroCAD – HydroCAD Software Solutions LLC (<http://www.hydrocad.net/>)

- Widely used commercial software for hydrology and hydraulics calculations for and stormwater and drainage design.
- Version 9.1 and higher supports partially-filled pipes, but only one 'n' value.

FHWA Hydraulic Toolbox. (<https://www.fhwa.dot.gov/engineering/hydraulics/software.cfm>)

- Contains a variety of relatively straightforward calculators including channel analysis, rock/sediment gradation, rational method hydrology, riprap analysis, and bridge scour analysis.

USDA NRCS Cross-section Hydraulic Analyzer (<http://go.usa.gov/0Eo>)

- Spreadsheet tool to apply Manning's equation to a single cross section at normal depth.
- Inputs: cross section data, profile slope, roughness (Manning's n), bank stations. Outputs: rating table including area, wetted perimeter, hydraulic radius, discharge, velocity, shear stress, and more.
- Can compute a relative roughness (n) which varies with flow depth based on (Limerinos 1970).

4.2.2 Roughness Factor, ' n '

Manning's equation is used to estimate velocity in a stream or pipe utilizing a roughness coefficient (n), where $V = 1.49/n * R^{2/3} S^{1/2}$ (V = velocity, R =hydraulic radius and S =slope). Culvert designers are familiar with choosing representative roughness or Manning's ' n ' factors for culvert materials such as concrete or corrugated metal, but often less familiar with estimating friction factors for natural channels or stream channels constructed within culverts. Table 4.1 of the MnDOT Drainage Manual lists reference values for ' n '. Online help for US Forest Service's FishXing software includes a table of ' n ' values for many situations, taken from Ven Te Chow's classic 1959 book, Open-channel hydraulics:

http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm

Appendix C of FHWA HEC 26 (Kilgore et al. 2010) includes several methods for estimating ' n ' from particle size, and methods for estimating the friction factors for sand bed streams under various flow regimes. However, for many low gradient streams, woody debris and vegetation, and not the substrate grain size, control the channel roughness. If correlated flow and water level observations such as high water marks exist, these can be used to back-calculate ' n ' at the given conditions. Hydraulic controls which induce tailwater may be far downstream of the subject culvert on low gradient streams.

Another useful tool for flow resistance estimation is the USDA Forest Service's Stream Channel Flow Resistance Coefficient Computation Tool (<https://www.fs.fed.us/biology/nsaec/products-tools.html>). This spreadsheet-based tool provides comparison of tabular, photographic, and quantitative predictions of flow resistance (Manning's n or Darcy-Weisbach f) appropriate for the slope, particle sizes (D_{50} , D_{84}), and hydraulic radius. The download package includes several in-depth references on flow resistance coefficients.

Although widely used, obtaining reliable results from the Manning's equation depends largely on the representativeness of the slope, hydraulic radius, and roughness ' n ' estimate. Section 4.3.3 of the MnDOT Drainage Manual (MnDOT 2000) recommends calibration with local high water marks or gauged streamflow data, as well as a method to subdivide the channel and floodplain by roughness and features. For a channel, representative ' n ' values will be different as the flow depth (hydraulic radius) changes, approaching constant values when the hydraulic radius as compared to the scale of the boundary roughness (bed material, etc.) is sufficiently large (NCHRP Report 734, Ch 7, Tullis 2012). Chapter 2 of the NCHRP 734 report presents recommended entrance loss coefficients (k_e) based on model studies for buried invert or embedded culverts differing from entrance loss coefficients of traditional culverts.

4.3 BED SEDIMENT STABILITY AND MOBILITY

Observing and predicting how and when sediment moves through streams is a field of considerable study and very important in the designs of culverts for AOP and stream connectivity. Of the factors that influence sediment movement, the particle size and size distribution (Section 3.6), channel energy slope (Section 3.4.1), and water depth (Sections 3.5 and 4.2) are most significant. Sediment packing and surface armoring may also influence under what conditions sediment moves on a streambed. In this section, sediment transport refers to the process of erosion and deposition of streambed and bank materials in relative equilibrium or gradual change. Situations of non-equilibrium sediment events can include headcuts and channel degradation or aggradation in unstable streams and should be examined with respect to channel bed and/or bank stability (Section 3.2). Several additional references on bed stability and mobility are, *Stability Thresholds for Stream Restoration Materials* (Fischenich 2001), FHWA HDS 6 (Richardson et al. 2001), and FHWA HEC 20 (Lagasse et al. 2012).

In designing a culvert to be compatible to a stream, and thus minimize barriers to AOP, important questions regarding the sediment transport are related to the stability or mobility of sediment particles:

- At what flows is the existing channel bed mobile? At what flows (if any) is it stable?
- If sediment (bed material) is placed inside the culvert, how does the mobility of the sediment in the culvert compare to the mobility of the sediment in the existing channel? Will the placed and natural sediments become mobile at the same flows that the existing channel is mobilized?
- If grade controls or key bed pieces are to be used, will they remain stable at the design flood?

Two processes of sediment transport are bedload, which refers to sediment rolling, sliding or moving by saltation (jumping or bouncing) along the bed surface, and suspended load, which refers to particles suspended by turbulence in the stream and moving at the speed of the stream flow. This section deals primarily with bedload sediment, especially as it relates to culvert design.

The movement of sediment is related the energy available in the stream (Section 4.1). During flood flows, bed material that is normally stationary (stable) may become entrained by the flow and become mobile. As flows drop, there is no longer enough energy to keep particles entrained, and they settle and deposit. In assessments of sediment movement, the D_{84} particle, or particle with diameter larger than 84% of all particles by mass, is often noted as a particle of interest since in a mixed-size bed; larger particles such as the D_{84} and D_{95} often have significant influence over the bed movement. The frequency of movement of the D_{84} , or of any sediment particle, depends on the frequency at which hydraulic forces from the stream flow overcome the resistance of the particle to motion. In a high-gradient stream with step-pool pattern, the D_{84} particle may move on the order of decades. In a pool-riffle type stream with moderate to low gradient, the D_{84} particle may move every several years. A sand bed stream may be transporting sand grains as bed material during almost all flows; during high flows the sand can be suspended, deepening the channel, then re-deposited, as flood flows recede.

In a stream with an armored bed (Section 3.6), two phases of bedload transport are observed. Phase I bedload transport refers to the transport of fine sediment (silt, sand) over the immobile armor layer.

Phase II bedload transport occurs when the armor layer itself is mobilized or “breached”, or in streams where there is no effective armor layer (Gubernick, Higgins, and Gran 2017).

An analysis of the mobility/stability of bed material both in the stream channel and within the culvert, including comparing the values, is suggested for culverts covered by this document. Conducting a basic analysis of bed stability will help a designer know what to expect in terms of sediment movement.

Stability analysis is especially important in the following situations (Gubernick, Higgins, and Gran 2017):

- Steepened channel (design slope greater than existing slope)
- High floodplain conveyance with significant contraction to a culvert
- High entrenchment ratio (Section 3.7)
- Unstable or degraded channel
- For stability of key bed or grade control features
- For stability of bank material

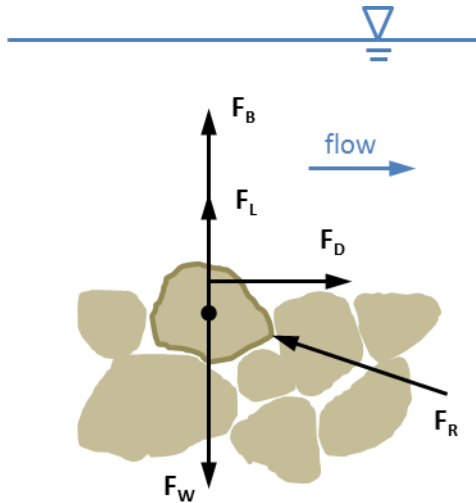
Expectation of the frequency of sediment movement may be applied to other areas of culvert design as well. For example, a metal culvert placed on a stream with a frequently mobilized fine gravel bed would have a much shorter life expectancy than the same metal culvert used in a stream where bed materials move infrequently, and hence may not be the optimal choice for the first stream.

There are two general methods to estimate bed stability / mobility, explored in the following sections:

1. Critical and applied shear stress
2. Critical unit discharge

4.3.1 Critical and applied shear stress

Figure 4.3.1 is a free body diagram of an individual sediment particle in the top layer of a streambed with driving and resisting forces in balance. In practice, the forces are computed and used as shear stresses acting on an area of the bed. If the applied shear stress exceeds the critical shear stress for a given particle, the particle will begin to move and become entrained in the flow. This analysis is best applied at riffles to determine or check the size of particles moved by the stream.



Forces and proportionality:

Buoyant force: $F_B \sim \gamma d$

Lift: $F_L \sim \tau_0 d$

Drag: $F_D \sim \tau_0 d$

Weight: $F_W \sim (\gamma_s - \gamma) d$

Resisting force: F_R

where,

d = particle size, ft

γ = unit weight of water, lb/ft³

γ_s = unit weight of sediment, lb/ft³

τ_0 = applied shear stress, lb/ft²

Figure 4.3.1. Forces on a streambed particle (adapted from Figure 7.4, Julien 1995)

4.3.1.1 Applied shear stress

For steady, uniform, two-dimensional flow, the average boundary shear stress (applied) shear stress is estimated based on the stream parameters as:

$$\tau_o = \gamma R S \quad (\text{Equation 4-2})$$

where,

τ_o = average boundary shear stress, lb/ft²

γ = unit weight of water, lb/ft³

R = maximum hydraulic radius, ft (often approximated by y = maximum depth, ft, if width to depth ratio is sufficiently large)

S = energy slope, ft/ft

(from eqn. 7.9, FHWA HEC 26, Kilgore et al. 2010)

The applied shear stress should be calculated for the scoured channel or active channel width, which may be narrower than the bankfull width. Referring to Taylor and Love (2003), Kilgore et al. (2010) define the active channel as the channel identified by the ordinary high water (OHW) mark. The OHW mark is “the elevation delineating the highest water level that has been maintained for a sufficient period of time to leave evidence on the landscape.”

Flow within a culvert barrel is typically not uniform; therefore, hydraulic radius and slope can vary in the longitudinal direction. In cases with shallower mid-culvert flow, for instance, inlet control and high tailwater, shear stress should be calculated at the minimum in-culvert depth. This can be conservatively estimated by the normal depth (Kilgore et al. 2010, pg. 7-14). The highest applied shear stress should be used for comparison to the critical shear stress to determine if the particle in question will move under the calculated conditions. Note that in areas of high flow complexity (e.g. culvert inlet and outlet), sediment mobility (scour) can vary based on the turbulence created by the inlet or outlet geometry (Ho

et al. 2013). If inlet or outlet areas of the culvert are of particular concern, or if the approach flow is not aligned with the culvert barrels, more sophisticated modeling may be needed (i.e. 2- or 3-D models) to predict sediment mobility.

In the case of pressure flow, the appropriate depth value to calculate applied stress is the height of the hydraulic grade line (HGL) above the bed, calculated in Equation 4-3 as the energy grade line (EGL) elevation minus the bed elevation (Z_{bed}) minus the velocity head (FHWA HEC 26 pg 7-17, Kilgore et al. 2010).

$$y = (EGL - z_{bed}) - \frac{V^2}{2g} \quad (\text{Equation 4-3})$$

4.3.1.2 Critical shear stress

Critical shear stress, the shear stress at the threshold of movement, is often calculated using the Shield's equation. If stability of the bed is desired at a given flow (applied shear stress), the critical shear stress can be referred to as the maximum permissible shear stress, τ_p . Other equations for critical shear stress have been developed; it is up to the designer to ensure the chosen analysis methods are appropriate to the stream and site. FHWA HEC 26 (Kilgore et al. 2010) recognizes three cases for critical shear stress for non-cohesive (i.e. granular) sediment as shown in Table 4.3.1

Table 4.3.1. Formulae for critical (maximum permissible) shear stress in non-cohesive sediments. Equations from Kilgore et al. 2010. These equations are based on representative grain sizes, D_{50} , D_{75} , and, D_{84} (the median, 75th, and 84th percentile, respectively).

Particle size	Equation	Notes
$D_{75} < 0.05$ inch (1.3 mm)	$\tau_p \left(\frac{lb}{ft^2} \right) = 0.02$ $\tau_p \left(\frac{N}{m^2} \right) = 1.0$	Estimate for fine-grained non-cohesive soils; May considerably overestimate critical shear for fine-grained materials; see Table 4.3.2.
0.05 inch (1.3 mm) < D_{75} < 2 inch (50 mm)	$\tau_p \left(\frac{lb}{ft^2} \right) = 0.4 D_{75}(inch)$ $\tau_p \left(\frac{N}{m^2} \right) = 0.75 D_{75}(mm)$	Coarse grained non-cohesive soils
0.25 inch (10 mm) < D_{84} < 10 inch (250 mm) (range from FSSSWG 2008, Section 6.4.4)	$\tau_p \left(\frac{lb}{ft^2} \right) = \tau_{50}^* (\gamma_s - \gamma) D_{84}^{0.3} D_{50}^{0.7}$ (Modified Shields Equation)	Non-uniformly graded natural bed materials; equation only valid for bed slope $\leq 5\%$; $D_{84}/D_{50} \leq 30$; τ_{50}^* = Shields parameter for D_{50} particle size); γ_s = specific weight of the stone, lb/ft ³ (N/m ³) γ = specific weight of the water, ~62.4 lb/ft ³ (9810 N/m ³)

The Shields parameter τ^* is based on the D_{50} and is read from the Shield's diagram, calculated based on the angle of repose of the bed sediment, or read from the table below (Table 4.3.2). An equation for cohesive bed stability is given in Appendix D of FHWA HEC 26 (Kilgore et al. 2010).

Table 4.3.2. Angle of repose, Shields parameter, and uniform bed critical shear stress for non-cohesive sediment, adapted from Julien (1995).

Particle class		Particle size D (mm)	Angle of repose ϕ (degrees)	Shields parameter τ^* [note 1]	Critical shear τ (Pa) for uniform bed [note 2]	Critical shear τ (lb/ft ²) for uniform bed [note 2]
boulder	very large	2048	42	0.054	1791	37
" "	large	1024	42	0.054	895	19
" "	medium	512	42	0.054	448	9.4
" "	small	256	42	0.054	224	4.7
cobble	large	128	42	0.054	112	2.34
" "	small	64	41	0.052	54	1.13
gravel	very coarse	32	40	0.050	26	0.54
" "	coarse	16	38	0.047	12	0.254
" "	medium	8	36	0.044	5.6	0.118
" "	fine	4	35	0.042	2.72	0.057
" "	very fine	2	33	0.039	1.26	0.026
sand	very coarse	1	32	0.030	0.48	0.0100
" "	coarse	0.5	31	0.033	0.27	0.0055
" "	medium	0.25	30	0.048	0.193	0.00403
" "	fine	0.125	30	0.072	0.146	0.00306
" "	very fine	0.0625	30	0.110	0.111	0.00232
silt	coarse	0.03125	30	0.166	0.084	0.00176
" "	medium	0.015625	30	0.252	0.064	0.00133
Notes:						
1. τ^* calculated from Julien (1995) equations 7.4b-d for non-cohesive (granular) material with specific gravity (SG) of 2.65 at 20°C (68°F).						
2. Critical shear stress τ shown in the two columns at right is calculated for uniform sediment of size D, where $\tau = \tau^* \cdot D \cdot (SG-1) \cdot g$						

With hydraulic parameters (depth, energy slope) for several flows, a spreadsheet can be developed to calculate applied and critical shear stresses for particles to determine under what flows certain particles (D_{84} , D_{50} , etc.) mobilize. Finally, if a mix of sediment material is to be developed to fill in a culvert, it is important to use the same methods and assumptions to evaluate allowable shear stress for both existing and design particles.

4.3.2 Critical unit discharge

The critical unit discharge method of estimating mobility / stability was developed by Bathurst (1987) and is similar in principle to the shear stress method discussed above. A particle will move if the driving

force based on the discharge per unit of active channel width ($q=Q/w$) is greater than threshold resisting force, which is based on the properties of the particles and the bed slope. This method is suited for slopes of 3 % or greater (Kilgore et al. 2010), especially in streams where the particle sizes or large wood elements are relatively large compared with the flow depth (FSSSWG 2008). References for application of this method include Appendix E, Section E.2.2 of the USFS Stream Simulation manual (FSSSWG 2008) and Section 7.6.2 of FHWA HEC 26 (Kilgore et al. 2010).

4.4 FLOODPLAINS

The following definition of the regulatory floodplain in Minnesota is given by the MN DNR: “Under state law, the floodplain is the land adjoining lakes and rivers that is covered by the "100-year" or "regional" flood. This flood is considered to be a flood that has a 1 percent chance of occurring in any given year.” (http://www.dnr.state.mn.us/waters/watermgmt_section/floodplain/fema_app.html) The 100-year flood is also called the Base Flood by the agency responsible for federal floodplain regulations, the Federal Emergency Management Agency (FEMA). Floodplain regulations restricting increases to Base Flood Elevations (BFEs) apply in floodplains including at bridges and culverts. Information on floodplain regulations and resources in Minnesota may be found at:

http://www.dnr.state.mn.us/waters/watermgmt_section/floodplain/regulations.html

Flow charts listing procedures to report hydraulic and hydrologic data and flood elevation impacts are available from the following DNR website, which has a section dedicated to floodplain requirements specifically for bridges and culverts:

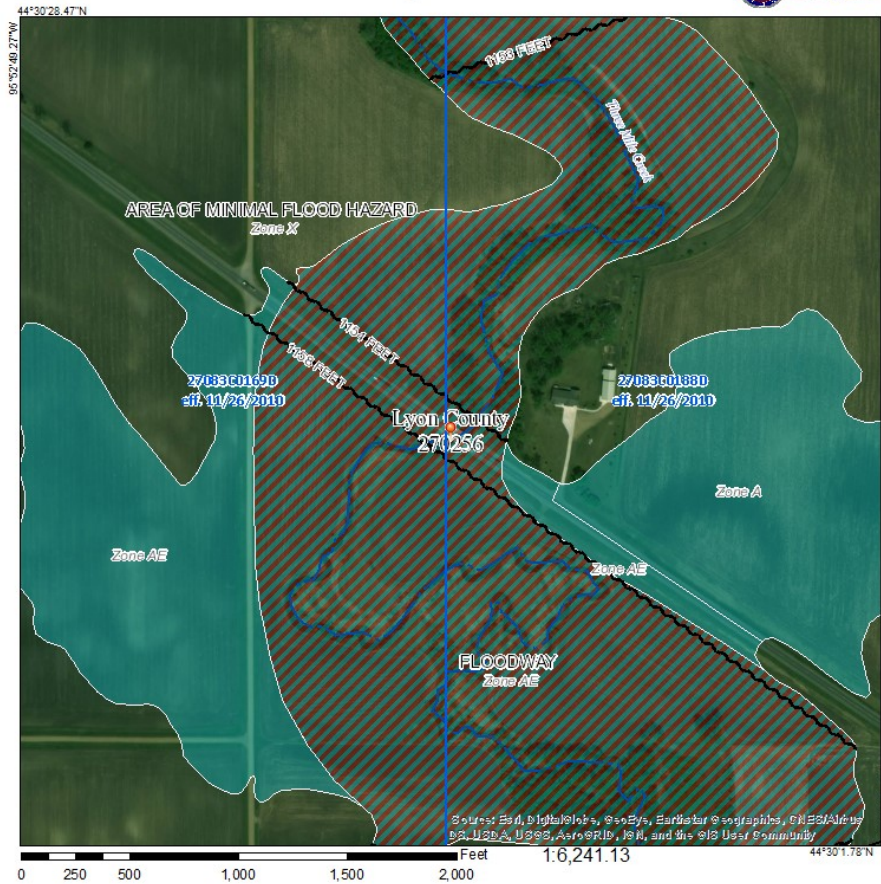
http://www.dnr.state.mn.us/waters/watermgmt_section/floodplain/tech_resources.html

FEMA’s Flood Map Service Center (<https://msc.fema.gov/portal>) has a search feature to quickly retrieve flood maps, flood studies, and 1997 and later letter amendments (LOMRs, LOMAs). Figure 4.4.1 shows a portion of a Flood Insurance Rate Map (FIRM) accessed through the Map Service Center.

Another Minnesota-specific resource for flood mapping is:

http://www.dnr.state.mn.us/waters/watermgmt_section/floodplain/fema_firms.html

National Flood Hazard Layer FIRMette



Legend

SEE FIS REPORT FOR DETAILED LEGEND AND INDEX MAP FOR FIRM PANEL LAYOUT

SPECIAL FLOOD HAZARD AREAS

- Without Base Flood Elevation (BFE) Zone A, V, VE, VE-1
- With BFE or Depth
- Regulatory Floodway Zone AE, AO, AH, VE, AR

OTHER AREAS OF FLOOD HAZARD

- 0.2% Annual Chance Flood Hazard. Areas of 1% annual chance flood with average depth less than one foot or with drainage areas of less than one square mile Zone X
- Future Conditions 1% Annual Chance Flood Hazard Zone X
- Area with Reduced Flood Risk due to Levees. See Notes. Zone X
- Area with Flood Risk due to Levees Zone D

OTHER AREAS

- Area of Minimal Flood Hazard Zone X
- Effective LOMRs
- Area of Undetermined Flood Hazard Zone D

GENERAL STRUCTURES

- Channel, Culvert, or Storm Sewer
- Levee, Dike, or Floodwall

OTHER FEATURES

- Cross Sections with 1% Annual Chance Water Surface Elevation
- Coastal Transect
- Base Flood Elevation Line (BFE)
- Limit of Study
- Jurisdiction Boundary
- Coastal Transect Baseline
- Profile Baseline
- Hydrographic Feature

MAP PANELS

- Digital Data Available
- No Digital Data Available
- Unmapped

This map complies with FEMA's standards for the use of digital flood maps if it is not void as described below. The base map shown complies with FEMA's base map accuracy standards.

The flood hazard information is derived directly from the authoritative NFHL web services provided by FEMA. This map was exported on 2/25/2018 at 12:44:07 PM and does not reflect changes or amendments subsequent to this date and time. The NFHL and effective information may change or become superseded by new data over time.

This map image is void if the one or more of the following map elements do not appear: base map imagery, flood zone labels, legend, scale bar, map oration date, community identifiers, FIRM panel number, and FIRM effective date. Map images for unmapped and unmodernized areas cannot be used for regulatory purposes.

Figure 4.4.1. Example Flood Insurance Rate Map (FIRM) for a portion of Lyon County, MN.

Hydraulic models are available through the following MN DNR website for some stream segments: http://www.dnr.state.mn.us/waters/watermgmt_section/floodplain/fema_app.html If a FEMA hydraulic model exists, it should be used and modified for hydraulic calculations to conform to the elevation requirements.

4.5 STRUCTURAL AND GEOTECHNICAL ANALYSIS

Although not part of this guide, structural analysis of the culvert structure and geotechnical analysis of foundations and soil fills are a required part of any culvert design. The complexity of analysis will depend on factors including the subsurface conditions encountered, structure type, roadway classification and ADT, and acceptable level of risk.

Several Minnesota design resources are:

- MnDOT LRFD Bridge Design Manual (<http://www.dot.state.mn.us/bridge/lrfd.html>)
- MnDOT Geotechnical Manual (<http://www.dot.state.mn.us/materials/geotmanual.html>)

The MnDOT LRFD Bridge Manual Section 10.4.1 specifically covers scour depths to be used in strength, service limit, and extreme event limit states for structural and foundation design. Spread footings are not allowed except where anchored in bedrock.

4.6 DESIGN DOCUMENTATION

The process of planning and constructing a culvert is only a short portion of the total lifespan of the infrastructure, which hopefully will endure longer than the careers of the designers and builders. Documenting design decisions and the goals of the design should help engineers, land managers, and maintenance personnel to determine whether the culvert is functioning as designed, or needs to be modified or maintained. For example, if a culvert is designed to be embedded so that bed material always occupies a portion of the barrel, this should be documented so that a maintenance crew unfamiliar with the design goals does not view the bed material as a blockage and remove it. However, if the buildup of bed sediment is greater than expected, a judgement can be made, based on the design intent and subsequent observations, whether or not it is excessive and warrants removal. Developing design documentation may also help to demonstrate to regulators or other stakeholders why certain design decisions were feasible or not, given local conditions.

Comparison of later field observations to carefully documented design calculations and assumptions can also help to determine if the methods used to develop calculations and assumptions are adequate or can be improved in future designs. Monitoring and maintenance considerations are briefly discussed in Section 6.10 .

Suggested items of documentation:

- Intent or goals of the design in light of AOP or stream connectivity considerations. For example, if the culvert designed due to site constraints is a “hydraulic design” with the goal of passing a particular fish species at a particular time of year, it would be inappropriate to expect the same type of performance, in terms of passage for a wide variety of organisms, as a culvert designed for full geomorphic simulation.

- Reason for major design choice(s). For instance, in the example above, perhaps the site was severely constrained by utilities that could not be relocated, but was previously a critical barrier for the particular fish species considered in the design.
- As-built survey with dimensions, inlet and outlet elevations, streambed elevations, construction details, etc.
- Design peak discharge and elevations.
- Stream data collected for design such as profile, grain size distributions, channel features, etc. including geomorphic assessment documentation (Chapter 3).
- Quantity, type, and design elevations of sediment placed inside the culvert (or expected to wash in). If the culvert is designed to be filled with sediment, a painted “fill” line can be used in construction, and for checking whether sediment depth is as expected. Offset marks, such as 36 inches above the expected bed level, could be useful for long-term monitoring as well.
- Expected changes to the stream as a result of the culvert. For instance, if the decision has been made in design (in consultation with stakeholders) to lower an existing perched culvert and allow a headcut to travel upstream, this should be noted so a migrating nickpoint is not seen as a surprise.
- Fish or aquatic life species targeted for improved passage, if applicable.
- If the culvert is specifically designed to exclude passage, such as to block invasive species, this should be noted.
- Risk assessment information.
- Location, elevation, and other properties of grade control and armoring features, even if designed to be buried below other bed material.
- Subsurface information (soil borings, etc.).

Suggestions for documentation in this section are not intended to replace agency-required documentation.

CHAPTER 5: AOP DESIGN METHODS

This section describes different methods for improving AOP and stream connectivity at culverts. Beginning with a decision tool in Section 5.1 based on stream slope and other characteristics, a framework for selecting appropriate AOP methods is provided. Following that, five general categories of AOP are described: bridges, stream or geomorphic simulation, hydraulic simulation, embedded or recessed culverts, and hydraulic design. Bridges (Section 5.2) avoid blockage of AOP entirely by avoiding confining the stream while the other four categories employ different strategies to achieve AOP. Geomorphic simulation (Stream Simulation) (Section 5.3) typically achieves the greatest degree of passage and reduced maintenance over time by recreating stream-like characteristics in the culvert focusing on continuity of sediment transport. Hydraulic simulation (Section 5.4) using HEC 26 or other design frameworks does not attempt to recreate bed conditions or sediment transport but designs to provide specific depth and velocity requirements for target fish species. Embedded or recessed culverts (Section 5.5) attempt to achieve AOP by burying the culvert invert below the streambed flowline and matching the culvert width to stream width, with less analysis than geomorphic simulation. Lastly, hydraulic design (Section 5.6) attempts to create suitable hydraulics in the culvert by designing baffles or adding boulders or other features to reduce velocity and/or alter flow width and depth characteristics and is presented for possible use in retrofit situations.

5.1 DESIGN METHOD SELECTION

The selection of appropriate AOP methods at culverts depends on the characteristics of individual streams. Numerous stream classification systems have been developed to help scientists and engineers characterize and assess streams including the Rosgen system and the Montgomery and Buffington (1997) classification schemes. These two are shown in relation to channel slope (gradient) in Figure 5.1.1 (Montgomery and Buffington) and Figure 5.1.2 (Rosgen).

Slope is used here because it is one of the key parameters in stream geomorphology and hydraulics and is highly correlated with bed sediment size, channel roughness and energy dissipation. For convenience, four slope categories (<0.2%, 0.2-1%, 1-3%, >3%) are used in the figures in this section. While stream slope or gradient is important in identifying appropriate AOP design strategies, it should be noted that there can be significant variation in stream characteristics even within a slope range or category, and some overlap in categories is possible, especially near the category breaks. While classification helps to group streams into similar types and facilitate communication it is not sufficient analysis for AOP design; site-specific assessment is always necessary as described in Chapters 3 and 4.

The Rosgen system is generally applicable in all stream slope classes in Minnesota (See Table 5.1.1 for a summary of Rosgen channel types). While there is much overlap of type by slope, the use of entrenchment, sinuosity, and bed type helps to distinguish Rosgen types. On the other hand the Montgomery and Buffington system was developed in steeper slope environments in the mountainous west. Although not reflected in classification schemes, silt bed streams without dunes and other very low gradient streams are prevalent in Minnesota (L. Aadland, pers. Comm. 2018).

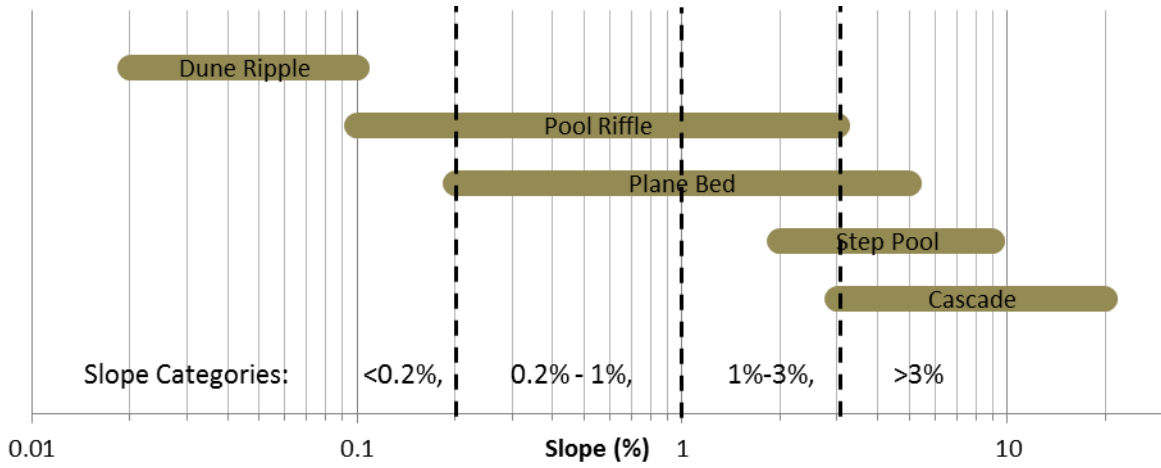


Figure 5.1.1. Channel slope and Montgomery and Buffington (1997) classifications.

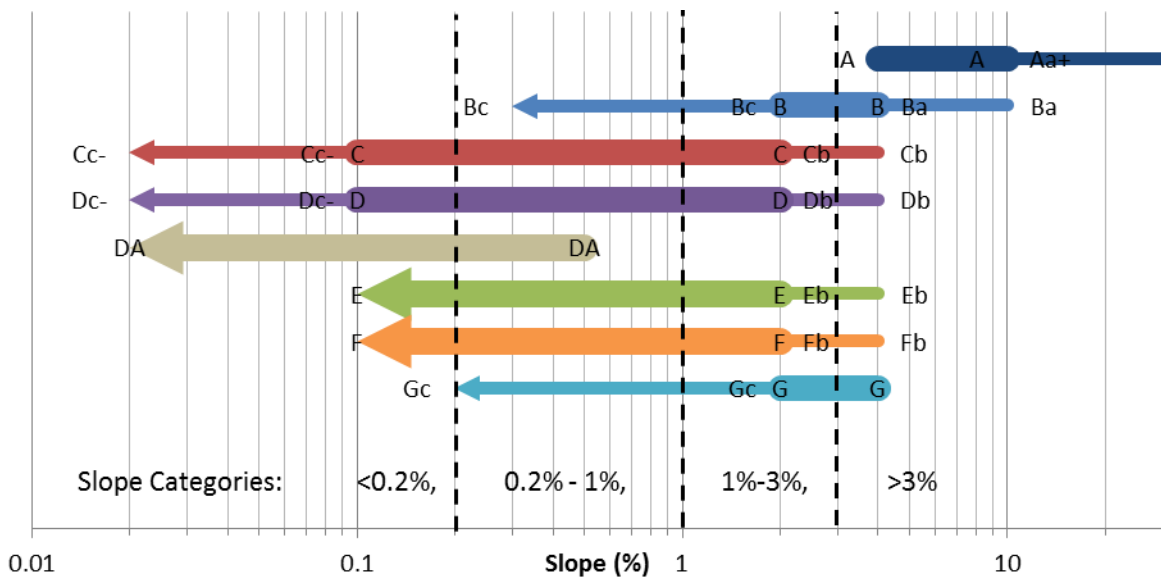


























Figure 5.1.2. Channel slope and Rosgen (1996) classifications.

Table 5.1.1. Rosgen stream types and associated geomorphic, culvert design, and AOP issues in Minnesota.

Rosgen Stream type	Channel Characteristics: slope, bed material, floodplain	Culvert design applications and considerations	Potential AOP issues	Applicable AOP methods
A	Steep slope >4%, often boulder or bedrock bottom, little or no floodplain, found mostly on Lake Superior shore	Head-cutting potential; scour at outlet; maintenance of bedload transport important	High shear force & velocity, high bedload potential; scour and hydraulic jump at outlet	Geomorphic simulation or bridge
B	Intermediate slope, coarse bed, small floodplain	Small floodplain, maintenance of bedload transport important	Mod. shear force + velocity, Mod. bedload potential; scour and hydraulic jump at outlet	Geomorphic simulation or hydraulic simulation
C	Low slope, often sand or fine sediment on bed, Moderate somewhat entrenched channel,	Moderate width floodplain; moderate sinuosity, a variety of approaches applicable with C type	Low shear force, often high sediment load; potential for aggradation	Embedded culvert and geomorphic simulation approaches
D	Braided channel, low slope, often sand bed, not entrenched	Not very frequent type in Minnesota, typically on larger rivers where bridges would be used	High bedload, high rate of channel movement, aggradation potential	Bridge may be necessary due to channel mobility
E	Highly meandering channel, often sand or fine sediment on bed, not entrenched with wide floodplain	Low gradient, potential for aggradation	Risk for reducing access to floodplain by culvert	Embedded culverts, geomorphic simulation approaches and/ or other less intensive AOP approaches
F	Highly entrenched stream with greater width than a gully type (G)	Typically unstable, larger channels often at the scale requiring bridges	Little floodplain; low shear force, high sediment load; potential for aggradation	Geomorphic simulation or bridge
G	Gully-like, entrenched channel	Head-cutting concerns, undermining culvert	Unstable channel type; typically non-perennial streams supporting less aquatic life	Actively cutting gullies may not be suitable for culvert placement until grade control is in place

After determining the stream slope and type from field measurements, the culvert designer can use Figure 5.1.3 as a preliminary screening guide for the suitability of different AOP practices by stream slope category. The stream slope categories depicted in Figure 5.1.3 were selected because they represent the range of stream slopes commonly found in Minnesota streams, based on USGS data, with the vast majority of stream miles estimated as having <1% slope (see Table in Appendix F: Stream slopes in Minnesota).

Culvert design method	Channel slope range			
	< 0.2 %	0.2 – 1 %	1 – 3 %	> 3%
Bridge Spanning channel and banks				
Geomorphic Simulation (USFS Stream Sim)				
Hydraulic Simulation (FHWA HEC 26)				
Embedded (initially filled)				
Recessed (initially non-filled)				
Hydraulic design (species-specific)				





Symbol Key	
	Generally appropriate
	Mostly appropriate, with some additional design considerations
	May be appropriate, with major additional design considerations
	Generally NOT appropriate

Figure 5.1.3. Culvert design method suitability by slope range. Suitability is ranked primarily on AOP and stream connectivity factors, and, in part, on a general cost-benefit evaluation.

A listing of design goals by method is shown in Figure 5.1.4. As indicated by the generally appropriate category, bridges are likely suitable in all conditions and slope ranges for AOP. Among the AOP practices geomorphic simulation is applicable across the broadest range of slope categories and is particularly useful in the steeper classes with coarse bed materials. Recessed, non-filled culverts are applicable to low-slope situations where stream sediment is highly mobile. Embedded and hydraulic simulation designs have a range of applications. Hydraulic design for passage of specific fish species is recommended primarily in a retrofit situation or where a more inclusive design is not feasible. General characteristics of the identified slope ranges are below, including some reasoning for recommendations given:

Slope category: < 0.2%

Typical characteristics of streams in this slope category include:

- Bed material: generally sand or finer (silt, clay)
- Sediment transport: bedload may be constantly transported; suspended load of fine sediment
- Stability: often easily erodible bed and banks, channel may move rapidly
- Bedform pattern: mobile bedforms depending on flow – ripples, dunes, sand-waves, plane-bed, antidunes (Buffington and Montgomery 2013)
- Channel roughness: mobile bedforms, dominant due to small particle size of bed
- Bank roughness: sinuosity, vegetation; shrubs or wood if present

Preferred design method: Recessed culvert since there are generally no persistent bedforms to simulate, and fine sediment will fill in culvert relatively quickly to create substrate.

Potentially suitable design methods: Embedded, geomorphic simulation, hydraulic simulation, and non-recessed (traditional hydraulic capacity), provided this design does not create a velocity or depth barrier and is checked for susceptibility to scour and headcutting.

Additional considerations: potential for headcuts and channel degradation is high, slightly entrenched streams (wide floodplain) will benefit from floodplain culverts (Section 6.2), design of grade control must take into account scour in fine-grained beds.

Slope category 0.2 – 1.0%

Typical characteristics of streams in this slope category include:

- Bed material: gravel, armoring may be present
- Sediment transport: bedload periodically transported, suspended load of fine sediment
- Stability: varies depending on characteristics
- Bedform pattern: alternating pools and riffles with bars or plane bed (few bedforms)
- Channel roughness: bedforms dominant due to small particle size of bed
- Bank roughness: vegetation, shrubs or wood pieces if present, sinuosity

Preferred design method: Embedded culvert design; culvert should be filled with sediment because bedload transport is slower and could take years to fill; may or may not need to create banks and bedforms such as pool and riffle sequence.

Potentially suitable design methods: geomorphic simulation, HEC 26, recessed

Additional considerations: slightly entrenched streams (wide floodplain) will benefit from floodplain culverts (Section 6.2), design of grade control must take into account scour in fine-grained beds.

Slope category 1.0 – 3.0%

Typical characteristics of streams in this slope category include:

- Bed material: gravel and cobble, generally armored
- Sediment transport: bedload periodically transported
- Stability: fairly stable
- Bedform pattern: plane bed (few bedforms) or alternating pools and riffles with bars
- Channel roughness: riffle bedforms
- Bank roughness: boulders, large wood

Preferred design method: The geomorphic simulation approach is most suitable because persistent bedforms are important for maintenance of channel slope and for AOP. Bedforms should be constructed because they may take many years to form.

Potentially suitable design methods: HEC 26 (where similar to geomorphic simulation), Embedded

A recessed (non-filled) design is generally not appropriate.

Slope category >3%

Typical characteristics of streams in this slope category:

- Bed material: cobble to boulder, armored
- Sediment transport: bedload moves infrequently
- Stability: fairly stable if stream flows over bedrock or is armored with boulders / large cobbles
- Bedform pattern: sequence of steps and pools, or random boulders if steeper
- Channel roughness: step structures and boulders
- Bank roughness: boulders, large wood

Preferred design method: Geomorphic simulation is the method of choice because persistent bedforms are important to hold the channel slope and to maintain AOP. They should be constructed because they otherwise may take years to form.

Potentially suitable design methods: HEC-26 (where similar to geomorphic simulation), embedded

A recessed (non-filled) design is generally not appropriate.

Figure 5.1.4 suggests which culvert design methods for AOP and stream connectivity are generally appropriate or not appropriate to meet a number of common design goals, which are listed across the top row.

Culvert design method	Provide hydraulic conveyance and flood capacity	Extreme event resiliency	Provide sediment and debris passage (stream connectivity)	Allow aquatic organism passage	Minimize construction cost	Minimize design effort
Bridge Spanning channel and banks	●	●	●	●	⊗	○
Geomorphic Simulation (USFS Stream Sim)	●	●	●	●	○	⊗
Hydraulic Simulation (FHWA HEC 26)	●	○	○	●	○	○
Embedded (initially filled)	●	○	○	●	●	●
Recessed (initially non-filled)	●	○	○	○	●	●
Hydraulic design (species-specific)	●	⊗	⊗	○	●	○

Symbol Key	
●	Generally appropriate
●	Mostly appropriate, with some additional design considerations
○	May be appropriate, with major additional design considerations
⊗	Generally NOT appropriate

Figure 5.1.4. Culvert design method suitability by goal.

5.2 BRIDGE SPANNING NATURAL CHANNEL AND BANKS

Bridges allow the greatest degree of AOP, not restricting passage any more than upstream or downstream reaches.

5.2.1 Method Definition and Design Intent

Definition:

In this context, an elevated structure carrying a road, railroad, or path above a river or stream, where there is no soil fill (embankment) between the traveled surface and the top of the waterway. In a bridge, the traveled surface (deck) typically rests on separate abutment supports on the stream bank at each end, and the natural streambed generally continues through the structure.

Three-sided Bridge Structure: A flat top (box culvert) or arch top structure that rests on footings on the stream banks, having no structural bottom, so that the natural streambed continues through the structure. The roadway is constructed on soil fill above the structure, which is buried. These structures may also be called open bottom culverts, bottomless culverts, three sided culvert, long span arches, or Bebo® bridges. Three-sided bridge structures share some similarities with bridges (open natural stream bottom, built on pilings or footings) and some similarities with culverts (contiguous vertical and horizontal members, pipe-like joints, and both are buried structures with soil fill between the top of structure and the roadway).

Note: MnDOT classifies culvert structures (three-sided or enclosed) as bridges, "...when horizontal opening width is 10 feet or greater measured perpendicular to the roadway centerline." (MnDOT Drainage Manual Section 5.1.1).

Design Intent:

With respect to benefits for AOP and stream connectivity, a bridge should be designed to span the stream banks, allowing the natural stream to continue through, thus preserving all the natural capacity of the channel for transit of aquatic organisms as well as sediment and debris. Bridge structures and foundations must be designed to meet applicable FHWA and MnDOT requirement.

From Section 12.3 of the MnDOT LRFD Bridge Design Manual (2018):

In general, precast three-sided structures may be used where:

- A. Design span is less than or equal to 42 feet. Larger spans may be considered on a case-by-case basis, but only with prior approval of the Bridge Design Engineer. Span is measured from inside face of sidewalls along the longitudinal axis of the unit;
- B. Rise is less than or equal to 13 feet. Rise is measured from top of footing/pedestal wall to bottom of top slab;

- C. Fill height is less than or equal to 10 feet but is greater than or equal to 3 feet. Fill heights larger than 10 feet may be considered on a case-by-case basis, but only with prior approval of the Bridge Design Engineer;
- D. Skew is less than 30°;
- E. No foundation limitations exist such as unusually weak soil;
- F. No site access limitations exist for transporting and erecting the three-sided structures;
- G. Clogging from debris or sediment precludes the use of multiple barrel structures.

Section 12.4 of the MnDOT LRFD Bridge Design Manual (2018), p. 12-25, contains requirements for design approval of long span corrugated steel structures.

5.2.2 Benefits

Bridges have multiple benefits over culverts for AOP and prevention of maintenance issues, as described below:

- Bridges may be used to avoid blocking active floodplains and debris-flow prone locations
- For wide streams or rivers, bridges are often the only reasonable crossing option. The maximum MnDOT standard span for box culverts is 16 feet, although 20 foot spans have been produced (<https://lrrb.org/media/reports/TRS1203.pdf>). Arch structures up to 60 feet in span have been used in Minnesota (<http://www.cts.umn.edu/sites/default/files/files/sessions/17werner.pdf>).
- If the bridge opening is wider than the bankfull width of the stream, a natural streambed can be continuously maintained through the structure, allowing for natural organism passage, and natural channel processes (transport of sediment and debris).
- Bridges are most effective structure for streams with high debris loads, due to higher vertical clearance and less restriction.
- Deck-type bridges may be effective in low-fill situations – bridges typically require less height from the streambed as compared to a buried structure such as a culvert.
- If considered in design, a bridge can allow for terrestrial wildlife passage along the stream banks which could reduce wildlife-vehicle collisions. Details for a passage bench may be found in Best Practices for Meeting DNR General Public Waters Work Permit GP 2004-0001 (Leete 2014)
- Accelerated construction techniques such as precast members can be used to shorten the start to finish construction time of bridges.
- Often the stream channel is free-flowing under the bridge during part or all of the construction process, avoiding the need for bypass pipes or pumping.
- A three-sided bridge structure may be used to create a bridge-like opening in high fill situations without the need for high abutments or riprap slopes.
- For three-sided bridge structures with adequate fill height, continuity of horizontal and vertical roadway curves is easier than with deck-type bridge.

5.2.3 Key Design/Implementation Considerations

Bridge (deck-type)

- Bridges may have a higher initial cost than comparable single or multiple barrel culverts, but should not be automatically ruled out, especially where large culverts would be needed, as in the case of access restrictions, construction timing requirements, or other constraints.
- For relatively short span, straightforward bridges, concrete is the preferred material in Minnesota. Steel bridge structures can be more flexible where soil movement is likely, but require maintenance of corrosion protection (repainting). Timber bridges are often limited in span and susceptible to decay, most suitable for low traffic only.
- A discussion of structure type may be found in the MnDOT Bridge Manual (2018), Section 2.3.2, p. 2-38 to 2-40.
- If the bridge opening is too narrow (less than bankfull width) or constricts flows on the floodplain too much, streambed and bank scour may be induced, eroding streambed material, which alters sediment transport and AOP characteristics.
- Clearance between the water surface and lowest point on the bridge is important. Varying clearance distances apply depending on the watercourse. Clearances are defined in Leete 2014 and the MnDOT LRFD Bridge Manual, (MnDOT 2018).
- Foundations or footings must be designed for scour and streambed grade changes. Assess head cutting potential and design countermeasures such as grade control rock weirs if needed (see Section 6.3 of this document). Refer to MnDOT LRFD Bridge Design Manual Section 10.4.1 (p.10-10) for scour criteria, and Section 12.3.3 (p.12-20) for scour protection guidelines. The LRFD Bridge Design Manual does not allow spread footings for streams or rivers, unless they are anchored into rock (Section 10.4.1, p.10-10). For pile bent piers, the pile tips should be driven a minimum of 10 feet below the scour elevation. (Section 10.5, p.10-15)
- If footing and/or pier scour countermeasures (i.e. riprap) are so extensive that the natural streambed is constricted, the environmental benefits of a bridge versus a closed bottom structure may be negligible.
- Lateral stream movement (meandering) over the design life of the bridge should be accounted for.
- Avoid placing supporting piers in the stream where possible, and avoid or limit piers placed within the bankfull width, since these may accumulate debris.
- If a bridge is replacing a fixed-bottom culvert, the “new” streambed below the bridge may need to be constructed and should be similar to a reference reach in terms of slope, cross-section, and bed material composition.

Three-sided bridge structure (open bottom culvert)

- Where a deck-type bridge or three sided bridge structure are both alternatives, perform an economic analysis to determine the preferred option.
- Review design and implementation considerations for deck-type bridges above.
- Typical MnDOT design criteria include span 42 feet or less, rise less than 13 feet, fill height between 3 and 10 feet, and skew less than 30 degrees (MnDOT Technical Memo No.16-02-B-01, MnDOT (2016)).
- See MnDOT LRFD Bridge Design Manual, Section 12.3 for structural design and limitations: <http://www.dot.state.mn.us/bridge/pdf/lrfdmanual/section12.pdf>, and Technical Memo No.16-02-B-01 (<https://techmemos.dot.state.mn.us/>).
- Three-sided bridge structures normally require pile foundations in Minnesota; shallow spread footings are allowed on erosion resistant bedrock. Arch-shaped structures get effectively narrower as elevation (stream water level) increases. If not considered carefully, an arch that spans the bankfull width between footings could end up with a much narrower top width and reduced flow area at actual bankfull flow. Manufacturers offer various design shapes with different ranges of rise (height) and span (width).

5.2.4 Maintenance Considerations

- Bridge inspections are very important and should be done according to pre-determined schedules, and as needed such as after extreme flow events.
- Maintenance requirements depend on the materials selected, details of construction, and local conditions.

5.2.5 Example



Figure 5.2.1. Side-by-side precast box beams with sheet pile abutments, Blue Earth County Bridge 07547. (Chris Werner presentation CTS, <http://www.cts.umn.edu/sites/default/files/files/sessions/17werner.pdf>)

5.3 GEOMORPHIC SIMULATION (STREAM SIMULATION)

5.3.1 Method Definition and Design Intent

Definition:

Geomorphic simulation refers to a culvert design which attempts to recreate stream channel conditions through the culvert by matching characteristics, including slope, width, bed materials, and bedforms, derived from a nearby stable reference reach. While geomorphic simulation is a general category of design (see Table 2.3.1), this section focuses on the Stream Simulation techniques developed by the US Forest Service (FSSSWG 2008).

Design intent:

By establishing conditions that simulate those found in the adjacent stream it is assumed that the widest array of aquatic organism will be able to pass through with no more difficulty than similar adjacent reaches of the stream (Cenderelli et al. 2011).

5.3.2 Benefits

Geomorphic simulation likely provides passage for the widest variety of aquatic organisms of all the AOP passage techniques. By providing bed material similar to a natural reference stream, benthic organisms may live in the culvert and move upstream more easily than in hydraulic-only AOP practices. The coarse bed materials help to slow velocity and provide a variety of velocities and depths similar to that provided by other AOP methods.

In terms of geomorphology, this approach helps to provide continuity of sediment movement upstream-to-downstream through the culvert. This should reduce potential for scour downstream and aggradation upstream. This approach allows for some lateral and vertical adjustment due to high flows, sediment input, or wood movement while maintaining AOP and capacity to pass flow. Explicitly accounting for possible vertical bed adjustment is important to the resilience of the simulated bed.

At the same time maintenance needs such as dredging and removal of excess material should be minimized relative to hydraulics-only practices or traditional culverts that don't address AOP. Wood jams and high flow over-topping are reduced in geomorphic simulation since many of the structures have been found to pass greater than a 100-year flood (Gillespie et al. 2014).

5.3.3 Key Design/Implementation Considerations

In Stream Simulation, geomorphic assessment is important including collection of detailed longitudinal profile, cross-section, and bed material data (see Chapter 3 for assessment methods). A comprehensive document on all aspects of the method is *Stream Simulation: An Ecological Approach to Road-Stream Crossings*, by the US Forest Service (FSSSWG 2008). Steps for geomorphic simulation design of the stream channel through the culvert are shown in Figure 5.3.1 (R. Gubernick, pers. Comm. 2018). Development and analysis of a longitudinal stream profile (Figure 5.3.2) is central to this method, and includes determination of the likely range of change in bed elevations, or vertical adjustment potential (VAP) (Figure 5.3.3). For closed-bottom culverts, an important consideration is embedment below the maximum anticipated scour depth, which is estimated by multiplying the maximum pool depth (excluding plunge pools from undersized culverts) by a factor of 1 to 2, depending on sediment and bedform characteristics. Construction of bedforms and banks to simulate the reference reach conditions is another central tenant of this method.

Appropriate settings: As depicted in Figure 5.1.3, this method is suitable for most settings. Geomorphic simulation is appropriate and may be necessary at steeper gradients and on stream types where stream stability and organism passage depends on persistent bedforms such as boulder steps.

Inappropriate settings: Geomorphic simulation may not be suitable for short-term or temporary road crossings where a long-term solution isn't required. In certain urban settings streams having very little bedload and little fish life the potential benefits of geomorphic simulation are likely to be minimal. Similarly in flat-gradient sand-bottom, often highly mobile streams there may be little added value to this approach.

Stream Simulation Channel Design Process

1. Identify one downstream design elevation control point and two upstream design elevation control points to connect the upstream and downstream channel through the road-stream crossing.
2. A) Delineate design channel profile(s).
B) Calculate the design gradients.
C) Calculate the percent difference in gradients between the design profiles and the channel slope segments.
3. A) Select your preliminary design gradient profile.
B) Select a preliminary reference reach.
4. Using the selected reference reach and conditions at the crossing, adjust (if necessary) the upper and lower vertical adjustment potential lines through the crossing.
5. A) Using the reference reach identify the type of bedforms to construct in the design channel.
B) Determine the number of existing, stable grade controls in the design profile.
C) Determine location of any controls on pools from stream-structure geometry.
D) Delineate the number and spacing of bedforms to be constructed in the design channel.
E) Explore another design profile (return to step 3)?
6. A) Delineate the depth of sediment to fill plunge pool.
B) Delineate base of structure or footing (embedment depth).
7. Delineate the long-term channel-bed surface through the crossing following channel adjustments (headcutting, erosion, etc.).

Figure 5.3.1. Stream Simulation channel design process. (R. Gubernick, pers. Comm. 2018)

<u>Longitudinal Profile Assessment Process</u>
1. Identify pools and grade controls.
2. Determine the types of grade controls along the longitudinal profile.
3. Assess the relative stability of each grade control.
4. Determine the geomorphic controls of the pools (Note: compare the longitudinal profile with the planform map)?
5. Delineate slope segments.
6. Calculate the elevation change, length, and gradient of each slope segment. Determine the percent difference between adjacent segments.
7. Determine the maximum scour depth (residual pool depth) for each slope segment and culvert plunge pool. How does culvert pool scour depth compare to other pool depths along profile?
8. Determine the number of and distance between grade controls for each slope segment.
9. Identify and delineate the extent of sediment aggradation (thickness and length) upstream from culvert inlet.
10. Identify the shape of the longitudinal profile.
11. Delineate the upper vertical adjustment potential line along the longitudinal profile. Indicate the geomorphic evidence used to delineate the upper vertical adjustment potential line.
12. Delineate the lower vertical adjustment potential line along the longitudinal profile. Indicate the geomorphic evidence used to delineate the lower vertical adjustment potential line.

Figure 5.3.2. Longitudinal profile assessment steps for Stream Simulation, as used in USFS training. Vertical adjustment potential (R. Gubernick, pers. Comm. 2018.)

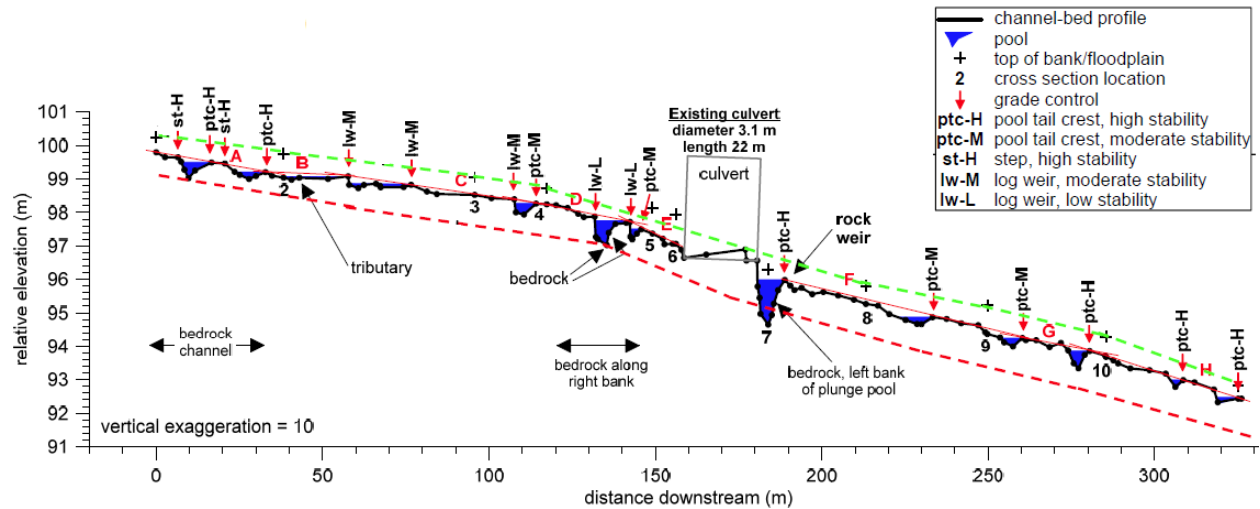


Figure 5.3.3. Longitudinal profile example for Stream Simulation. The upper green dashed line shows the upper Vertical Adjustment Potential (VAP) and the lower red dashed line shows the lower VAP. (R. Gubernick, pers. Comm. 2018. Used in USFS training.)

5.3.4 Operation & Maintenance Considerations

Geomorphic simulation generally allows for reduced maintenance since the frequency of sediment aggradation and scour holes should be greatly reduced. However, there is still a need to periodically check for wood jams, which is more of a function of the stream and watershed wood-loading rate than the culvert design itself.

- Culverts classified as bridges should be inspected per bridge inspection cycle requirements.
- Regular inspections for all culverts are advisable, especially during or after large flood events.
- After a large flow, it may be prudent to verify that the expected streambed state (stable bed or mobile bed) matches the design intent.

5.3.5 Design examples

There are several design examples in (FSSSWG 2008), including alignment and profile examples in FSSSWG 2008 Section 6.1.3, and a sediment mobility and stability example in appendix E.3.



Figure 5.3.4. Swift spring flows through a culvert in Superior National Forest, northern Minnesota. Bankline rocks protect the footings from scour and simulate the bank roughness of the stream channel, allowing lower velocity regions near the bank. (P. Leete photo, 2014)

5.4 HYDRAULIC SIMULATION (FHWA HEC 26)

5.4.1 Method Definition and Design Intent

Definition: A streambed stability-based approach to providing AOP through culverts, as outlined in FHWA HEC 26 (Kilgore et al. 2010). Natural sediment is placed in the embedded culvert barrel, and, based on the comparison of permissible and applied shear stresses, is underlain by oversized sediment if required for bed stability at peak flows.

Design Intent: The design attempts to provide hydraulic conditions (depth and velocity) within the range of variation found in the stream channel upstream and downstream of the crossing at AOP design flows, so that if organisms can pass those existing reaches, they should be able to pass through the culvert as well, since the forces and stresses will be similar.

The design process is arranged in a series of 13 steps as illustrated by the flow chart in the figure below. As stated in HEC 26, “Five fundamental tests are applied as part of the procedure. If any test is failed, design adjustments are specified. The tests are:

1. Does the culvert satisfy the peak flow requirements?
2. Is the bed material in the culvert stable (no movement or sediment inflow equals outflow) for the high passage design flow?

3. Is the bed material in the culvert stable for the peak design flow? (An anchoring layer/device below the bed material may be required to satisfy this test.)
4. Is velocity in the culvert for the high passage design flow consistent with upstream and downstream channel velocities?
5. Is depth in the culvert for the low passage design flow consistent with upstream and downstream channel depths?"

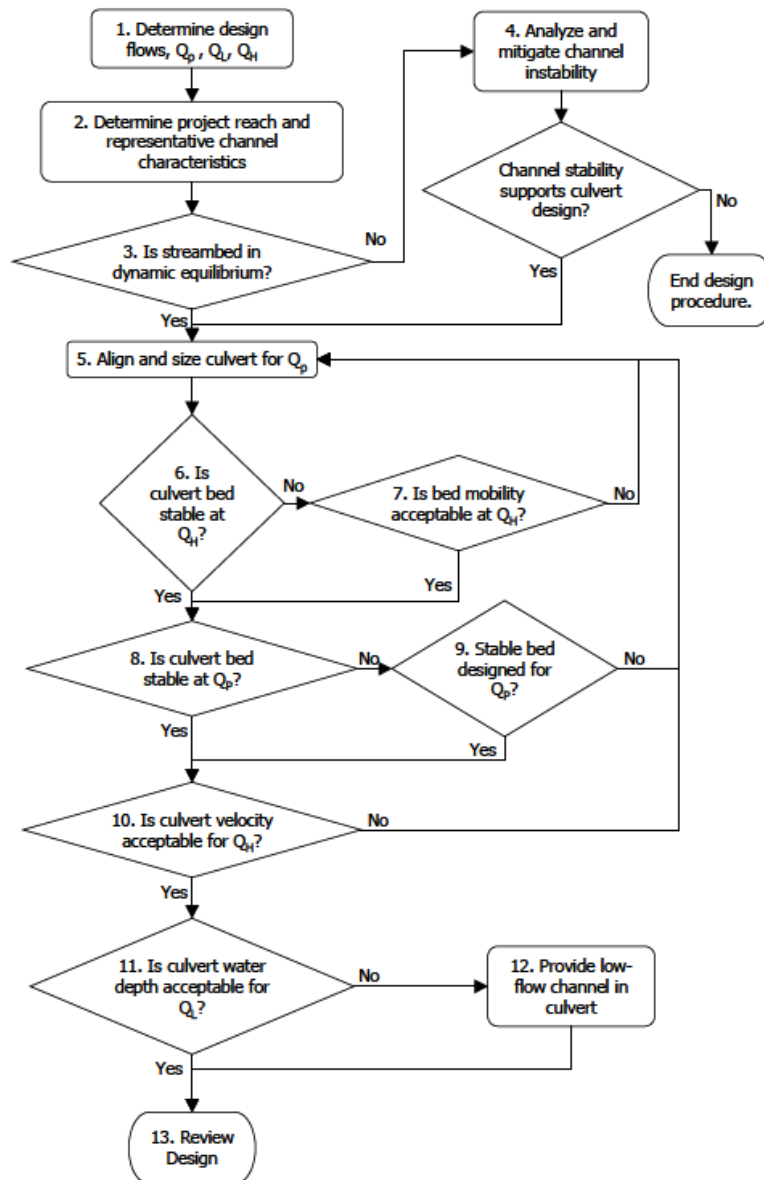


Figure 5.4.1. FHWA HEC 26 Hydraulic Simulation Design Chart (From HEC 26 Figure 7.1)

5.4.2 Benefits

- The method does not attempt a species-specific design, but rather bases the design on the hydraulics of the upstream and downstream channel, so that species-specific information is not needed.
- The bankfull width is not treated as an independent parameter in culvert design, and thus does not need to be determined directly; culverts designed using this method may end up to be wider or narrower than bankfull width.
- Channel instabilities are specifically analyzed and mitigated as part of the design process.
- Bed material gradation in the natural streambed, as well as armoring, is taken into account.
- Bed stability is quantified - critical shear stress of the design bed sediment at incipient motion is calculated and compared to the applied shear stress based on the design hydraulic and culvert geometry. This should be done with caution; critical shear should not be assumed to match Shields relations in heterogeneous sediments (Montgomery and Buffington 1997); a modified Shields approach is recommended.
- The primary reference and appendices contain useful information on Manning's roughness for various bed materials, permissible shear stress calculations, and project examples.

5.4.3 Key Design/Implementation Considerations

- Three discharges are considered: 1.) Peak flow or flood flow Q_p , such as the 50- or 100-year flow; 2.) the high passage design flow, Q_H , which is the maximum flow for which AOP is desired; and, 3.) the low passage design flow, Q_L , which is the minimum flow for which AOP is desired.
- There is currently no guidance in Minnesota on the high passage (Q_H) and low (Q_L) passage flows; high and low passage flows should be developed in consultation with a DNR Area Hydrologist. Referencing work by Clarkin, et al. (2003), Tables 5-1 and 5-2 in FHWA HEC 26 summarize guidelines from other states and agencies. For example, Oregon uses the 10% exceedance flow during a species specific migration period for the high passage flow, and the 2-yr, 7-day low flow (7Q2) or 95% exceedance flow for species specific migration period for the low passage flow.
- To achieve a stable bed at peak flows, an underlayer of stable, larger than native size (oversize) sediment may be placed in the culvert beneath the native bed material. Note that if the culvert is narrow relative to the stream (next bullet) the native bed material may not refill as expected on the falling hydrograph limb.
- It may be possible to arrive at a design which satisfies the shear stress-based stability criteria utilizing a relatively narrow culvert with relatively large sediment, but is not compatible with the upstream and downstream channel characteristics (Figure 5.4.2). Large roughness elements can create turbulent conditions that are impassible to fish. Results of this method should be compared to the stream channel to ensure compatibility for the stream stability and organism passage. Likewise, small culverts with large sediment may pose an increased risk of debris and ice accumulation.



Figure 5.4.2. Boulders added to this culvert are much larger than the apparent bed material, and occupy a significant fraction of the cross sectional area (photo B. Hansen)

5.4.4 Maintenance Considerations

- Culverts classified as bridges should be inspected per bridge inspection cycle requirements.
- Regular inspections for all culverts are advisable, especially during or after large flood events.
- After a large flow, it may be prudent to verify that the expected streambed state (stable bed or mobile bed) matches the design intent.

5.4.5 Example

Refer to Appendices H, I, and J of HEC 26 (Kilgore et al. 2010) for examples of this method. Examples are worked using both HY-8 and HEC-RAS software programs for calculations. The Sickie Creek example in Appendix J is especially relevant to Minnesota as it is a sand bed stream.

5.5 EMBEDDED AND RECESSED CULVERTS

5.5.1 Method Definition and Design Intent

Definition: Recessed culverts are installed with the culvert invert set below the streambed elevation to allow natural sediment transport to continue through the culvert. Other names for this general method include sunken, countersunk, or depressed culverts. As used in this document, an embedded culvert is recessed below the streambed elevation and filled with natural streambed sediment at construction.

Design intent: The intent is to maintain streambed characteristics and processes through the culvert, with the goal of providing bed roughness to aid in the passage of aquatic organisms and continuity of sediment transport to support stream stability and long-term passage.

5.5.2 Benefits

- Generally improved low-flow depths compared to non-recessed designs.
- Recessed or embedded culverts represent a method of geomorphic simulation that may account for some characteristics of a stream channel.
- Somewhat simpler design procedure than other methods for less complex stream crossing sites.
- Aspects of this method are becoming common culvert design practice in Minnesota.

5.5.3 Key Design/Implementation Considerations

Since a sediment bed is important to AOP and stream connectivity, it is essential to consider how the bed will initially form in the culvert, whether placed at construction or allowed to wash in by stream action, and how the bed will be maintained in the culvert over time.

Sediment retention in recessed and embedded culverts has been examined in several previous Minnesota studies. Hansen et al. (2011) reported on field observations of 13 culvert sites where the culvert invert was below the streambed (recessed). Of the six sites that lacked sediment in the recessed culvert barrel, causes were culvert slope steeper than channel bed, and lack of transportable sediment or bed load in the stream. Kozarek and Mielke (2015) found in laboratory experiments of box culverts that initially filling the culvert resulted in less risk of upstream erosion or head cuts as well as helping to ensure sediment remained in the culvert under both bankfull flow and simulated storm hydrographs. Constructed geomorphic structures such as steps, ribs, boulders, and riffles were critical to the stability of sediment in high gradient culverts (greater than 3% slope).

Based on these studies and others, the following design recommendations are suggested:

- Set the culvert width equal to or slightly greater than bankfull width. Bankfull width is a critical dimension of this method and can be difficult to determine in some situations such as degraded streams and urbanizing watersheds with changing hydrology (Section 3.5).
- Set the culvert slope equal to the stream slope.

- Site specific data on hydrology, grain size distribution, sediment mobility and shear stress, armoring, and roughness elements is required to be able to predict the movement of sediment into and through the culvert.
- For multi-barrel culverts, embed one barrel below the streambed (Section 6.1).
- The need for building structures or additional stability measures inside or outside of the culvert should be identified from the site specific data. An Ohio study by Tumeo and Pavlick (2011) found that sediment was not retained in recessed culverts over 1% slope.
- Fill the culvert with a grain size mix representative of the stream to protect against upstream scour or head cuts. (This may not be necessary in very mobile bed streams with high sediment supply). If streambed material is available onsite such as from excavation below the culvert, it can be used for this purpose. Material should not be excavated from the stream banks or bed to fill the culvert as this could destabilize the stream, contrary to the goal of connectivity.
- In many cases, additional sediment will need to be brought in to provide a continuous sediment bed through the culvert. The culvert fill material should be a dense, well graded (poorly sorted) sediment mix with the range of sizes found in the reference channel, and at least as angular in shape as the reference channel. Large pieces (D95 to D50 range) provide the bed structure for smaller sizes to fill in. Bed material should be placed and compacted mechanically or by washing in the fines during construction (FSSSWG 2008).
- Where a mobility analysis (Section 4.3.1) indicates the grain size mix representative of the stream will be mobile at considerably lower flows than in the stream channel, a layer of stone sized to be stable at high flows may be needed to be incorporated to retain a sediment bed within the culvert. This stable material can be incorporated or placed below the representative native bed material to ensure some material and roughness remains in the culvert even if the upper layer is mobilized and washed out during a large flood.
- For high gradient streams (typically >3%), install structures - steps, pools, cascades, large boulders, ribs, riffles - made up of large interlocking pieces within the culvert to maintain sediment stability in culverts and to prevent headcuts upstream. These structures are also critical to providing flow complexity (resting areas, etc.) needed by fish and aquatic organisms for upstream passage. See Woods Creek example (Section 3.11.1). Size, type, and spacing of structures should be determined by a reference reach survey.
- Also for high gradient streams, structures upstream of the culvert and on the upstream end inside the culvert are the most susceptible to failure and should be sized accordingly. No structures are recommended less than one-half to one times bankfull width from the upstream end of the culvert (within the culvert).
- Other considerations
- Recessed culverts should be assessed for the potential for headcut formation and migration, resulting in the eventual lowering of the streambed to the (formerly) recessed culvert elevation. This requires geomorphic assessment upstream and downstream of the culvert, potentially up to a half-mile or more, which is beyond the scope of analysis done for most culverts.
- Addition of grade control may be required.

- Bed stability can be checked using methods listed in FHWA HEC 26 (Section 5.2) or USFS Stream Simulation (Section 5.3). Excess shear stress and subsequent bed instability can result to pressure flow situations or funneling too much floodplain water to a channel culvert.

Sediment Bed Construction for Embedded Culverts

Both USFS Stream Simulation (FSSSWG 2008) and FHWA HEC 26 (Kilgore et al. 2010) include sections on specifying culvert bed material for embedded culverts. Another approach that has been used in Minnesota is to combine standard riprap with native stream material or imported material having a similar gradation. Where this approach is used it is important to ensure enough fine material is incorporated to fill pore spaces so that water flows over the surface of the bed, and not sub-surface. Position the larger immobile stones (key pieces) as necessary to create a stream-like channel. Shaping of a low flow or pilot channel at construction is highly recommended to provide habitat and passage features.

The following series of pages (Figure 5.5.1 to Figure 5.5.4) comprise a flow chart for design of recessed or embedded culverts.

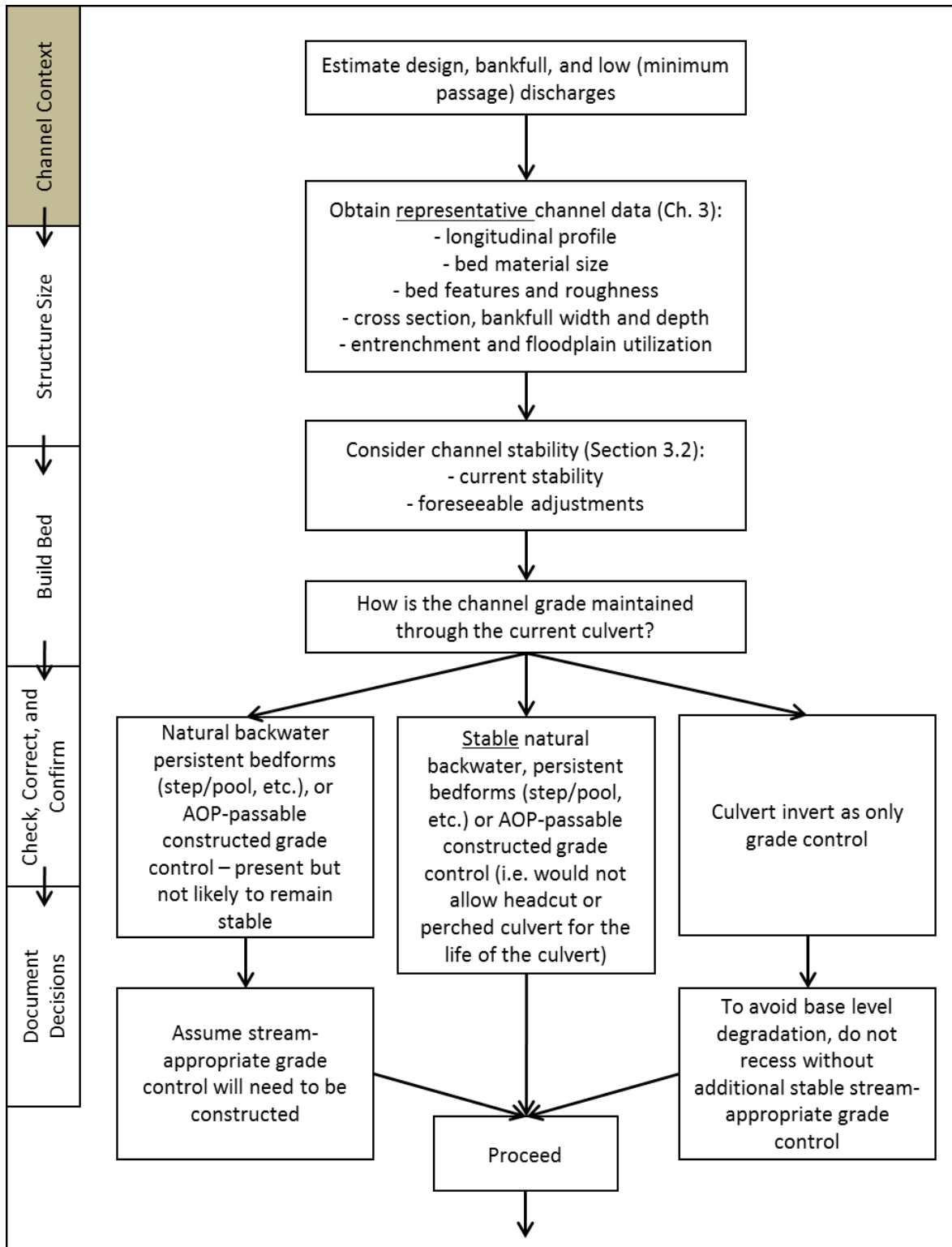


Figure 5.5.1. Design chart for recessed or embedded culverts: Channel context

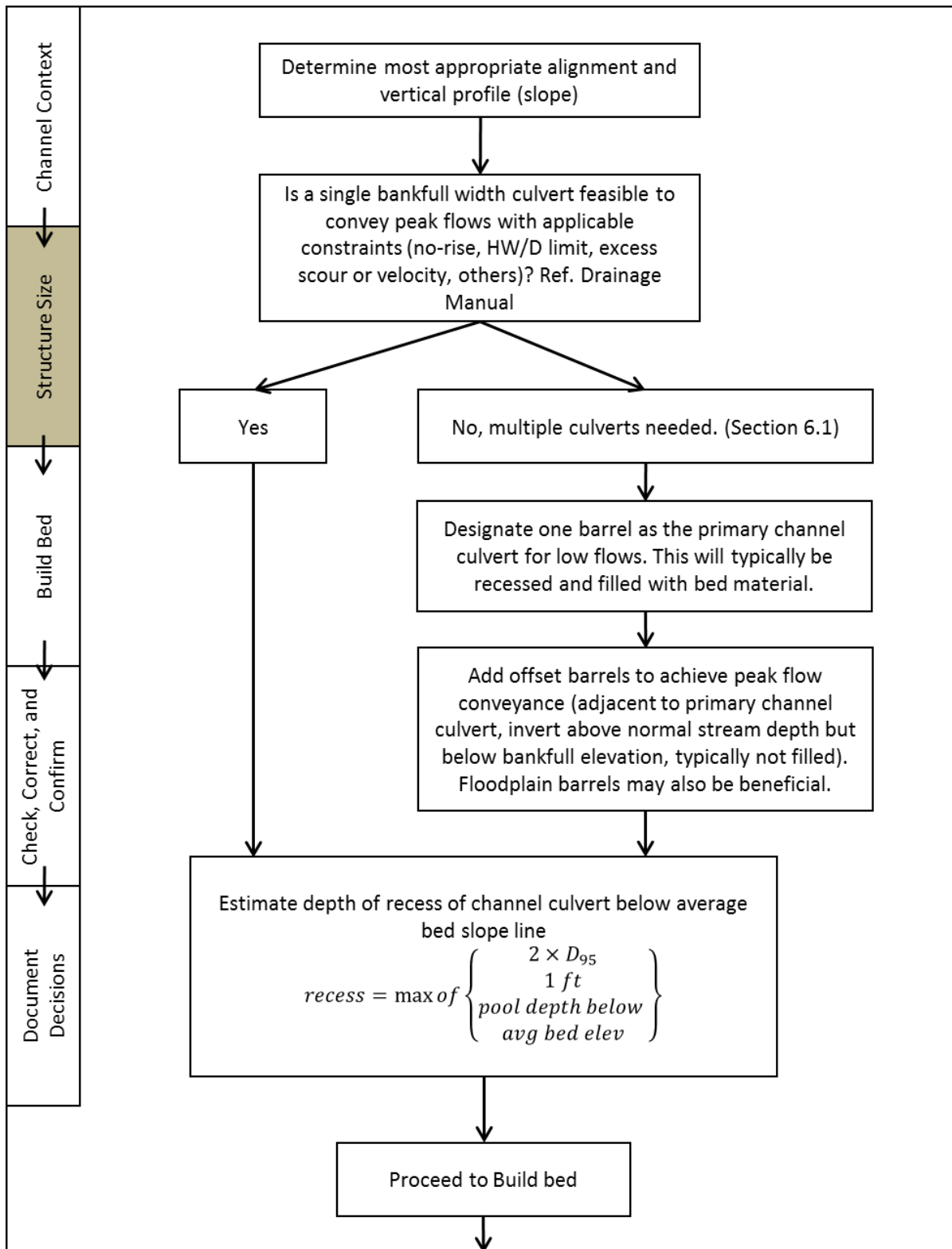


Figure 5.5.2. Design chart for recessed or embedded culverts: Structure size

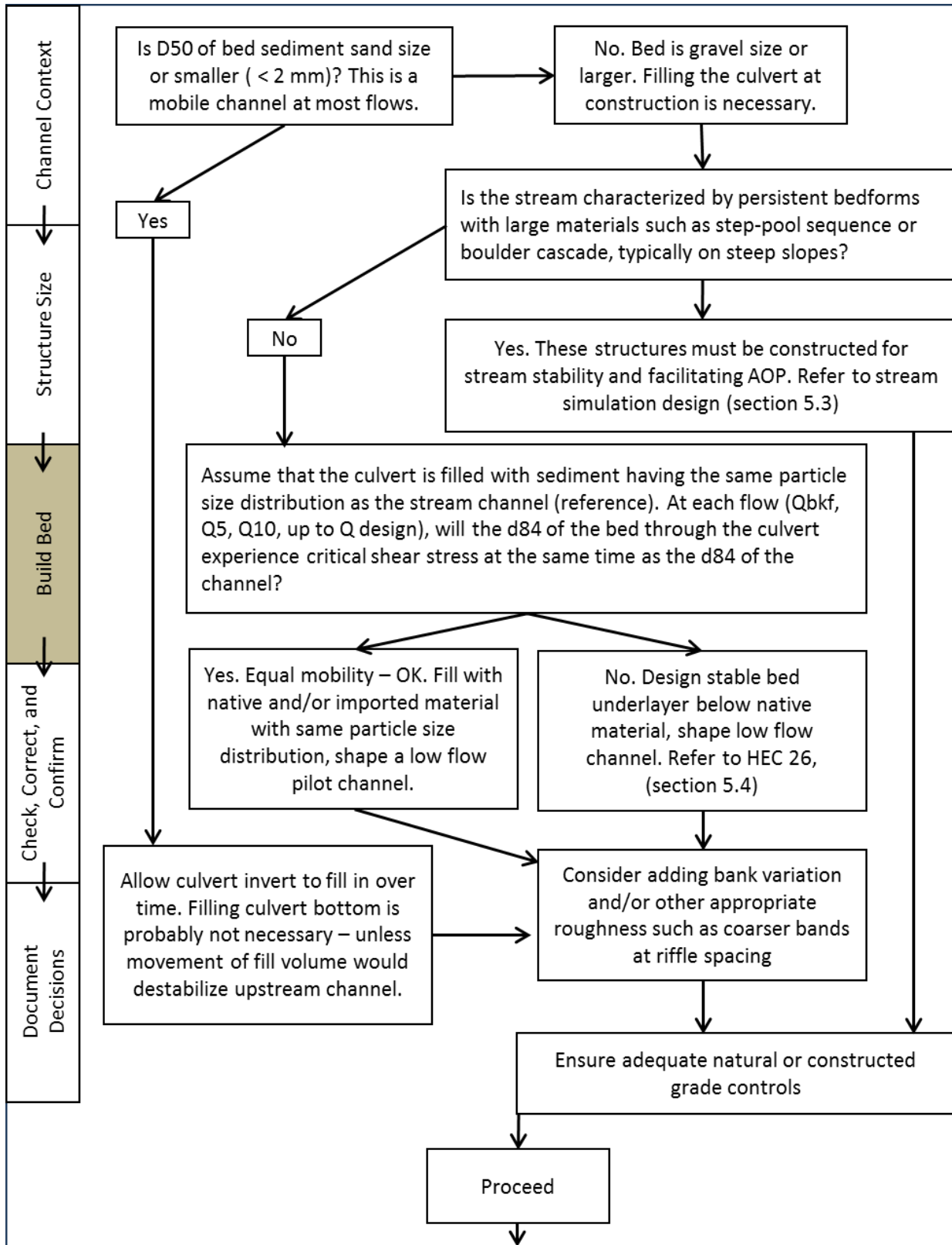


Figure 5.5.3. Design chart for recessed or embedded culverts: Build bed

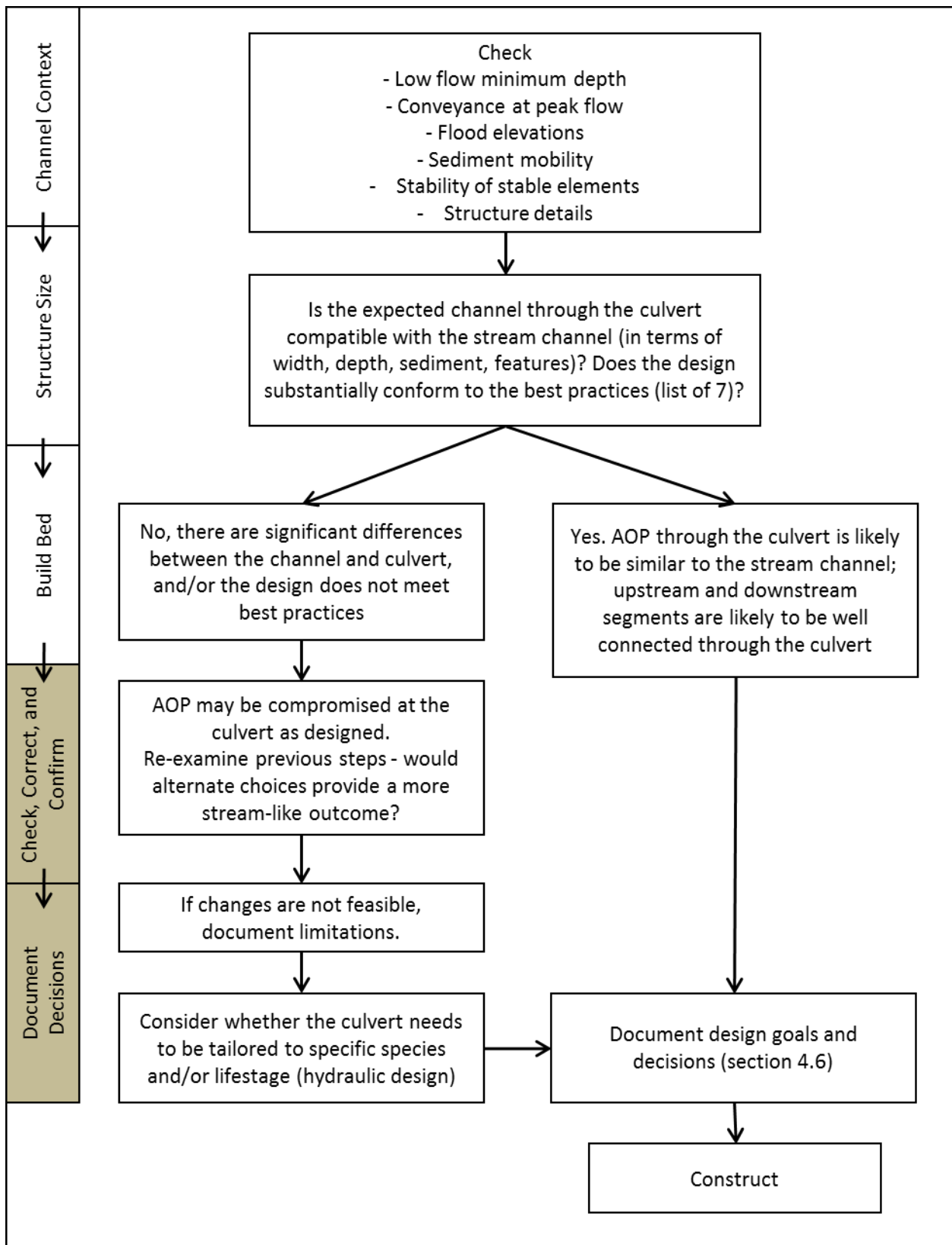


Figure 5.5.4. Design chart for recessed or embedded culverts: Check, correct, confirm, and Document Decisions

5.5.4 Maintenance Considerations

One maintenance consideration is to determine whether the amount of sediment in the culvert barrel is appropriate, i.e. adequate to facilitate AOP, or excessive, such that peak flow capacity is reduced due to aggradation. Comparison of observed conditions with documented design assumptions (Section 4.6) may be helpful.

- Culverts classified as bridges should be inspected per bridge inspection cycle requirements.
- Regular inspections for all culverts are advisable, especially during or after large flood events.
- After a large flow, it may be prudent to verify that the expected streambed state (stable bed or mobile bed) matches the design intent.
-

5.5.5 Design Example – Le Sueur Creek

This example presents a hypothetical recessed / embedded culvert design based on a road crossing of Le Sueur Creek in Le Sueur County. The example follows the flowchart in Figure 5.5.1 to Figure 5.5.4 and builds upon site assessment material including figures and tables presented in Section 3.11.2 . An aerial photo of the site is shown in Figure 5.5.5.

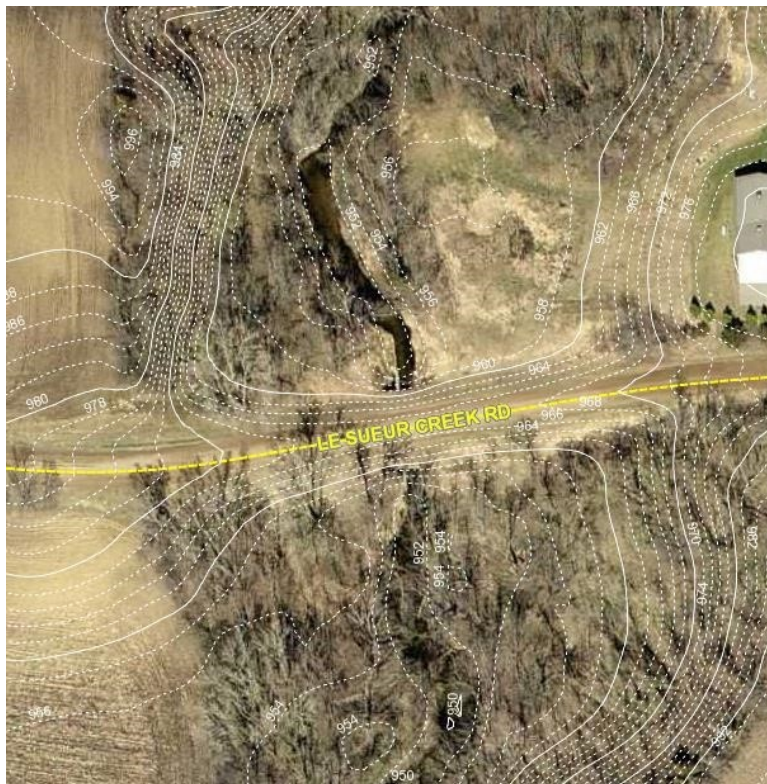


Figure 5.5.5. Le Sueur Creek at Le Sueur Creek road, with flow from top to bottom of the figure. LiDAR-derived contour data is shown overlaid on an April 2010 aerial photo. Accessed through Le Sueur County GIS viewer.

Existing Culvert Data

Existing culvert data is summarized in Table 5.5.1. There is considerable sediment build up at the inlet and outlet of the west barrel as noted previously. Where light reaches into the barrels, sediment is vegetated and is essentially a high stream bank. Mid-barrel there is about 12 inches of very fine sediment.

Table 5.5.1. Existing culvert data for Le Sueur Creek example.

	East Barrel (main channel)	West Barrel
Width x Height	12 x 10 ft	12 x 10 ft
Length	100 ft	100 ft
Slope	0.20%	0.20%
US station	3+57	3+57
US invert el.	947.5	947.5
Inlet sediment	0 - 0.5 ft	3-4 ft
DS station	4+57	4+57
DS invert el	947.3	947.3
Outlet sediment	0.1 ft	3-4 ft

Channel Context step from Figure 5.5.1

- Refer to Section 3.11.2 for representative channel data
- How is the channel grade maintained through the culvert?
 - Several rip-rap rocks in the channel immediately downstream of the culvert.
 - Gravel and small cobble riffles downstream.
 - A large debris jam at the first bend downstream.
 - The stream appears to be currently stable, but existing natural grade controls could be mobile in large flows – may consider burying riprap below the native bed downstream of the culvert as supplemental grade control.

Structure Size step from Figure 5.5.2

- Determine most appropriate alignment and vertical profile.
 - The existing alignment is generally OK as observed in the field. Alignment is discussed in Section 3.11.2 .
 - The preferred vertical profile is 0.19% to match the stream grade (Figure 3.11.6)
- Is a single bankfull width culvert feasible to convey peak flows with applicable constraints?
 - At 28 ft bankfull width, the span is too big for a conventional concrete box culvert. A three sided bridge structure could work, but since bedrock is not present pile foundations would be required for a MnDOT project (Section 5.2.3).
 - Assume multiple culverts will be used. Assume two 14 foot wide concrete box culverts to start, though other combinations that add up to bankfull width or greater (16+12, 20+8,

etc.) may be possible. With the amount of large woody debris in the stream, use of multiple culverts should be considered carefully (Section 6.1.3).

- Designate one barrel as the primary channel culvert for low flows.
 - The channel (primary) culvert will be on the outside of the bend (east) and will convey the stream thalweg and low flows.
- Add offset barrels to achieve peak flow conveyance (adjacent to primary channel culvert, invert above normal stream depth but below bankfull elevation, typically not filled). Floodplain culverts may also be beneficial.
 - One offset culvert will be located immediately to the west of the channel culvert, invert elevation to be decided.
 - Floodplain culvert barrels located away from the channel will not be used in this example, but could be increasingly helpful for a broader floodplain with higher entrenchment ratio.
- Estimate depth of recess of the channel culvert below average bed slope line (See Figure 5.5.6) to a maximum of:
 - $2 \times D_{95} = (2 \times 107 \text{ mm} = 214 \text{ mm} = 8.4 \text{ inches})$
 - 1 ft
 - Pool depth below average bed elevation. Referring Figure 3.11.6, the deepest pool appears to be 1.2 feet below the average bed elevation.
 - Max = 1.2 ft; set the invert of the channel culvert 1.2 feet below the average slope line.

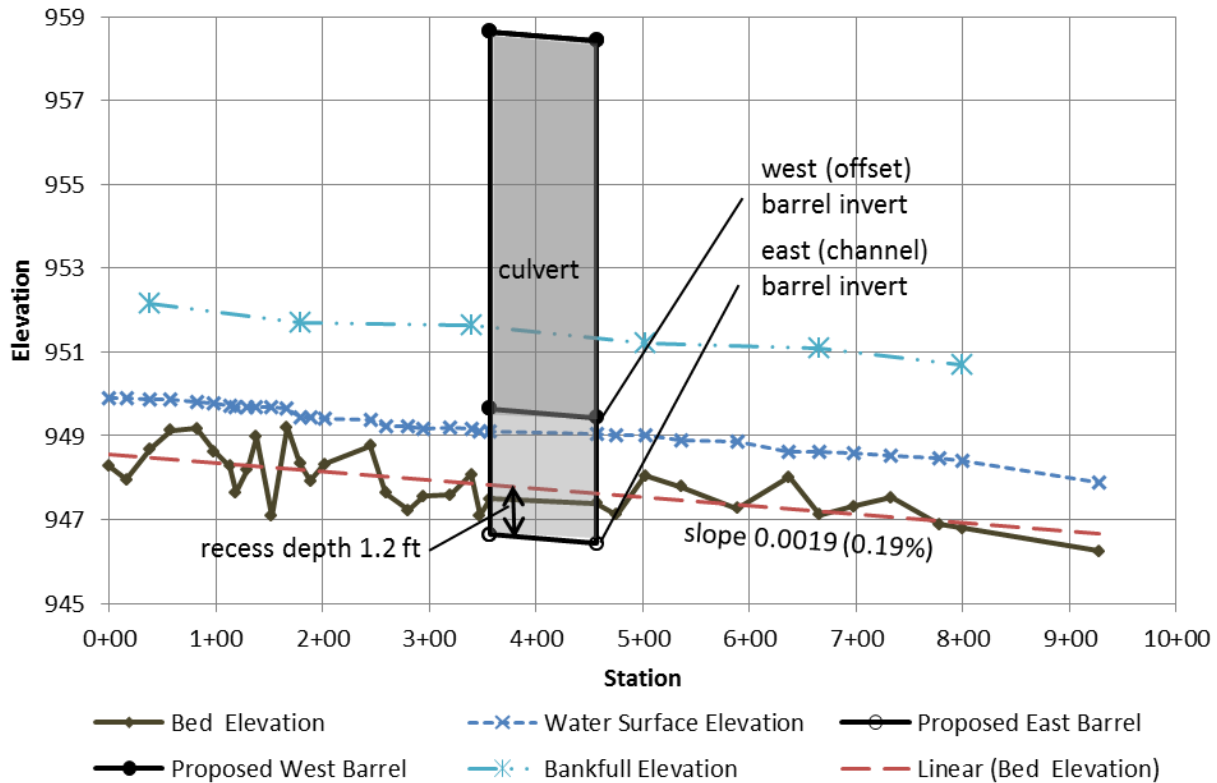


Figure 5.5.6. Design vertical profile for Le Sueur Creek example. Station and elevation in feet.

Structure design details calculated or assumed so far are summarized in Table 5.5.2.

Table 5.5.2. Le Sueur Creek example preliminary culvert details. US = upstream (inlet), DS = downstream (outlet).

	East Barrel (main channel)	West Barrel (offset)
W x H (ft)	14 x 12	14 x 9
Length(ft)	100	100
Slope	0.19%	0.19%
US station	3+57	3+57
US Invert	946.64	949.64
Sediment depth	1.2 (installed average)	0.5 (assumed accumulation)
US flowline	947.84	950.14
US crown	958.64	958.64
DS station	4+57	4+57
DS invert	946.45	949.45
Sediment depth	Same as US	Same as US
DS flowline	947.65	949.95
DS crown	958.45	958.45

Build Bed step from Figure 5.5.3

- Is D_{50} of bed sediment sand size or smaller?
 - No, $D_{50} = 11\text{mm}$, medium gravel size (see Figure 3.11.9). Filling the culvert at construction is necessary to allow adequate sediment transport and prevent creation of a headcut. If sediment is not initially placed in the culvert, it may take years to form a sediment bed that is consistent with the stream reach.
- Is the stream characterized by persistent bedforms with large materials such as step-pool sequence or boulder cascades, typically on steep slopes?
 - No – a series of pools and riffles is observed in the reference reach. The gravel pieces forming the heads of riffles probably move every few years on average. Step structures or boulder cascades do not need to be constructed as they would be out of place for the stream.
- Assume that the culvert bottom is filled with sediment having the same particle size distribution as the stream channel. Will the D_{84} particle in the culvert experience be exposed to critical shear stress at the same flows as in the reference channel?
 - $D_{84} = 43\text{ mm}$, very coarse gravel (see Figure 3.11.9)
 - Calculate critical shear stress for the D_{84} particle using the modified Shield's equation (Section 4.3.1.2), $\tau_p \left(\frac{\text{lb}}{\text{ft}^2} \right) = \tau_{50}^* (\gamma_s - \gamma) D_{84}^{0.3} D_{50}^{0.7}$
 - Shield's Parameter $\tau_{50}^* = 0.050$ (Table 4.3.2)

- γ_s = specific weight of the stone, assume 165 lb/ft³
 - γ = specific weight of the water, assume 62.4 lb/ft³
 - $D_{84} = 43 \text{ mm} = 0.14108 \text{ ft}$, $D_{50} = 11 \text{ mm} = 0.03609 \text{ ft}$
 - Critical shear stress $\tau_p \left(\frac{\text{lb}}{\text{ft}^2} \right) = 0.050 \left(165 \frac{\text{lb}}{\text{ft}^3} - 62.4 \frac{\text{lb}}{\text{ft}^3} \right) 0.14108 \text{ft}^{0.3} 0.03609 \text{ft}^{0.7} = 0.28 \frac{\text{lb}}{\text{ft}^2}$
- Calculate applied shear stress for a series of flows in the culvert and in the reference reach channel cross sections. The equation (Section 4.3.1.1) is, $\tau_0 = \gamma R S$
- Applied shear stress at the representative channel cross section (Figure 3.11.8), was estimated using the USDA NRCS Cross-section Hydraulic Analyzer (see link in Section 4.2.1) and is summarized in Figure 5.5.7. In an actual situation, consideration of several cross sections for shear calculations would be preferred.

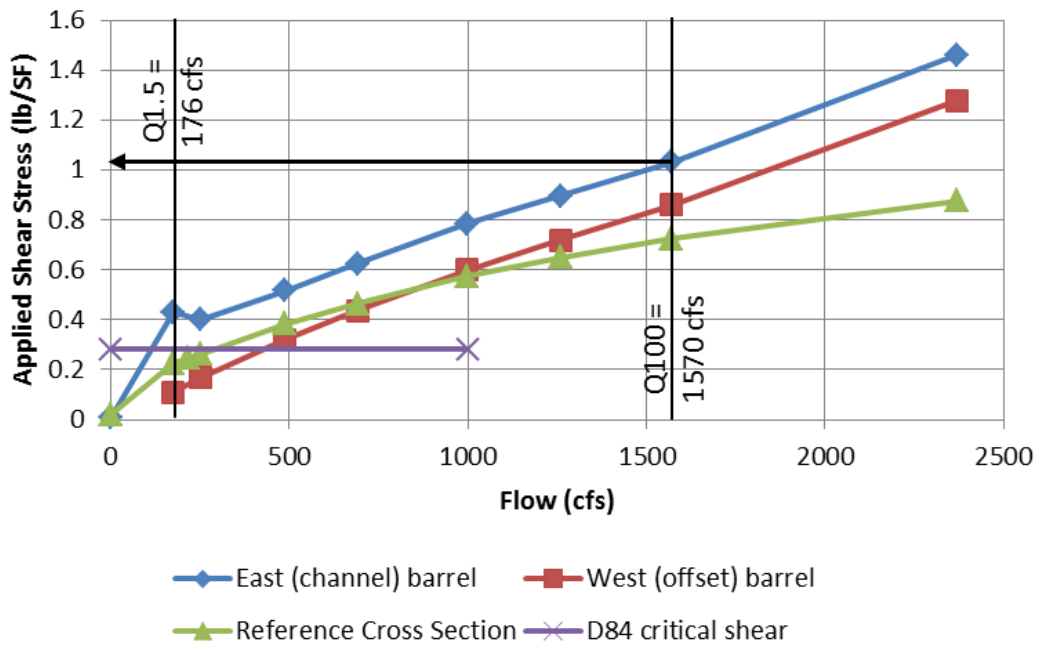


Figure 5.5.7. Applied shear stress for Le Sueur Creek embedded culvert design example. There is an inflection point in the reference cross section line near 1,000 cfs which likely corresponds to the flow accessing a much wider floodplain. The jump in shear stress at Q1.5 for the east barrel versus the Q2 appears to be related to the calculation of energy slope.

- Applied shear stress in the proposed culvert was calculated using water surface profiles generated in a HY-8 model (also Section 4.2.1). First, a “crossing” consisting of two different culverts (east channel culvert and west offset culvert) was tried, but unfortunately HY-8 could not resolve the flow in each barrel – it did not add up to the input total. A workaround using a “user-defined section” (Figure 5.5.8 and Figure 5.5.9) having a different ‘n’ value for the bottom (sediment) and sides (concrete) appears to function properly. Water surface profile data and shear data reported by HY-8 is an average across both “barrels”. The data was pasted into a

spreadsheet and depth (and thus hydraulic radius R and energy slope S) and applied shear stress in each barrel were calculated. Maximum applied shear stress occurred at the culvert outlet for all cases except the very low flow (1.3 cfs) and is shown in Figure 5.5.7.

- Note that although this workaround was used and appears to yield correct results, use of an alternative application for calculations may be preferable.

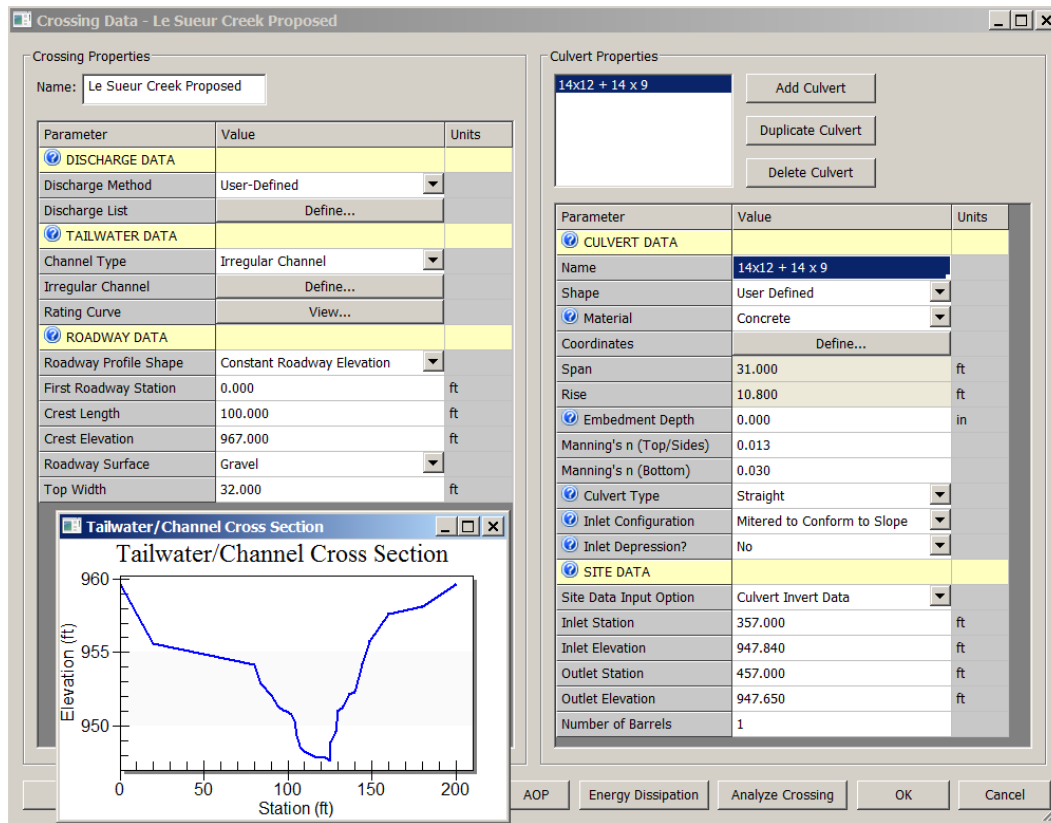


Figure 5.5.8. Data input screen for a HY-8 model of the Le Sueur Creek embedded culvert design example. The inlet elevation corresponds to the design (average) bed elevation, noted as the flowline elevation on the following figure.

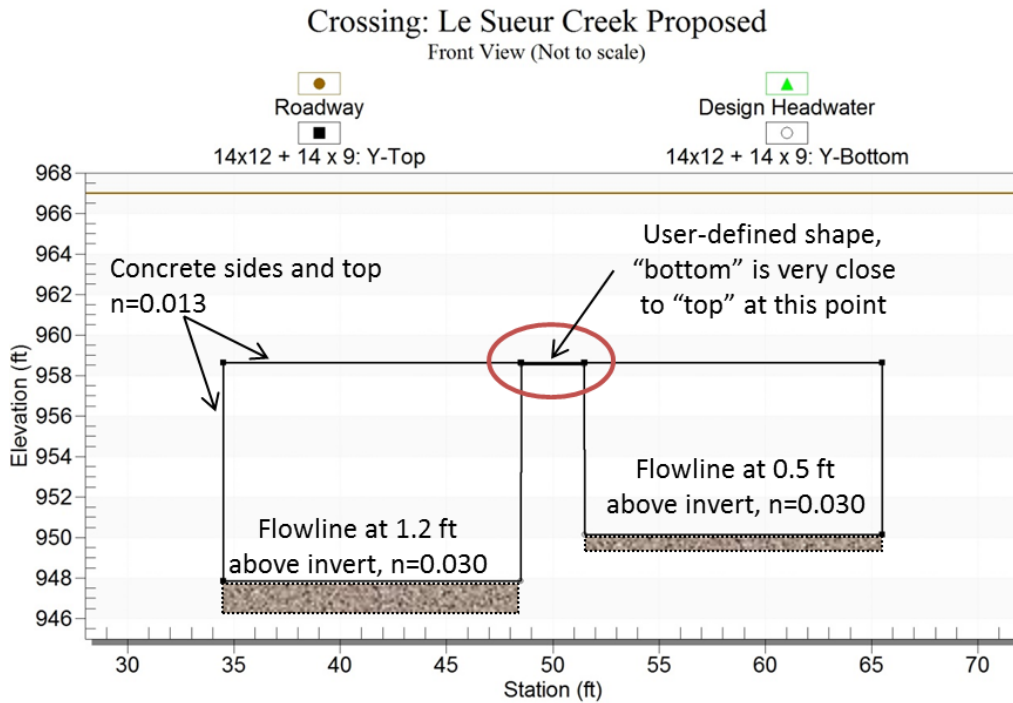


Figure 5.5.9. User-defined shape used in HY-8 to simulate the proposed two-barrel, vertically offset culvert for the Le Sueur Creek embedded culvert design example. Notes are added as well as shaded areas to show the assumed amount of streambed materials or fill in each culvert.

- As shown in Figure 5.5.7, applied shear stress is higher in the east (channel) barrel than the reference cross section everywhere, therefore mobility of the D_{84} particle will not be equal in the culvert and the reference cross section – the D_{84} will move on the sediment bed in the east culvert barrel before the channel due to higher shear stress.
 - Design stable bed underlayer below native material, shape low flow (pilot) channel. Refer to HEC 26 (Kilgore et al. 2010).
 - Referring to Figure 5.5.7, applied shear stress in the east barrel is ~ 1.05 psf at the Q100 flow, which is the design flow. The D_{50} of the underlayer should be stable at this applied shear stress
 - Attempt to identify a stable material. Apply the modified Shield's equation (Section 4.3.1.2) to determine the critical shear stress of possible materials. Referring to Figure 5.5.10, a graphical representation of several standard MnDOT riprap gradations developed as a design aid, D_{50} for Riprap I is ~ 75 mm (0.25 ft) and D_{84} is ~ 130 mm (0.43 ft). Referring to Table 4.3.2, $\tau_{50}^* = 0.052$ for the D_{50} .
 - $\tau_p \left(\frac{\text{lb}}{\text{ft}^2} \right) = 0.052 \left(165 \frac{\text{lb}}{\text{ft}^3} - 62.4 \frac{\text{lb}}{\text{ft}^3} \right) 0.43 \text{ft}^{0.3} 0.25 \text{ft}^{0.7} = 1.57 \frac{\text{lb}}{\text{ft}^2}$
 - $\tau_p = 1.57 \frac{\text{lb}}{\text{ft}^2} > \tau_0 = 1.05 \frac{\text{lb}}{\text{ft}^2}$; since the calculated critical shear stress exceeds the calculated applied shear stress, median Riprap I particle will be stable at the design

flow. However, the riprap alone lacks the smaller particles to form a dense mix without voids that is capable of supporting the streambed through the culvert.

- The native stream material has also been plotted on Figure 5.5.10. If not enough native material of similar composition is available onsite, an alternative can be specified. In this case it happens that the native material gradation is similar to the finer edge of MnDOT Granular Filter material. By trial and error, an underlayer mix of 1/3 granular filter (fine) and 2/3 Riprap I (plotted in Figure 5.5.10) has a $D_{84} \sim 115$ mm, $D_{50} \sim 47$ mm. This mixture has $\tau_p = 1.11 \frac{\text{lb}}{\text{ft}^2}$ for the D_{50} , which slightly exceeds the critical shear stress at design flow.

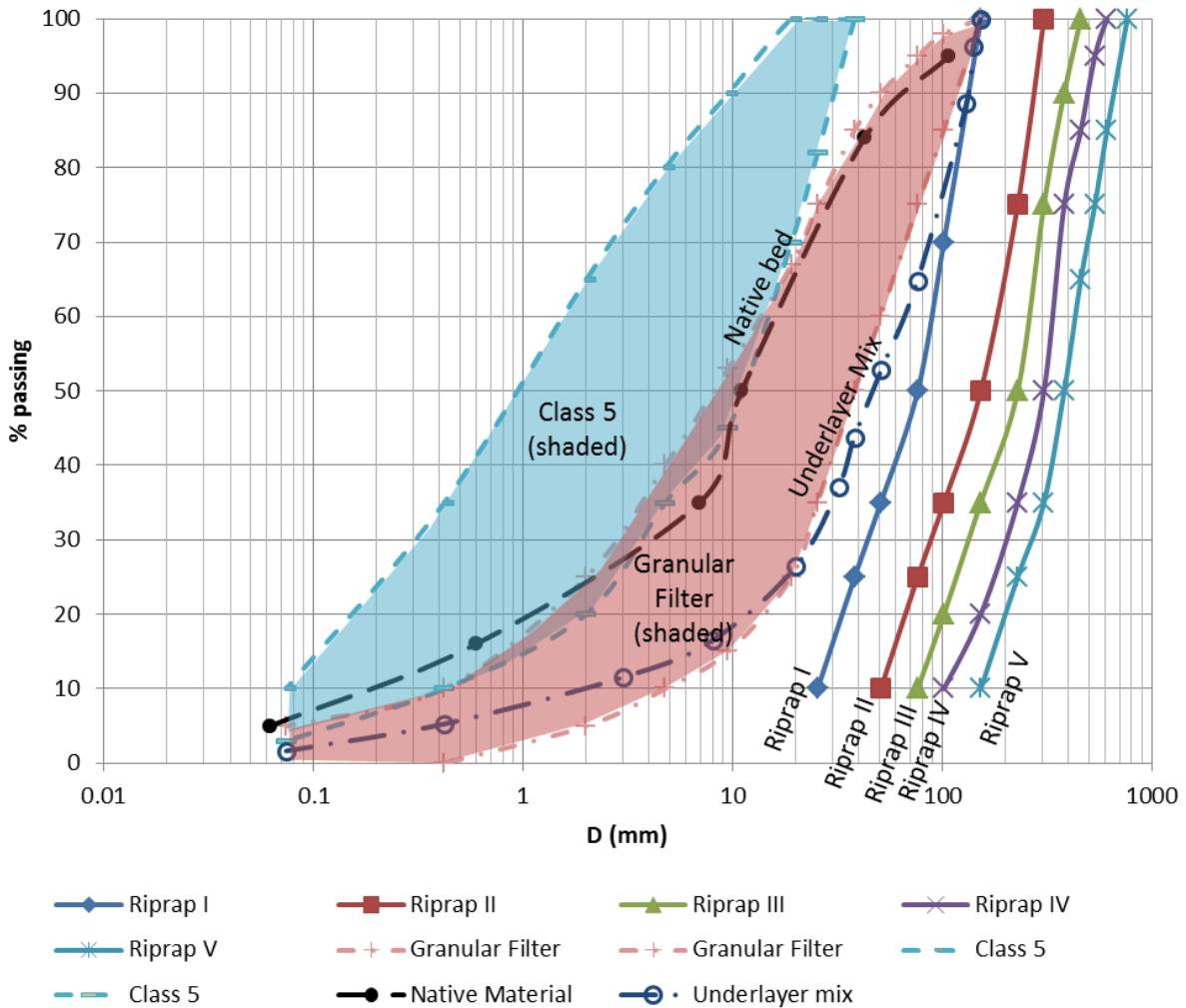


Figure 5.5.10. Comparative gradations of possible culvert channel bed fill materials for Le Sueur Creek example.

- Section 7.9 of HEC 26 (Lagasse et al 2012) suggests a minimum stable underlayer thickness of $1 \times D_{95}$ for box and pipe arch culverts, about 0.5 feet in this case. The same reference suggests a minimum native material top layer thickness as the maximum of $1 \times D_{95}$ or 1 foot. If the initial recess depth of 1.2 feet below the

flowline is retained, subtracting 0.5 feet for the underlayer leaves only 0.7 feet of native material on top. This is probably reasonable since the underlayer is partially composed of the smaller native material.

- Initial shaping of a low-flow pilot channel is desirable to allow low-flow passage and to speed the natural process of channel organization through the structure – this is discussed in a subsection below. A sketch of the bankfull, normal, and low flow channels is shown in Figure 5.5.11.

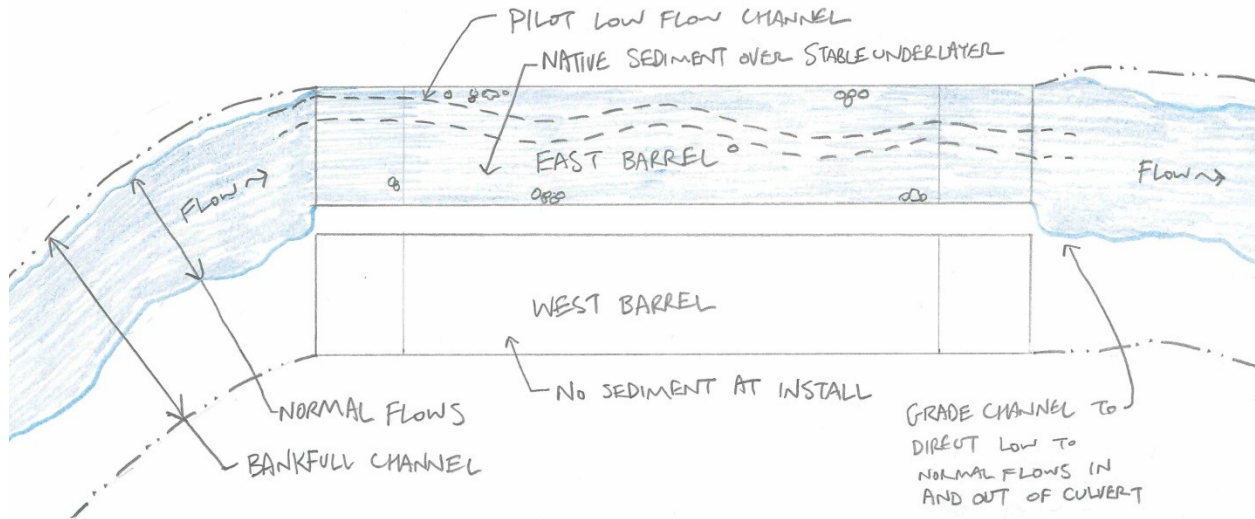


Figure 5.5.11. Plan view sketch of Le Sueur Creek example culvert indicating initial sediment fill and channel shaping.

- Consider adding bank variation and/or other appropriate roughness such as coarser bands at riffle spacing
 - Bank variation – providing bank line rocks or built banks is probably not necessary in this case. Depending on the aquatic species present, bank line rocks may be beneficial, and may help to maintain the low flow channel.
 - Cobbles and small boulders are found in the reference reach and could be strategically added to the culvert bed to increase habitat and refuge areas within the culvert.
 - For the upper layer of native sediment, placing slightly coarser bed material at the riffle spacing observed in the reference reach will allow the riffle-pool sequence to form faster.
- Ensure adequate natural or constructed grade controls
 - See Channel Context above.

Check, Correct, and Confirm step and Document Decisions step from Figure 5.5.4

- Check:
 - Low flow minimum depth
 - Assuming an initial flat bed inside the 14 foot wide channel culvert, minimum flow ($Q=1.3$ cfs, see Section 3.11.2), $S=0.0019$, $n=0.03$, water depth per Manning's equation is 0.16 feet, and velocity is 0.6 feet per second. This is quite shallow for passage of many adult fish. An initial low-flow pilot channel should be created in the sediment. If the low flow channel is modeled as a trapezoid with bottom width of 2 ft and 2h:1v sideslopes, using Manning's equation with the same parameters, water depth is 0.45 feet and velocity is 1.0 feet per second at $Q=1.3$ cfs. This is a more reasonable low flow depth for organism passage.
 - Conveyance at design flow
 - Per the HY-8 calculations, there appears to be adequate conveyance at the design flow, headwater elevation is 957.64 (HY-8 assumes a ponded condition), maximum depth in the culvert is 955.90 near the inlet, and the inlet crown elevation is 958.64 (Table 5.5.2).
 - Flood elevations
 - Existing flood elevations were not calculated for this example, so there is no basis for comparison.
 - Sediment mobility
 - Due to increased shear stress in the culvert barrels (Figure 5.5.7) at flood flows, the same size bed particle will become mobile at lower flows in the culvert than in the channel during flood flows. Over time the bed through the culvert may become somewhat coarser than the stream channel during flood flows, but not unreasonably so, judging by the stone sizes observed in some parts of the channel (Figure 3.11.5). There is considerable fine sediment supply in the channel which will be mobile in the channel and culvert multiple times per year.
 - Stability of stable elements
 - A stable underlayer has been provided and the stability checked at the design flow.
 - Structure details (not in the scope of this example)
- Is the expected channel through the culvert compatible with the stream channel (in terms of width, depth, sediment, features)? Does the design substantially conform to the best practices?
 - Design the culvert slope to match stream channel slope
 - Culvert slope matches stream slope.
 - Place the culvert to best match stream alignment
 - Existing alignment appears to be adequate and will be retained.
 - Design the culvert opening to bankfull channel width or slightly greater
 - Estimated bankfull width = 28 ft, culvert opening (total at bankfull) = 28 ft.
 - Provide flow depth comparable to channel depth for aquatic organism passage (not over-wide and too shallow)

- During low (non-flood) flows, water will pass through the main barrel in which a pilot channel for very low flows has been created. This will help to ensure adequate depth for passage.
 - Provide a continuous sediment bed with roughness similar to the channel
 - A sediment bed will be placed at culvert installation, providing bottom roughness and some habitat.
 - Account for sediment transport and debris passage
 - Sediment mobility and stability has been taken account in design. The presence of large woody debris in the stream combined with the two barrel design warrants vigilance to detect possible issues with large debris.
 - Design for longevity and resilience
 - Design choices including concrete culverts, adequate total width, and looking at grade controls and sediment help to promote adaptability of the design and long term viability of the culvert and road infrastructure, as well as aquatic organism viability and stream health.
- Document design goals and decisions
 - Notes on the design intent, details, and sediment are below. A summary of the design parameters for the proposed culvert is shown in Figure 5.5.5.
 - *Design intent:* The crossing has been designed with aspects of geomorphic simulation and hydraulic simulation. Riprap calculated to be stable at the design flow has been placed below native (and/or simulated native) streambed materials which form the normal channel through the culvert. These materials have been provided at construction as the building materials of a stream-organized channel through the culvert which is expected to provide depths, velocities, and structures similar to those found in the stream channel.
 - *Design details:* The stream thalweg is routed through the east barrel on the outside of the bend. Refer to tables and figures for additional details.
 - *Maintenance:* Large woody debris should be removed from the culvert inlet if present, especially if longer than a single barrel width. Large debris should be removed from inside the barrels, especially if jammed against any surface. Sediment in the lower (east) barrel is expected and should not be removed unless excessively accumulated above 1.5 to 2 feet above the culvert invert on average (10 to 10.5 feet below the crown). The west barrel is designed without sediment; accumulation above 0.5 feet above the invert of the west barrel should be removed.
 - *Expected stream changes due to the culvert:* A slight re-grade in the first 1-200 feet upstream of the culvert may occur as aggraded sediment is transported through the culvert.

5.5.6 Design Example – Moody Creek

This design example is based on a hypothetical culvert replacement on Moody Creek at West Splithand Road in Itasca County. Moody Creek is a very low-gradient (0.05%), sand bed stream located near Grand Rapids, Minnesota. The stream is characterized by extensive timberlands and wetlands upstream, and the crossing site is near the stream outlet to Splithand Lake. Figure 5.5.12 is an aerial photo of the site and immediate context.



Figure 5.5.12. Aerial image of site context for Moody Creek example, with base data from Itasca County GIS. Flow in the creek is from left to right.

Most data presented in the example is taken primarily from field observations gathered by Brad Hansen and Sara Mielke in September 2010 as part of their work published as Hansen et al (2011), supplemented by observations of the current authors. Note that if this were an actual design situation, changes over the intervening 8 years would mean the previous data should be checked or more likely collected anew.

Moody Creek is classified as E5 in the Rosgen classification scheme. Two of the three existing arch culverts are shown in Figure 5.5.13.



Figure 5.5.13. Existing Moody Creek culverts (Hansen et al. 2011)

Channel Context step from Figure 5.5.1

- Estimate design, bankfull, and low (minimum passage) discharges
 - From StreamStats, Design flow = $Q_{100} = 542$ cfs, Bankfull flow = $Q_{1.5} = 103$ cfs, minimum passage flow = 95% duration = 5.0 cfs. The drainage area is 20.8 square miles.
- Obtain representative channel data
 - A longitudinal profile at the culvert site is shown in Figure 5.5.14.
 - Bed material size. The bed is sand, with characteristics shown in Table 5.5.3, developed from a sieve analysis of bed material. The bed is not armored.

Table 5.5.3. Moody Creek example bed particle size from sieve analysis.

Class	mm	Description
D ₉₅	2	Coarse sand / fine gravel
D ₈₄	1.2	Coarse sand
D ₅₀	0.4	Medium sand
D ₁₆	0.2	Fine sand
D ₅	0.09	Very fine sand

- Bed features and roughness.
 - As typical of sand bed streams, roughness is generated by mobile bedforms. Bank roughness is generated by vegetation.

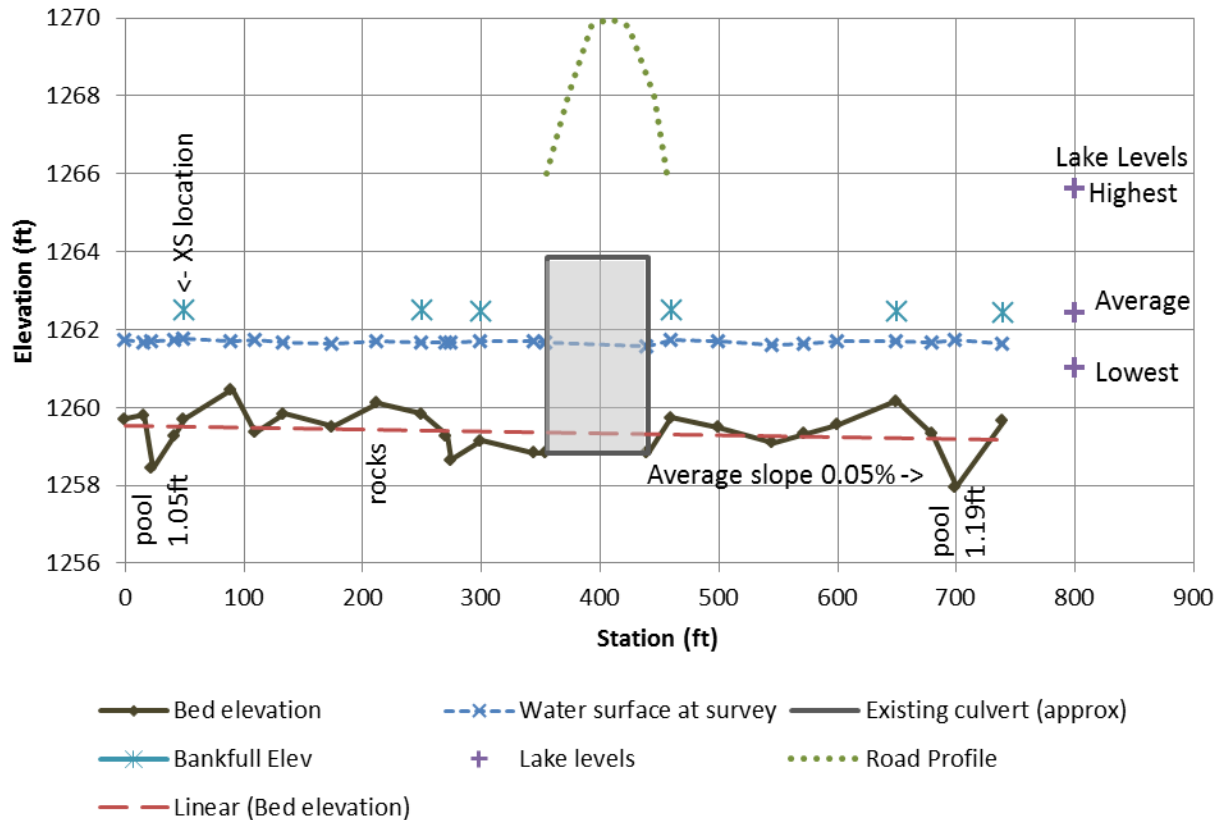


Figure 5.5.14. Longitudinal profile of Moody Creek. Split Hand Lake levels are adjusted to NAVD 88 datum from (<https://www.dnr.state.mn.us/lakefind/showlevel.html?downum=31035300>)

- Cross section, bankfull width and depth
 - From field measurements, the bankfull width is 19.8 ft, mean bankfull depth is 2.1 ft, and maximum bankfull depth is 2.77 ft. A cross section is shown in Figure 5.5.15. Note that while this section is representative of the stream as it parallels the roadway, the steep left bank does not represent the wide floodplain adjacent to the less-altered stream reaches
 - For comparison, the Eastern region geomorphology curve suggests a width of 26.3 ft and 1.7 ft mean bankfull depth. The measured dimensions are somewhat narrower and deeper, but the field measurement seems reasonable.
- Entrenchment and floodplain utilization
 - Entrenchment ratio: referencing the cross section in Figure 5.5.15, the width of the flood-prone area (valley width at two times the maximum bankfull depth) is 110 ft. The entrenchment ratio is 110 ft flood prone area width / 19.8 ft bankfull width = 5.6, classified as slightly entrenched (Section 3.7).

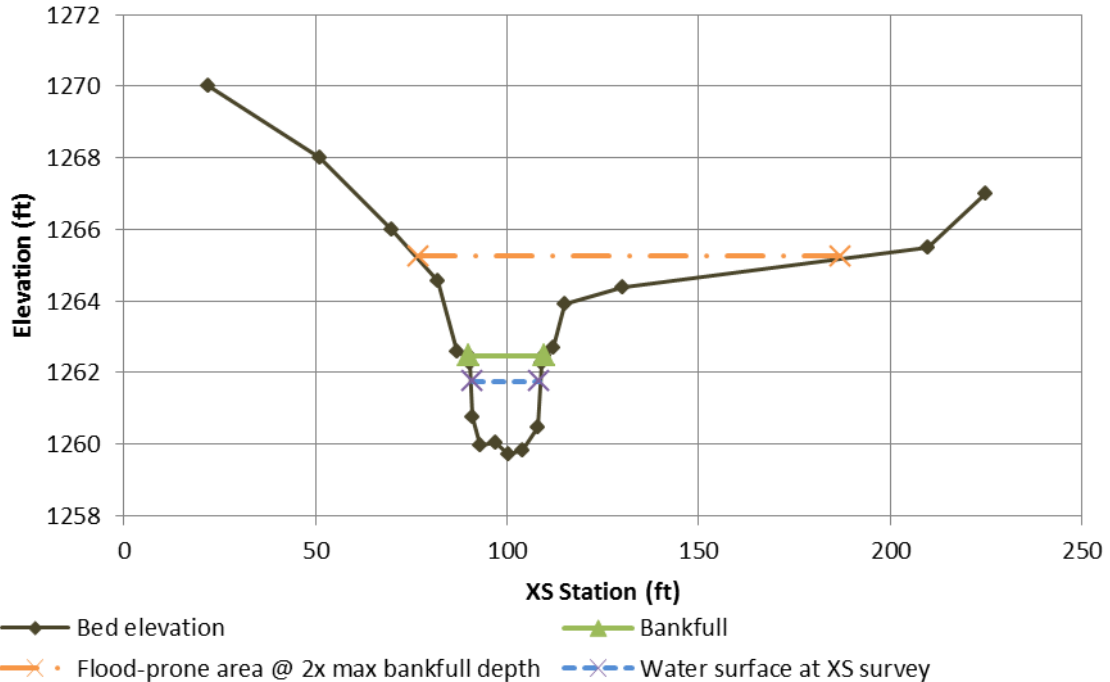


Figure 5.5.15. Cross section for Moody Creek example.

- Consider channel stability, current stability, and foreseeable adjustments
 - The Pfankuch stability index was rated at 87 (fair) both upstream and downstream. It is likely the channel will continue to evolve and become more sinuous in the straightened reach adjacent to the roadway.
- How is the channel grade maintained through the culvert?
 - The stream crossing is located approximately 2,400 feet upstream of Split Hand Lake. It appears that the culvert is often or perhaps always backwatered from the lake, which has a dam-controlled outlet. The backwater is thus a stable grade control; the streambed may exhibit local variation but is unlikely to downcut significantly.

Structure Size step from Figure 5.5.2

- Determine most appropriate alignment and vertical profile.
 - The existing inlet alignment is poor, nearly 90 degrees. The stream was re-routed and straightened for road construction, as shown in the aerial photo in Figure 5.5.16. If adequate right of way exists, it may be possible to shift the new culvert alignment north and reduce the inlet angle.
 - Design culvert slope = stream reach slope = 0.0005 ft / ft, or 0.05%. This is essentially a flat structure.



Figure 5.5.16. This 1947 aerial photo was likely taken not long after construction of the road and straight, parallel channel for Moody Creek. Cut off meanders are visible near the tee intersection. (photo from Minnesota Historical Aerial Photographs Online, <https://www.lib.umn.edu/apps/mhapo/>)

- Is a single bankfull width culvert feasible to convey peak flows with applicable constraints?
 - Try a single concrete culvert 20 ft wide, comparable to the 19.8 ft bankfull width.
- Estimate depth of recess of the channel culvert below average bed slope line to a maximum of:
 - $2 \times D_{95} = (2 \times 2 \text{ mm} = 4 \text{ mm} = 0.16 \text{ inches} = \text{negligible})$
 - 1 ft
 - Pool depth below average bed elevation. Referring to the Figure 5.5.14, the deepest pool appears to be 1.2 feet below the average bed elevation.
 - Set the invert of the channel culvert 1.2 feet below the average bed elevation line.

The preliminary culvert design parameters (Table 5.5.4) were analyzed in HY-8 as indicated in Figure 5.5.17. A tailwater rating curve was generated from a user-defined cross section in HY-8. The tailwater rating curve was adjusted upward where an analysis showed lake elevations would be higher. Table 5.5.5 is a summary of the results. The culvert operates under outlet control at all analyzed conditions.

Table 5.5.4. Preliminary culvert design parameters for Moody Creek example.

Width x height (ft)	20 x 8	
Length (ft)	100	
Slope	0.05%	
	Inlet	Outlet
Station	3+48	4+48
Invert elevation	1258.13	1258.08
Assumed sediment depth (ft)	1.2	1.2
Flowline	1259.33	1259.28
Crown	1266.13	1266.08

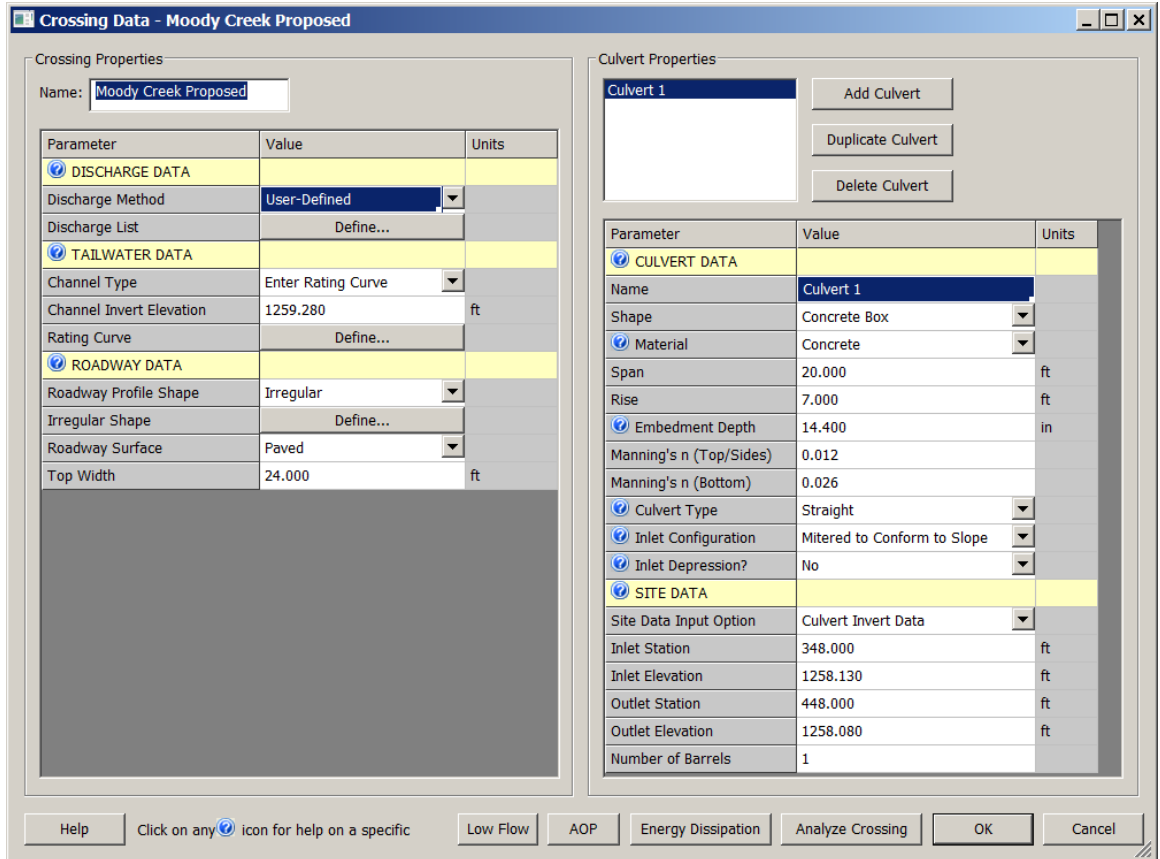


Figure 5.5.17. HY-8 input screen for Moody Creek example.

Table 5.5.5. HY-8 result summary for Moody Creek example.

Discharge	Culvert Discharge (cfs)	Headwater Elevation (ft)	Outlet Elevation = Tailwater (ft)	Outlet Velocity (ft/s)	Maximum applied shear stress (lb/sf)
Q_low_95	5	1262.50	1262.50	0.08	0
Q1.5	103	1262.59	1262.50	1.6	0.037
Q2	136	1263.11	1263.00	1.83	0.045
Q5	225	1263.85	1263.63	2.59	0.085
Q10	296	1264.56	1264.28	2.96	0.107
Q25	390	1265.17	1264.87	3.49	0.147
Q50	461	1265.64	1265.18	3.91	0.176
Q100	542	1266.07	1265.50	4.36	0.214
Q500	739	1267.01	1266.08	5.43	0.229

Build Bed step from Figure 5.5.3

- Is D_{50} of bed sediment sand size or smaller? This is a mobile channel at most flows.
 - Yes, $D_{50} = 0.4\text{mm}$, medium sand.
 - Allow culvert invert to fill in over time. Filling the culvert bottom is probably not necessary – unless movement of fill volume would destabilize the upstream channel.
 - What effect will movement of the fill volume (1.2 ft x 20 ft x 100 ft = 89 cubic yards) have on the upstream channel? For a sense of scale, this is equivalent to removing 3 inches from a 16 ft wide channel bed for 600 ft upstream. It may be prudent to fill or at least partially fill the culvert with sand bed material to guard against destabilization, especially since the stream is near the toe of the roadway embankment upstream of the culvert. There is no need to fill the culvert with coarser material such as gravel, and doing so may disrupt the equilibrium of sediment (sand) movement.
- Consider adding bank variation and/or other appropriate roughness such as coarser bands at riffle spacing
 - Bank variation could be added through the culvert with some bank rocks. This would help to direct the low flow channel and increase habitat diversity.
- Ensure adequate natural or constructed grade controls
 - The natural backwater acts as a grade control and is expected to be persistent. Additional controls are not needed.

Check, Correct, and Confirm step and Document Decisions step from Figure 5.5.4

- Check:
 - Low flow minimum depth
 - In this situation, assuming a ponded condition from the minimum lake level provides adequate minimum depth through the culvert.
 - Conveyance at design flow
 - Conveyance is adequate; the culvert is free-flowing up to Q100 (Table 5.5.5).
 - Flood elevations
 - See previous tables. This location is not a regulated flood plain.
 - Sediment mobility
 - The sediment bed through the culvert is assumed to be mobile at nearly all flows.
 - Stability of stable elements
 - Stable rocks are not part of the culvert bed design. If bank line rocks were included in the culvert, they should be analyzed for stability at design flows. Rip rap scour protection may be required along inlet or outlet guide banks, but is not included as part of this example.
 - Structure details (not in the scope of this example)
- Is the expected channel through the culvert compatible with the stream channel (in terms of width, depth, sediment, features)? Does the design substantially conform to the best practices?
 - Design the culvert slope to match stream channel slope
 - The culvert slope is set equal to the channel slope.
 - Place the culvert to best match stream alignment
 - The proposed culvert alignment is slightly improved over the existing culvert alignment. The inlet and outlet should be graded from the new culvert back to match the channel to eliminate the over-wide pool downstream.
 - Design the culvert opening to bankfull channel width or slightly greater
 - Proposed 20 ft wide culvert > 19.8 ft bankfull width
 - Provide flow depth comparable to channel depth for aquatic organism passage (not over-wide and too shallow)
 - Lake level records indicate that adequate water depth will remain through the culvert even under low flow/low level conditions.
 - Provide a continuous sediment bed with roughness similar to the channel
 - It is assumed a sand bed will form through the culvert. Providing the bankfull width through the culvert will allow channel development similar to outside the culvert.
 - Account for sediment transport and debris passage
 - See previous response. Debris with length up to the bankfull width should be able to pass through unimpeded. Ice buildup may be expected at this northern location; the substantial culvert width and height should allow passage of flow even when ice is present.
 - Design for longevity and resilience

- Since the proposed design accounts for the previous factors, it is expected that this culvert will maintain AOP through the stream. Hydraulic analysis shows the culvert will provide good reliability at high flows.
- Document design goals and decisions
 - Culvert details are shown in Table 5.5.4.
 - *Design intent*: The crossing has been designed with aspects of geomorphic simulation and hydraulic simulation. It is expected that a sand bed similar to the channel will develop through the structure, allowing similar aquatic organism passage and sediment transport as the stream reaches. This sand bed sediment will be mobile at most flows.
 - *Design details*: A single bankfull width concrete box culvert has been designed to accommodate the channel.
 - *Maintenance*: Sediment is expected in the culvert barrel and should remain in place unless excessive build up occurs (>1.5 feet average or significantly above upstream and downstream levels). Large woody debris should be removed from the culvert inlet if present, especially if longer than the barrel width. Large debris should be removed from inside the barrel, especially if jammed against any surface.

Note: The presence of the nearby lake influenced the design example. If the situation were different, other items such as grade control structures to mitigate against potential head cuts and low-flow channel features may need to be included in the design to adequately address AOP and stream connectivity.

5.5.7 Historical note

One method for installing recessed culverts developed in Minnesota has been referred to as MESBOAC. The MESBOAC approach was developed by U.S. Forest Service Hydrologist, E. Sandy Verry as a practical approach to designing culverts that addresses a broad variety of potential AOP problems with traditional culverts. MESBOAC stands for:

- Match culvert width to bankfull stream width
- Extend culvert length through the side slope toe of the road
- Set culvert slope the same as the stream slope
- Bury the culvert
- Offset multiple culverts
- Align the culvert with the stream channel
- Consider headcuts and cutoffs

This method aims to provide guidance to hydrologists and fisheries scientists on hydraulic and geomorphic design issues. It also points out some of the main AOP issues to traditional engineers that may be unfamiliar with them. This approach has been used in parts of Minnesota by the Minnesota DNR and US Forest Service. Although there is little published literature about details of the method, it was described in the appendix of Version 4 of Best Practices for Meeting DNR General Public Waters Work Permit GP2004-0001, (Leete 2014).

5.6 HYDRAULIC DESIGN (BAFFLES, WEIRS, OR HYDRAULIC STRUCTURES)

5.6.1 Method Definition and Design Intent

In their 2007 FHWA report, Design for fish passage at roadway-stream crossings: synthesis report, Hotchkiss and Frei define Hydraulic Design as "... techniques [that] create water depths and velocities that meet the swimming abilities of *target fish populations during specific periods of fish movement*. General considerations include the effect of culvert slope, size, material, and length. Flow control structures such as baffles, weirs, formal fishways, or oversized substrate are commonly utilized to create adequate hydraulic conditions." (emphasis added) (Hotchkiss and Frei 2007)

In targeting specific aquatic organism populations (usually a fish species) and specific movement periods, the movement needs of non-target species are not considered in hydraulic design, nor are other factors of ecological stream connectivity such as free movement of sediment and debris. Subsequently, the hydraulic design method for AOP should generally be seen as a temporary solution (NRCS National Engineering Handbook Part 654, Technical Supplement 14N, NRCS 2007).

This section will primarily discuss baffles and weirs as a means to create target depths and velocities in a culvert by dissipation of energy. Since these structures will necessarily reduce the hydraulic capacity of an existing culvert and create locations for debris to lodge, potentially causing plugging, the designer should proceed carefully.

5.6.2 Benefits

- Hydraulic design is best applied in a retrofit situation (Section 6.5) where replacement of a barrier culvert is not presently feasible, yet passage of a target species is a desired outcome.

5.6.3 Key Design/Implementation Considerations

In general the design steps for hydraulic design AOP are:

- Obtain target species and life stage swim data (refer to Appendix B for a listing of fish data)
- Derive required depth and velocity limits for specified passage time periods.
- Obtain expected streamflow data during target passage periods in consultation with the DNR Area Hydrologist. See Appendix B for additional information.
- Design baffle system to meet depth and velocity criteria at target passage flows.
- Check hydraulic capacity at design (high) flows, including any assumptions of debris build up, etc.

Most design guidance for baffles is from coastal states and targeted to salmonids having higher swimming abilities than Minnesota warm water fish (Hansen et al. 2009). Chapter 6 of the Washington Department of Fish and Wildlife (WDFW) Water Design Crossing Guidelines presents a guide for hydraulic design, including baffle design (Barnard et al. 2013). Baffles may function as discrete, individual weirs at lower flows, with a repeating pattern of weir, plunge, and pool. At higher flows,

baffles tend to work together as roughness elements, creating a streaming flow pattern (Barnard et al. 2013). Avoid placement of a baffle within one pipe diameter of the inlet (NRCS 2007). Recommended baffle configurations for circular and box culverts and design equations for height and spacing, and slope-based recommendations are also included. These designs are applicable for slopes equal to 3.5% or less (Barnard et al. 2013). Higher slopes would require a fish ladder.

Hotchkiss and Frei (2007) summarize hydraulic design standards such as minimum water depth for the states of Washington, Oregon, and Maine. Minnesota does not have recognized design standards for baffles. Hansen et al. (2009) found that while they have been installed in several counties, baffles are perceived negatively in Minnesota due failures stemming from design, installation, and maintenance issues. Hansen et al. (2009) also provide cost estimates for baffles, while noting that costs are highly variable based on site characteristics.

In certain cases, baffles or sills may be used to retain sediment in steep culverts, in support of geomorphic simulation or another design method. Refer to Section 6.2.2.4 of the USFS Stream Simulation guide for a discussion of buried bed retention sills in step-pool culverts (FSSSWG 2008). However, the WDFW discourages the use of bed retention sills in favor of correct sizing of stable culvert fill materials.

An end sill, which is a single weir at the downstream culvert end, may be used to provide a backwater and retain sediment in the culvert in a low gradient stream (Kilgore et al. 2010 HEC 26, Appendix G). However, a more natural downstream grade control (Section 6.3) may be more appropriate.

5.6.4 Operation & Maintenance Considerations

- Frequent maintenance is essential for culverts with baffles and weirs. Washington Department of Fish and Wildlife notes that inspection and removal of woody debris should be done at least annually (Barnard et al. 2013).
- Baffles or weirs as a retrofit may be difficult to install and prone to failure. Barnard et al. (2013) state, “Nearly all baffle installations are damaged at one time or another over their life spans.”
- Baffles or weirs are only appropriate on culverts 5 feet or more in diameter to permit worker entry for inspection and maintenance (Barnard et al. 2013).

5.6.5 Local design example

Two examples of baffles in Minnesota culverts are shown in Figure 5.6.1 and Figure 5.6.2 below. Baffles in the first design are designed purely to slow down the flow but could create turbulence that could be difficult for fish to swim through. Baffles in the second example initiate meandering and varying patterns of sediment deposition which can facilitate AOP under low flow scenarios; this retrofit can be appropriate in culverts with wide, shallow flow.



Figure 5.6.1. Steel offset baffles bolted to a round concrete culvert as a retrofit. St. Louis County (from Fig. 4.5, Hansen et al. 2009)



Figure 5.6.2. Alternating concrete baffles retaining gravel to cobble size material in a culvert near Red Wing, MN. Photo courtesy of B. Hansen.

CHAPTER 6: ADDITIONAL CONSIDERATIONS

This section describes design elements that are not common to all stream crossings, but which may be necessary in certain situations. It is divided into two main sections physical issues: hydrologic, hydraulic, and geomorphic considerations (sections 6.1 to 6.5) and practical issues, including logistical, legal, and cost considerations (sections 6.6 to 6.10).

6.1 MULTIPLE BARREL CULVERTS

Multiple side-by-side culverts set to the same invert elevation have been often used in Minnesota as a cost-effective method to convey large flows without resorting to a bridge. To convey peak flows, the total width of all barrels is often wider than the stream channel. When the cross-sectional area of the multiple barrel culvert is greater than the cross sectional area of the stream at a given depth, the average velocity is decreased. This sometimes leads to sedimentation problems upstream, downstream, and in the culvert. During low flow periods, the water depth may be too shallow (typically over a smooth bottom such as concrete) for aquatic organisms to successfully move upstream. Due to these considerations, it is not recommended to place multiple barrel culverts that are significantly wider than the stream width at the same invert elevation. A strategy to address these issues is discussed below in terms of vertically offset multiple barrel culverts.

6.1.1 Method Definition and Design Intent

Definition: An installation of two or more side-by-side culvert barrels where some (one or more) barrels are set with a lower invert elevation, such that base flows are directed through the lowered barrels only (Figure 6.1.1) and (Figure 6.1.3).

Design Intent: At a multiple barrel stream crossing, the base-flow channel is directed through one (or more) barrel designated as the primary barrel, which is typically recessed below the streambed or embedded. The other barrels needed to convey peak flows are vertically offset, meaning the inverts are set above the base flow channel but below bankfull elevation and are dry at lower flows. When the base-flow channel is directed to a single barrel (or two barrels if necessary), the deeper flow facilitates passage by aquatic organisms, as well as facilitating more continuous sediment transport, with the result of less sedimentation, as compared to an over-wide, over-shallow channel.

At some sites where multiple culverts are all set at the same invert elevation, sedimentation may achieve the same effect at some times, however, the result may be less desirable, such as all flow directed through a side barrel rather than a central barrel.



Figure 6.1.1. Low flow passes the left (channel) barrel while the right barrel is partly filled with sediment in this culvert in Goodhue County (photo from Hansen et al. 2011)

6.1.2 Benefits

- Creating a preferential low flow barrel provides greater depth at low flow (versus wide, very shallow flow) which allows better navigation by aquatic organisms.
- Improved sediment transport, provided the lowered barrel(s) are not too narrow relative to the stream width.
- Retains some cost and other advantages of multiple barrel culverts, while improving AOP and stream connectivity, if well designed.
- Higher elevation culverts may be useful for temporary stream bypass during lowered culvert construction; may be helpful for construction sequencing.
- Reduction of the risk of wildlife-vehicle crashes by creating a passage route for terrestrial wildlife through the higher elevation (normally dry) culvert barrels.



Figure 6.1.2. Highway I-90 over Elk Creek, near Magnolia, MN showing a triple barrel box culvert with inverts at the same elevation. The culvert is significantly wider than the upstream channel; the channel widens as it approaches the triple box culvert (flow from top to bottom). Vegetation-covered sediment is present upstream and downstream of the culvert indicating deposition. Google Maps images.

6.1.3 Key Design/Implementation Considerations

- Multiple barrel culverts of any configuration are more susceptible to debris jams, such as logs and ice, than single spans, due to the presence of center divider(s). The bankfull width may be a reasonable estimate for the length of large wood (trees) possibly entering the stream (Merten et al. 2010).
- Invert and flowline elevations of the primary and vertically offset barrel(s) should be determined on a case by case basis, taking into account expected sediment depths in hydraulic modeling.
- Sediment or debris may be deposited in the higher elevation culvert barrels in smaller storms, reducing capacity for larger events (Figure 6.1.3). This is an issue if side culverts are set too high

(Hansen et.al. 2011, p 31). Some deposition of sediment should be expected and designed for (accounted for in hydraulic analysis), as well as growth of vegetation immediately upstream and downstream.

- Lowered primary culvert barrel(s) may need to be filled at construction with bed sediment (embedded) rather than simply recessed below the streambed elevation because they may not immediately fill with sediment as intended – refer to Section 5.5 .
- As with any culvert with a structural invert below the streambed elevation, a careful evaluation of headcut potential is required; mitigation by construction of structures or grade control may be needed.
- If the width of the recessed barrel(s) is significantly less than the bankfull width, velocity may be too high at baseflow, negating AOP benefits, and increasing scour. It is suggested to compare the channel velocity at the elevation when flow just begins to come into the other barrels with the culvert barrel velocity.
- Placing a culvert on a stream bend is not recommended, especially a multiple barrel culvert. If it is unavoidable, place the lowered barrel on the outside of the bend to capture the channel thalweg and maintain a low-flow channel. (Kozarek and Mielke 2015)
- Achieving proper foundation conditions on adjacent culverts with different invert elevations may require close attention during construction.
- Piping beneath the higher elevation culverts should be prevented with a cutoff wall.
- Crown elevations should be the same for all barrels to provide the same clearance at the expected high water to minimize issues with floating debris or ice.
- If the floodplain is wide, dispersed floodplain culverts (Section 6.2) combined with one or more culverts totaling bankfull width maybe more effective in conveying floodplain flows and reducing contraction scour than placement of multiple on-channel culverts that extend beyond the bankfull width.
- Multiple cell culverts are more appropriate in certain stream types than others. The following guidelines are from Maryland’s Waterway Construction Guidelines (Maryland Department of Environment 2000). Type B streams may be intermediate between C/E and F/G.

Table 6.1.1 Maryland’s guidelines for multiple cell culverts by Rosgen stream types (adapted from Maryland Department of Environment 2000).

Stream type (Rosgen)	Culvert recommendation
C, E	Developed floodplain; most effective stream types for multi-barrel culverts
F, G	Single-barrel culverts are more suitable than multi-barrel culverts for incised/entrenched channels with minimal floodplain
A, D	Multi-barrel culvert would likely impede AOP due to high slopes (A) and high bedload (D)

6.1.4 Maintenance Considerations

- Periodic inspections are recommended.
- Debris, such as tree trunks, wider than any culvert barrel should be removed.
- Expected sediment elevations in the primary and offset barrels should be recorded as part of the design process; if sediment buildup seems excessive during periodic inspections, measure or survey and compare to design intent. Upon consultation with the designer or hydraulics expert, remove sediment to design elevations if it is excessive (such as from an upstream bank failure, etc.). Alternatively, design elevations could be marked on the culverts directly at construction.

6.1.5 Example



Figure 6.1.3. Duschee Creek, Fillmore County (from Hansen et al. 2011, Appendix B)

An example of multiple barrel culverts and sedimentation is shown in Figure 6.1.3. The Duschee Creek site has two concrete box culverts, one of which has filled in with sediment and become vegetated in the upper right of the figure. At normal to low flows, the channel passes through the near barrel.

6.2 FLOODPLAIN CULVERTS

6.2.1 Method Definition and Design Intent

Definition: Floodplain culverts are culvert barrels placed outside the stream channel at the defined floodplain elevation to allow for conveyance of floodwaters during flow events that inundate the stream's floodplain. Unlike multiple barrels located in the main channel (Section 6.1), they are placed at the floodplain (bankfull) elevation and are active only during flood flows.

Design intent: Floodplain culverts are intended to counteract flood flow confinement by increasing conveyance on the floodplain outside of the main channel, as illustrated in Figure 6.2.1. Typical effects of flood flow confinement that negatively influence stream connectivity and AOP include contraction scour at flood flows, increased in-channel stream velocities and shear stress, over-widening of the channel upstream of the crossing, and sediment deposition or aggradation near the structure.

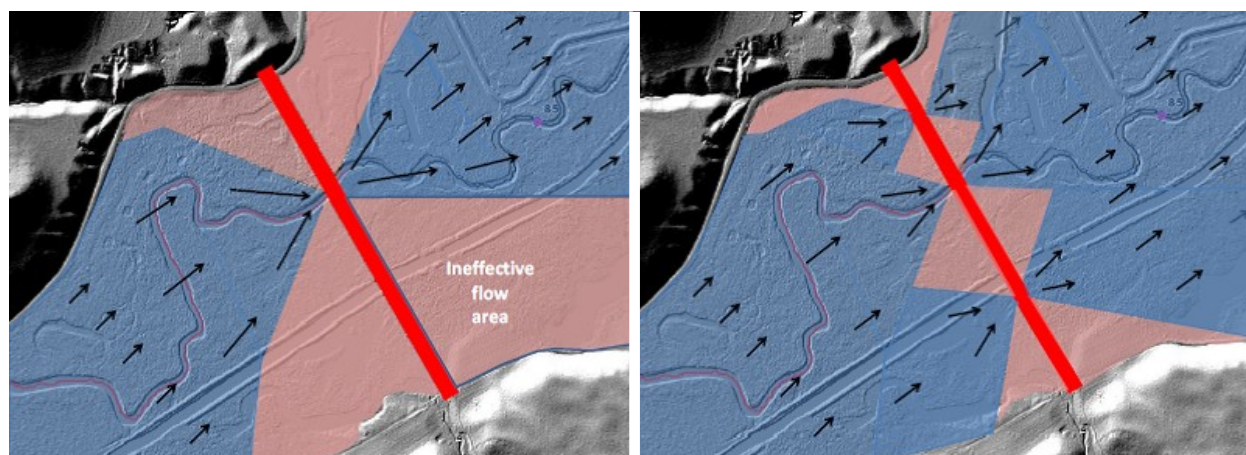


Figure 6.2.1. Illustration of using floodplain culverts to increase floodplain conveyance. During flood flows, a single on-channel opening leads to ineffective flow area (shown in pink) as well as contraction scour and other flood confinement effects. Adding two floodplain culverts (Adapted from Figures 50 and 51, Zytkevich and Murtada 2013).

6.2.2 Benefits

While floodplain culverts are dry at non-flood flows and thus are not intended to serve as passageways for aquatic organisms except during flows covering the floodplain, AOP may be improved at road crossings with floodplain culverts by:

- Reduced flood flow confinement, reduced channel bed shear stress and contraction scour at higher flows, promotion of channel-like velocities downstream of the main culvert, resulting in a lower likelihood of channel culverts becoming perched, and reduced aggradation upstream, as compared to funneling all water to on-channel culverts.

- Improved distribution of flow and sediment movement between the channel and floodplain, allowing better continuity of stream characteristics and habitat.
- When water is flowing across the floodplain, aquatic organism may use floodplain culverts for passage to avoid faster-moving channel flows.

Other benefits of floodplain culverts may include:

- May add resiliency to the crossing such as maintaining flow if the main channel culvert becomes blocked with ice or debris during a flood event.
- Additional flow area may be helpful to maintain regulated flood elevations at a crossing.

The state of Maryland uses floodplain culverts when on-channel culverts cannot meet policy and design objectives, primarily to relieve scour and erosion problems and to accommodate flood elevations for design discharges (Maryland State Highway Administration Office of Structures 2011).

6.2.3 Key Design/Implementation Considerations

- Floodplain culverts are intended for water conveyance across the floodplain, not sustained AOP or sediment transport. Therefore, floodplain culverts should be sized and designed for maximum hydraulic conveyance. Aquatic organisms may use floodplain culverts but AOP is not a design consideration.
- Floodplain culvert openings should be spread across the floodplain surface to the extent possible (Zytkovicz and Murtada 2013). Openings should be located well away from the channel banks to maximize effectiveness and avoid additional shear stress in the near bank region. Culverts may be placed on both sides of the channel in a very wide floodplain, or on the inside of a channel bend where the floodplain on the outside of the bend is constricted (Maryland State Highway Administration Office of Structures 2011).
- Floodplain culverts should be sited to align, where possible, with areas of natural concentration of flood flows, such as remnant flood channels (Gubernick, Higgins, and Gran 2017). If remnant flood channels do not exist, they can be created to direct water to the floodplain culverts to maximize floodplain conveyance.
- The channel culvert opening width should be set equal to or slightly greater than bankfull width (Section 2.4); floodplain culvert dimension should be determined by trial and error to meet objectives. Two dimensional analysis of floodplain flow may assist design.
- Scour protection and cutoff walls at floodplain culverts should be provided if warranted by expected flows and floodplain conditions.
- Ongoing research in floodplain culverts is supported by the MN DNR. Information on this approach is located here:
<https://www.dnr.state.mn.us/eco/streamhab/geomorphology/index.html>

6.2.4 Maintenance considerations

Floodplain culverts are designed to reduce maintenance needs by reducing channel scouring downstream and the need for cleanout of deposited sediment upstream. They also should reduce the frequency of wood debris jams by maintaining a typical (not over-wide) channel upstream of the road crossing (Furniss et al. 1998). The addition of one or more additional structures, however, will require road crews to monitor and maintain additional (typically dry) culverts. Fine sediment deposition may occur downstream of floodplain culverts, given that the flow velocity is considerably slower in floodplains than in the main channel. Bare sediment frequently becomes vegetated if it persists over a growing season and creates more permanent blockages, therefore they may need to be monitored after floodplain flow events.

6.2.5 Example



Figure 6.2.2. Three corrugated metal arch floodplain culverts flank a 12 ft x 6 ft concrete box culvert on the stream channel of a tributary to the Rock River, located in Kenneth Twp., Rock County. The on-channel culvert matches the bankfull channel width and the inverts of the floodplain culverts are set at the floodplain elevation. June 2017 photo courtesy of Kevin Zytkovicz.

6.3 GRADE CONTROL STRUCTURES

Method Definition and Design Intent

Grade control is defined as a structure, rock, log, bedrock outcrop, or group of elements which inhibits the vertical degradation or downcutting of a stream channel at that location, and which may reasonably be expected to be stable in flows up to the design flow of the culvert or beyond. Grade control may exist naturally in streams in the form of bedrock, erosion-resistant bed materials or bedforms, large woody debris, or natural backwater from other sources. The rate of downcutting in stable streams is generally low; however, in streams prone to headcutting or rapid bed erosion, grade control structures may be

necessary to prevent undermining of culvert, road berm and associated structures. In the photo in Figure 6.3.1, the culvert has become perched and may be in danger of undermining the apron. Conversely, in certain situations, such as upstream aggradation caused by a previous culvert set too high, maintaining the existing grade control elevation may be inappropriate. In these cases, the DNR Area Hydrologist and fisheries staff should be consulted when determining a suitable control elevation.



Figure 6.3.1. The significant perch and very shallow flow present several barriers to AOP at this culvert on the Nemadji River South Branch at TH 23 in Carleton County. A grade control structure was later constructed downstream (next figure). Photo courtesy of L. Aadland (2001).

Key Design/Implementation Considerations

The type of grade control structure preferred will vary by stream type, slope, and bed material (see Section 4.1 on energy relationships in streams). Certain stream characteristics including slope and bed materials make a channel more or less prone to bed erosion. Steeper gradients where streams are dropping down a valley wall or ridge, for example, tend to increase bed erosion as the stream's longitudinal profile works to adjust to the base level elevation. The greater shear forces occurring with steeper slopes favor the initiation of bed movement and potential formation of headcuts.

Streams running through fine-textured erodible materials are far more likely to headcut if de-stabilized and require placement of grade control structures if stability is shown to be a concern (see Section 3.2). For example, the critical shear force which is required to mobilize very large boulders is over 1000 times

greater than needed to mobilize very fine gravel. Certain stream types in the Rosgen classification system are more prone to headcutting. For example the Rosgen type G stream which is by definition a gully, is undergoing the headcutting process at high flows. Inherently less stable stream types such as these are more likely to require grade control structures to prevent culvert undermining.

Some commonly used grade stabilization structures are described in The National Engineering Handbook part 654, (NRCS 2007) (<https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/manage/restoration/?cid=stelprdb1044707>). These may include cross vanes, placement of boulders or cobbles, weirs, channel linings and other related structures. Technical Supplement 14G, Grade Stabilization Techniques, part of the NRCS National Engineering Handbook (NRCS 2007), includes design equations for these structures. Note that using rigid drop structures, check dams, and stilling basins also shown in this and other references as grade control structures is not recommended as it would also disrupt AOP and stream connectivity, similar to a perched culvert. Castro and Beavers (2016) list grade control alternatives to rigid structures: large roughness (wood and boulders), constructed riffles, steps, and cascades. Grade control measures should be resistant to undermining.

Rock ramps and rapids, or rock arch rapids, have been used successfully in Minnesota as grade control where dams have been removed (Aadland 2010). Constructed riffles may also be appropriate in some circumstances for grade control (Newbury 2013). Achieving proper slopes within limited right of way may be challenging; construction of a functioning project may require additional right of way or coordination with other project partners (see Section 1.2.3).

Less conventional approaches to grade control are often linked with stream restoration goals and may use strategic placement of larger erosion-resistant gravels, cobbles, or boulders to support fish habitat as an added benefit. Some projects utilize wood as cross vanes or check dams to dissipate energy and temporarily halt or greatly reduce bed erosion at that location. Wood vanes and the more naturally-appearing engineered wood jams also provide significant in-stream habitat benefits for fish and invertebrates. The 2016 Large Wood Manual (USBR & ERDC 2016) is an exhaustive reference on the use of large wood to promote stream stability. However wood is not suitable in all stream types for grade control. Criteria for using wood as grade control were defined by Castro and Sampson (2001). In summary, wood is suitable in all stream types where large wood is naturally a part of the geomorphic processes. They are very suitable for streams that are not very entrenched, such as Rosgen E and C types, and streams with a low bank height ratio (the ratio of bank height to bankfull height). Conversely, they are unsuitable in entrenched channels, for example Rosgen types G and F and streams with a high bank height ratio.



Figure 6.3.2. This series of rock weirs downstream of a formerly perched culvert (Nemadji River South Branch at TH 23 in Carleton County, see previous figure) improves passage and stream connectivity. The yellow star indicates the position of the same rock in low (left) and moderate (right) flows. Photos courtesy of P. Leete (2005).

6.4 WATER LEVEL CONTROL

In addition to conveying streams, some culverts function as a water level control, or low water outlet elevation for an upstream lake, pond, or wetland. In these situations the water level control should generally remain at the same elevation to maintain the upstream hydrology even when a culvert is replaced. If the culvert is to be constructed under General Permit 2004-0001, a provision states, “Permittee is responsible for maintaining existing water level control elevations.”

The culvert designer should confer with the DNR Area Hydrologist regarding the effects of possible changes to water level control. If the culvert dimensions, material, slope, etc., are changed from an existing culvert, the hydraulic rating curve (flow vs. elevation) will change, even if the base control elevation remains the same. This is particularly important for culverts downstream of lakes and other public waters or state wildlife areas. If possible, the water level control structure should be constructed to allow maximum stream continuity and AOP compatible with the goals of the level control – refer to discussion of grade control structures in Section 6.3 .

In very flood prone watersheds, water level control through culvert downsizing has been used in some locations to attempt to reduce downstream flooding. This has been particularly prevalent in the Red River basin of northwestern Minnesota where it was found that detention of headwaters runoff could reduce the downstream flood peaks on the main Red River. The practice is used primarily in small intermittent headwater streams that generally do not have AOP concerns. The practice of culvert downsizing is outside the scope of this guide; see the Agricultural BMP Handbook for Minnesota for guidelines on the suitability of water level control using culvert downsizing (Lenhart et al. 2017). This practice has potential negative effects on channel incision, sedimentation, and AOP. In addition, roadway embankments are not designed to retain water.

6.5 RETROFITS

In this section, “retrofit” refers to an in-place modification of an existing culvert with the goal of either: 1. extending the structural or hydraulic service life of an existing culvert with some type of repair or liner, 2. improving AOP through an existing culvert, generally by increasing roughness or introducing a backwater, or both 1 and 2.

Structural and hydraulic retrofits

In a 2014 report titled, *Culvert Repair Best Practices, Specifications, and Special Provisions – best practices guidelines*, Wagener and Leagjeld present options for rehabilitation and repair of culverts in Minnesota (Wagener and Leagjeld 2014). In general, retrofits intended to extend the structural or hydraulic service life result in a smoother culvert barrel with less friction (lower Manning’s n). Examples are slip-lining, which involves placing a slightly smaller-diameter rigid pipe inside of a failing culvert and grouting the space between old and new pipes, and cured in place (CIPP) liners (Figure 6.5.1), which are inserted into the old pipe and then inflated.

While the lower barrel friction compensates for the flow area lost to the culvert lining, the resulting increase in velocity may introduce or increase a passage barrier (Webb and Hotchkiss 2008). For this reason, this type of retrofit may not be allowed in Minnesota Public Waters – refer to chapter 2 of *Best Practices for Meeting DNR GP 2004-0001* (Leete 2014) for more information. Other retrofit techniques such as invert paving or spray-applied liners may be similar to the original culvert roughness or smoother, depending on the materials used and original situation. Potential effects on AOP and stream connectivity, particularly sediment and debris movement, should be considered as part of the structural retrofit design process.



Figure 6.5.1. Cured-in place liner inserted into a culvert and inflated with steam, on TH 61 near Grand Marais, Cook County. Photo courtesy of P. Leete, 2016.

Retrofits to improve AOP

Retrofits designed to improve AOP are sometimes employed in situations where a culvert is identified as a passage barrier but is not currently a candidate for full replacement, often because it is in serviceable structural and hydraulic condition. Baffles or sills, discussed in Section 5.6 on Hydraulic Design for AOP, can be installed within the culvert to increase local flow depth, roughness, and turbulence. Potential drawbacks to this approach include a reduction in peak flow capacity and increased probability of catching debris inside the barrel. A hydraulic analysis incorporating increased roughness and/or partial blockage should be done to determine if hydraulic parameters (headwater, etc.) at design flow are acceptable after installation of the retrofit baffles or sills. The effect of retrofits on sediment movement, scour, or accumulation, should also be considered.

Alternative designs to increase roughness inside the culvert barrel include placement of loose or grouted rocks or boulders, or other roughness elements. An example of one project incorporating formed roughness into a concrete overlay is shown in Figure 6.5.2. Another technique used with some success in promoting fish passage in New Zealand is the placement of mussel spat rope through culverts as shown in Figure 6.5.3. This technique has been investigated in Minnesota in a series of lab, field, and live fish experiments, and found to reduce velocity and increase flow refugia in the vicinity of the ropes (Kozarek and Hernick 2018). In the study, deployment was most effective in shallow, fast moving flow.



Figure 6.5.2. Paving a culvert invert prolongs the useful life but a new smooth bottom may contribute to an AOP barrier. Rock-like concrete shapes and bank lines formed monolithically with the invert pour (left) were part to this culvert retrofit to increase roughness at low flows. The culvert is on Deer Yard Creek (Spruce Creek) under TH61 in Cook County. Photos courtesy of P. Leete (2014).



Figure 6.5.3. A recent MnDOT project explored the use of ropes originally designed for ocean mussel aquaculture as a culvert retrofit to add local roughness and cover to enhance AOP in shallow, fast flows. Still water between the sets of ropes at low flow is shown in the left image, while local reductions in velocity near the ropes slightly higher flow are evidenced by variation in surface flow patterns at right. Both photos are looking upstream. Photos M. Hernick and R. Gabrielson (2017).

Construction of an aquatic organism-friendly grade control structure downstream of a culvert (Section 6.3) to induce a backwater through the culvert could be considered as a retrofit. Presumably the increased water depth through the culvert due to the backwater would reduce or eliminate barriers associated with excess velocity and shallow depth. An advantage of this method is that no work within the culvert is required. When considering if a downstream grade control structure is appropriate, a hydraulic analysis should be done to determine if design-flow hydraulic performance of the culvert is acceptable after placement of the grade control. The stability of the grade control at design flows should also be checked.

6.6 LIMITATIONS AND CONFLICTS

6.6.1 Structures and Utilities

Practical considerations of “fixed” obstacles such as utilities or structures located adjacent to the stream are important to consider in culvert design, and may limit the achievement of goals for AOP or stream connectivity. The location and depth of nearby utilities (electric lines, gas pipelines, telecommunications cables, etc.) should be taken into account to prevent unintended consequences due to changes in the stream as a result of changes in the culvert. For instance, utilities placed in a recently-deposited “sediment wedge” above an undersized culvert may become exposed if the excess sediment is transported away when a new culvert sized to accommodate sediment movement is constructed.

Where structures such as houses or agricultural buildings are within the floodplain (whether mapped and regulated by FEMA or not) of the stream, consideration should be given to how proposed changes in the culvert are likely to affect flood elevations at the structures. Refer to Section 4.4 for a discussion of requirements related to regulatory floodplains. Ideally this analysis should be done at more frequent (i.e. 10 year-recurrence interval) floods as well as for larger, less frequent (100-year-recurrence interval) flood flows.

Where possible, the crossing could be constructed to accommodate future utility changes that may reasonably be expected within the design life of the culvert (see Section 2.4.7). For instance, assume there is a sanitary sewer forcemain (pressure sewer) crossing below the stream not far downstream of a culvert to be replaced. The forcemain is not far below the streambed, and for this reason is covered by riprap armoring. Analysis of the longitudinal profile of the stream shows that the preferred streambed elevation through the culvert would be lower than the existing culvert. One solution could be to set the culvert at the preferred elevation then fill to the current, utility-influenced bed elevation while satisfying current requirements for width, peak flow, etc. It is likely that the forcemain will be reconstructed (lowered) within the design life of the culvert (possibly 75-100 years), and if this is the case, the stream may be allowed to naturally re-grade through the culvert if the forcemain is replaced since this has been anticipated in the culvert design.

Other stream crossings, both upstream and downstream on the same or connected streams, may significantly affect the movement of water, sediment, and debris through the stream at the culvert project site. Even though they may have no control over offsite locations, culvert designers should be aware of the effects of other stream crossings in the watershed. This is a point where communication and coordination among entities and levels of government is important, and a scheme for prioritization of replacement of “problem” culverts would be beneficial. Diebel et al. (2015) for example, describe a watershed-based inventory of the Pine-Popple watershed in northern Wisconsin

6.6.2 Right of way

Replacement stream crossings that further the goals of AOP and stream connectivity often require work outside the footprint of the culvert itself, such as providing grade control structures, guide bank grading, or forms of channel reconnection. However, when culverts are replaced on existing roadways, the right of way is already established, and may not be sufficient to accommodate these features that would be needed to accommodate AOP.

Where possible, the need for construction or permanent easements or other accommodations should be identified early in the design process. Over the design life of the culvert, the cost of acquiring easements or right of way associated with an improved stream crossing design should be considered against economic and environmental costs to maintain a stream crossing with unfavorable characteristics.

6.7 COST CONSIDERATIONS

6.7.1 Construction costs

Cost categories for culvert projects may include site assessment, design, materials, and installation and maintenance. Typically most of the project budget will go towards materials and installation with lesser amounts for design, site assessment, and monitoring & maintenance.

Hansen et al. 2009 investigated the cost of replacing traditionally-designed culverts with the MESBOAC design or similar AOP designs in Minnesota. MESBOAC was used because it has been a popular design framework in Minnesota for AOP concerns (Section 5.5.7). Hansen et al. found that the average MESBOAC design was 10% more, than the in-place replacement culvert built without consideration for AOP. This cost was for the structures only and not any related benefits from prolonged lifespan or reduced maintenance. Much of the project cost is determined by planning, design and staff time. All culvert projects will have mobilization, materials, and on-site management costs much of which are similar regardless of the culvert size or benefit to AOP. Therefore the increased cost of materials for implementing a MESBOAC design was small relative to overall project cost.

Other alternative culvert designs for AOP that have been used in Minnesota included baffles, roughened channels and backwater weirs. These tools are generally less expensive as they typically involve simple placement of baffles or roughness elements to reduce velocity in the culvert without a whole new design, often used as retrofits to existing culvert. As reported in Hansen et al. (2009), construction costs for baffles averaged \$4,000 or 12.5% of the total culvert construction cost, roughened channels averaged \$3,200 or 10%, and backwater weirs averaged \$4,850 or 15% of the total culvert construction cost.

The above analysis does not account for total life cycle costs which typically make alternative culvert designs more favorable because they typically last longer and require less maintenance as described in the following section.

6.7.2 Lifecycle costs

While construction costs for culverts are fairly well established, total lifecycle costs and benefits are less well documented. The construction of a culvert represents a flood plain encroachment with the associated flood risks and initial construction costs. Each design strategy can be evaluated for an annual capital cost and an annual economic risk (cost), the sum of which is called the total expected cost (TEC). Optimization of the economic and engineering analyses will produce the least total expected cost (LTEC) design alternative. While these cost analyses are well-defined, costs over the whole culvert lifecycle including maintenance and repair costs are not typically accounted for. Other factors that may not be accounted for include public safety and liability costs if culvert failures or wash-outs occur. Perrin et al. (2004) lists risk of failure or property damage, traffic safety, environmental and/or aesthetic considerations as well as nuisance issues as potential costs of culvert failures.

O'Shaughnessy et al (2016) performed a Cost-Benefit Analysis (CBA) to estimate lifetime net fiscal benefits of ecological design culverts versus traditional design culverts. Four costs (replacement, catastrophic failure, routine maintenance, and flood damage) were considered over a 70 year analysis period. The dataset of 461 culverts, in the Green Bay Wisconsin / Michigan watershed, and ecological costs and benefits such as impact on fisheries were not considered. Ecological design culverts, which the authors defined as having natural sediment beds and a width of 120% bankfull width, yielded net fiscal benefits versus traditional designs in 49% of the cases analyzed. Benefits were due to longer life span, reduced maintenance, and improved flood resiliency. The authors considered ecological design culverts to be most cost effective on smaller streams (bankfull width < 5 ft). When a culvert size of 110% bankfull width was considered, ecological designs achieved net fiscal benefits in 58% of cases.

Christiansen et al. (2014) used a similar dataset of culverts and similar cost-benefit analysis of hypothetical culvert replacement with stream simulation designs, but also included environmental and social benefits of improved fish passage (based on hatchery values), wetland restoration, and improved water quality. The analysis found net social and environmental benefits in 77% of cases analyzed, and net fiscal benefits in 44% of cases.

Gillespie et al. (2014) assessed life-cycle costs for culverts in Vermont following a large storm event associated following damage from Tropical Storm Irene in 2011. Culverts that were designed using the Stream Simulation approach were not washed out, saving replacement and/or repair costs. They found that the greater initial investment in the Stream Simulation culverts (9-22% more than traditional) provided greater societal benefits, exceeding the additional cost to design and install them. Repair of failed culverts cost anywhere from \$82,000 – \$247,000. With increased occurrence of large rainfall and extreme weather events the ability to pass larger floods without damage to culverts is likely to become increasingly important in upcoming decades.

6.8 CONSTRUCTION

6.8.1 Construction phase

Contractors as well as the entities responsible for construction observation may be unfamiliar with the goals of AOP and stream connectivity. They may also be unfamiliar with the means and methods available to achieve the design objectives. This brief section is provided with the sole intent of identifying possible issues related to construction, and providing references of what has been done successfully. It is not intended to prescribe what designs, or means and methods of construction are appropriate or permissible for any particular site, which is the duty of the engineer/designer and contractor, respectively. Notably, work must be done in accordance with the conditions of applicable general or site-specific permits (Section 1.3 , and Appendix D.). Below is a partial list of construction recommendations, followed by summaries of several references. For non-state-specific references, procedures should be adapted to the context of Minnesota streams, and applicable Minnesota regulations, standards, or permit conditions.

- Do in-stream work during time periods that are least-disruptive to aquatic organisms – refer to Section 6.8.2 . Work exclusion dates vary by region and species (i.e. trout streams). This often requires. Work exclusion dates are listed in Chapter 1 of Best Practices for Meeting DNR Public Waters Work Permit GP 2004-001 (Leete 2014).
- Provide stream diversion around the work area (keep the clean water clean);
- Handle excavation sump drainage from dewatering (dirty water) separately from stream water; route to a basin or other sediment treatment device in an upland area;
- Plan how to handle flooding or high flows during the project;
- AOP and stream connectivity goals of the design should be included in construction inspection; a statement of design intent may help in this regard (Section 4.6).
- If a streambed is constructed in the culvert with coarse materials (gravel, cobble), fine sand and silt should be “washed in” to the bed to fill voids and lower the bed permeability so that low flows remain on the bed surface (see Figure 7-14, FSSSWG 2008).

Guidance provided in Best Practices for Meeting DNR Public Waters Work Permit GP 2004-001 (Leete 2014)

http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html) is invaluable for compliance with permit conditions for culvert work in Minnesota. Work exclusion dates are listed in Chapter 1. Chapter 3 and the Appendix cover:

- Demolition of bridges over water, including management of regulated materials (lead paint, etc.);
- Erosion prevention and sediment control;
- In-water construction methods, including stream diversions, and;
- MnDOT Standard plans for a passage bench, temporary sediment control, and streambank bioengineering.

The USFS Stream Simulation manual (FSSSWG 2008) contains several sections related to construction. Chapters 7 and 8 contain suggestions on topics such as:

- Developing streambed material specifications (7.5)
- Stream bypass design (7.8);
- Construction inspection (8.1.4);
- Excavation safety (8.2.7)
- Placement of stream-simulation materials (8.2.11)

Appendix G.4 of the USFS Stream Simulation manual (FSSSWG 2008) is titled, Tips from Engineers and Biologists Experienced in Stream-Simulation Construction, and provides insight into situations such as:

- Dewatering, estimating pump sizes;
- Cofferdam options;
- Erosion control and revegetation;
- “Things that can go wrong”

Appendix H of the same document includes sample contract provisions and specifications for streambed construction, streambed simulation materials, and sample drawings. Note that the specifications in this reference apply specifically to US Forest Service projects, but could help to inform project-specific specifications or provisions where needed.

Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report (Hotchkiss and Frei 2007) published by the FHWA includes a brief section on construction in Chapter 9 which covers streambed material placement including QA/QC for vertical streambed controls (9.1.2), bed mix specification (9.1.3), and void sealing (9.1.4).

6.8.2 Timing of Work

Stream crossing construction requires significant advance planning and coordination to minimize risks and limit disruptions to natural resources. Factors to consider are low-flow periods, spawning or important time periods for aquatic organisms, and traffic disruption. Chapter 1 of Best practices for meeting DNR general public waters work permit GP2004-0001 (Leete 2014) provides a summary of restricted construction time frames for Minnesota streams. Permits and contracts should be in place in time for the non-restricted work periods.

In general, minimizing the duration of in-stream work limits the environmental, safety, and financial risks associated with these factors.

6.9 STRATEGIES TO BLOCK HARMFUL SPECIES

In some cases the fisheries or ecosystem management goal involves blocking species from movement. For example, artificial channels have been constructed connecting formerly fishless basins, and the free movement of aquatic organisms could be detrimental to local ecosystems. Often, limiting the spread of invasive species is a management goal. The sea lamprey (*Petromyzon marinus*) which invaded the Great Lakes from the Atlantic Ocean through the Welland Canal are often a target for “migration blockage” using physical, biological, and chemical control (Great Lakes Commission 2017). Low head dams have been successfully used in Lake Superior tributary streams since lampreys have limited jumping ability. There is little information on their movements through culverts, however.

Carp species have been a major concern of fisheries and natural resource managers for decades. The common carp (*Cyprinus carpio*) gets into lakes and wetlands, uprooting vegetation and contributing to water quality degradation. Consequently DNR and other fishery managers often want to block their movement into lakes. Water control structures and electric barriers can be used seasonally to block carp migration (MAISRC 2017). There has been considerable research into blocking several species of Asian carp, such as the bighead carp (*Hypophthalmichthys nobilis*) from migrating up the Mississippi River past the large dams at Hastings and St. Paul. Most of the work involves electric or sonic barriers near larger river dams. The use of barrier sites for targeted removal of invasive species is a subject of current research for the Minnesota Aquatic Invasive Species Research Center (MAISRC 2018).

In light of the limited information available on the effectiveness of culverts as barriers to movement of undesirable aquatic species, physical or behavioral barriers should be designed for management of specific species where necessary; use of culverts alone as barrier points may not be desirable or effective.

6.10 MONITORING AND MAINTENANCE

Following construction, the culvert site can be evaluated to in an attempt determine whether AOP goals have been met. One resource specifically geared to monitoring AOP is: Aquatic organism passage at road-stream crossings—Synthesis and guidelines for effectiveness monitoring, (Hoffman et al. 2012). Short of biological monitoring, important observations would include checking for a perched condition and whether adequate flow depth is likely to occur during low flows.

Monitoring of the geomorphic aspects of the stream crossing is also recommended to ascertain whether bed sediment has been retained in the culvert (if it is designed to be) and whether sediment appears to be moving normally through the culvert. Depending on the initial conditions of the crossing, adjustments to the channel in reaction to the new culvert are likely (and should be anticipated in design where possible), such as the erosion of aggraded deposits upstream or filling of a downstream scour hole. Additional references on monitoring may be found in Chapter 9 of HEC 26 (Kilgore et al. 2010) and Chapter 8.3 of the USFS Stream Simulation manual (FSSSWG 2008).

Monitoring could be done immediately after construction, after the culvert has experienced several years of flow, and especially after the first large flood event. Normal culvert inspections are recommended on all structures.

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APPENDIX A: GLOSSARY

Note: Selected terms are defined below for convenience or where terms are specifically used in this document. Several suggested references with more extensive glossaries are listed following the terms.

AOP (Aquatic Organism Passage) – As used in this guide, the degree to which organisms living in the water can traverse a stream crossing such as a culvert, as compared to the adjacent stream channel. A principal, but not exclusive, component of AOP is fish passage.

Bankfull flow – The discharge at which water fills the channel before beginning to flow onto the floodplain in a stream in equilibrium and not incising.

Barrel – The long, linear conduit portion of a culvert which conveys stream flows. The barrel may be made of concrete, metal., or plastic.

Bed load – Sediment moving along the channel bed by rolling, sliding, or saltation (jumping).

Bedform – A naturally formed ordering of streambed sediments, often in a repeating pattern. Dunes and ripples are examples of sand bed stream bedforms, while pools and riffles, and pools and steps are examples of bedforms in coarser streambed sediments.

Cascade – Steep channel geometry involving boulders and/or bedrock

Critical depth – Depth of flow at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry there is only one critical depth. (from MnDOT Drainage Manual 2000)

Crown – The inside top of the culvert. (from MnDOT Drainage Manual 2000)

Culvert – A structure sized hydraulically to convey surface water runoff under a highway, railroad, or other embankment (from MnDOT Drainage Manual 2000). In this document, a culvert incorporating aquatic organism passage and stream connectivity includes these factors in sizing as well.

Embedded culvert – A culvert constructed with an invert below the streambed elevation, filled with natural streambed material so that the flowline matches the streambed profile.

Ephemeral stream – A stream which flows only during and for a short duration after precipitation events in a typical year, with streambed located above the water table.

Floodplain – Nearly flat, alluvial lowland bordering a stream, which is subject to frequent inundation by floods. (from FHWA HDS 5)

Flowline – The flowline is the bottom invert of a culvert, or, in the case of a partially filled culvert (see Embedded), the top of the fill material, or bed surface.

Geomorphic simulation - A culvert design which aims to recreate natural channel conditions by matching characteristics including slope, width, bed materials, and bedforms, derived from a stable reference reach. Geomorphology (fluvial geomorphology) – A branch of earth science focusing on the evolution of landforms in relation to river and stream processes such as sediment erosion and deposition. Fluvial geomorphologists seek to understand and predict interactions between landscapes and streams.

Grade control – An element in the stream that controls the channel elevation and local channel slope. Natural grade controls may be large wood (logs), boulders, riffle crests, etc. Grade control or grade stabilization structures may be constructed to maintain a streambed elevation and prevent degradation.

Headcut – Channel degradation associated with abrupt changes in bed elevation that generally migrate in an upstream direction. (FHWA HEC 20)

Headwater (HW) – In the context of culverts, the water surface elevation just upstream of a culvert. If the road crossing is causing the streamflow to be constricted, the headwater elevation or stage will increase.

Hydraulic design – A culvert design which utilizes roughness elements such as baffles and weirs to meet species-specific fish passage swimming criteria during periods of fish movement. (Hotchkiss and Frei 2007)

Hydraulic simulation – A Culvert design which attempts to closely match stream flow characteristics found in natural channels through the use of natural and oversized substrate (from Hotchkiss and Frei 2007)

Inlet control – One of two basic types of flow control in culvert hydraulics where the culvert barrel is capable of conveying more flow than the inlet will accept; the inlet geometry is limiting. (FHWA HDS 5)

Intermittent stream – A stream flowing during certain times of the year when groundwater provides for stream flow; may not have flowing water during dry periods.

Invert – The inside bottom of a (closed-bottom) culvert. This may or may not correspond with the Flowline (see Flowline).

Longitudinal profile – Profile of a stream of channel drawn along the length of its thalweg. In drawing the profile, elevations of the water surface or the thalweg are plotted against distance as measured from an initial point. (from FHWA HDS 5)

Outlet control – One of two types of flow control in culvert hydraulics where the barrel is not capable of conveying as much flow as the inlet opening will accept; the barrel or downstream channel is limiting. (FHWA HDS 5)

Perennial stream – A stream flowing year-round in a typical year, fed by groundwater and flow from tributaries supplemented by precipitation.

Pool – The area in a natural channel deeper and often somewhat narrower than the average channel section. Pools are stream features that have residual depth and therefore will not drain free of water if flows are curtailed. (USBR & ERDC 2016)

Recessed culvert – A culvert constructed with an invert below the streambed. A recessed culvert may be filled with bed sediments (see Embedded) or allowed to fill in over time.

Refugia - Habitats or environmental factors that convey spatial and temporal resistance and/or resilience to biotic communities that have been impacted by biophysical disturbances.

Riffle - A natural, shallow flow area extending across a streambed in which the surface of flowing water is broken by waves or ripples. Typically, riffles alternate with pools along the length of a stream channel (e.g., in a gravel-bed channel). (FHWA HEC 20)

Road-stream crossing – The intersection of a stream and surface transportation alignment such as a highway, street, trail, or railroad.

Roughness – Channel characteristic that causes a drag on flow, limiting velocity and increasing diversity. Roughness elements include grains, bedforms, woody debris, manmade structures, and bank irregularities. (FSSSWG 2008)

Shear stress (unit shear force) – Force or drag developed at the channel bed by flowing water. For uniform flow, this force is equal to a component of the gravity force acting in a direction parallel to the channel bed on a unit wetted area. Usually in units of stress, lb/ft² or (N/m²). (from FHWA HDS 5)

Step Pool – A channel unit consisting of alternating series of steps, composed of cobbles or boulders, and plunge pools.

Stream connectivity – As used in this guide, the extent to which biological, physical, and hydrological processes continue uninterrupted through a stream crossing.

Stream simulation – USDA FS method for designing and building road-stream crossings intended to permit free and unrestricted movements of any aquatic species. (FSSSWG 2008).

Suspended load–Sediment suspended above the bed layer by turbulence.. (from FHWA HDS 5)

Tailwater – The depth of water on the downstream side of a culvert measured from the outlet invert, and an important factor in outlet control culvert hydraulics. (from FHWA HDS 5)

Thalweg – The deepest point within a channel cross section. (NRCS 2007)

Turbulence - Motion of fluids in which local velocities and pressures fluctuate irregularly in a random manner. (from FHWA HDS 5)

Wash load - Suspended material of very small size (generally clays and colloids) originating primarily from erosion on the land slopes of the drainage area and present to a negligible degree in the bed itself. (from FHWA HDS 5)

Suggested additional glossary references:

- MnDOT Drainage Manual, especially chapters 3, 4, and 5 (MnDOT 2000)
- Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report (Hotchkiss and Frei 2007)
- FHWA HEC 20 (Lagasse et al. 2012)
- FHWA HDS 5 (Schall et al. 2012)
- Stream Simulation: An Ecological Approach to Road-Stream Crossings (FSSSWG 2008)
- National Large Wood Manual (USBR & ERDC 2016)

APPENDIX B: PHYSICAL AND BIOLOGICAL BASIS FOR CONNECTIVITY AND PASSAGE

B.1. REVIEW OF SWIMMING ABILITY AND BEHAVIOR THAT EFFECTS PASSAGE OF FISH IN STREAMS

B.1.1. Overview

Aquatic organism passage (AOP) refers to linear passage through a culvert. Conditions created by culverts can impact numerous groups of aquatic organisms including fish, aquatic insect larvae, crabs and crayfish, mollusks, worms, turtles, snakes and salamanders. The issues most commonly raised by natural resource managers involve fish, particularly gamefish species as discussed in the following sections.

B.1.2. Passage of salmonids (family Salmonidae)

The majority of fish passage design in the United States has been focused on the *Salmonidae* family of fishes which includes salmon and trout. In the western U.S. in particular, the need to protect endangered species of salmon and increase populations of more common types for game-fishing has driven a lot of fish passage work (see Hansen et al. 2009 for a summary) particularly on large dams in Oregon, Washington and California (Kareiva et al. 2000). Salmon are strong swimmers with the ability to swim through fast-moving water and jump over rapids (see Hansen et al. 2009). Salmon are anadromous, meaning they migrate from the ocean to spawn in freshwater streams. The Brook Trout (*Salvelinus fontinalis*) and the naturalized, non-native Brown Trout (*Salmo trutta*) as well as the non-native Steelhead (*Oncorhynchus mykiss*), which are stocked in Lake Superior and are not self-sustaining (Biette et al. 1981) are the primary members of the salmonid family found in Minnesota streams.

B.1.3. Other taxonomic groups of fish

Non-salmonids and stream resident fish (defined as fish that do not migrate to or from the ocean or other large waterbody) have been less well-studied for their ability to get past culverts, dams or other blockages. Since there is a lack of data on many species, swimming abilities are sometimes estimated based on their body shape and similarity to better-known species. This was done for many fish listed in the FishXing model (USFS 2006). A list of some Minnesota fish species' swimming abilities is provided in Hansen et al. (2009)..

Bottom-swimming fish such as lake sturgeon (*Acipenser fulvescens*) or white sucker (*Catostomus commersonii*) tend to have different swimming abilities and behavior than mid-column swimmers that may limit them from passing through road culverts. It is not just the velocity of the water through the culvert that can prevent AOP, but other characteristics such as scour at the downstream end (perch), shallow depths, and excess turbulence can impede movement..

At times, culvert conditions can create behavioral barriers to aquatic organism movement. It is thought that some fish (and other aquatic life such as turtles) may be reluctant to swim through a dark tunnel

such as a culvert (Woltz et al. 2008). However, recent research in Minnesota was not able to demonstrate this effect for prairie stream fishes, including Topeka Shiners (Kozarek et al. 2017). Local hydraulics near the culvert outlet can prevent some fish from swimming upstream; for example some species may need an attraction flow at dams to be drawn into the area to swim upstream. Although culverts are different from dams because there is only one point in the stream to swim through, factors such as low flow and other flow variations may inhibit passage beyond the simple maximum velocity (Table B.1).

Catadromous fish (which are born in freshwater and migrate to the ocean to spawn) such as American Eel have different migration timing and swimming behavior than stream resident fish. Therefore management practices to improve their passage are different. American Eel (*Anguilla rostrata*) are not present in most of the state except for the Mississippi River.

There are a few circumstance, such as invasive species, where passage through culverts may not be desirable. Lampreys (*Petromyzon marinus*) were introduced to the Great Lakes through the Welland Canal (Becker 1983) and have wreaked havoc on native fisheries populations (GLFC.org 2017). They continue to be a problem and so the goal is often to prevent their passage upstream in Lake Superior tributaries, though in Minnesota’s north shore many are impeded by barrier waterfalls.

Table B.1. Properties that may affect the ability of aquatic life to pass through culverts

<i>Property or characteristic</i>	<i>Notes</i>	<i>Examples</i>
Maximum swimming speed	Affects ability to swim through fast-moving waters	<i>Salmonids</i> have a high maximum swimming speed
Duration of swimming effort	Is important for longer rapids or fish ladders where they must swim through fast water for an extended time	Long, steep culverts may be barriers to fish passage even if max velocity is moderate
Swimming water depth (bottom vs. mid-pool)	Fish that swim within the water column have different needs than fish that swim on the bottom	Sturgeon swim along the bottom and require different passage techniques
Behavior	need for attraction flow at dams; swimming patterns (bursts vs. sustained); seasonal movements to fulfill life cycle needs	Fish often move from lakes to rivers to spawn and vice versa for over-wintering
Light needs / dark aversion	Some fish and aquatic life may prefer light to swim or move through a culvert	Reptiles and amphibians may be sensitive to light
Migration – timing, water chemistry signals	Timing of migration, direction of migration, from ocean to river; lake to river, etc.	Turtle migration out of stream to nest on sandbars

B.1.4. Minnesota Fish

General fish passage issues in Minnesota culverts are described in Hansen et al. (2009) and Kozarek and Mielke (2015). Being landlocked, Minnesota does not have any native anadromous fish (with the possible exception of coaster brook trout that migrate from Lake Superior streams to the lake), although the steelhead introduced to Lake Superior migrate to North Shore streams. Salmonid passage is of major importance in the southeastern Driftless Area with Brook and Brown Trout and in northern / northeastern Minnesota.

There is also an abundance of stream resident fish in Minnesota, many of which have migration needs to move to suitable nesting, feeding or overwintering area. Some fish species such as walleye and lake sturgeon are known to migrate long distances to spawn, with walleye often moving from lakes to streams. Swimming ability is one of the factors influencing their ability to get past culverts.

Some of the key Minnesota fish species from a management and passage standpoint are listed in Table B.2. Aside from the salmonids which were discussed earlier, walleye, bass, sturgeon, pike and catfish are some of the key game fish or species of interest. Walleye (*Sander Vitreus*) are known to migrate long distances to spawn in rivers, for example in some of the southern Great Lakes (Pritt et al. 2013).

Table B.2. Major River Basins in Minnesota and Fish Passage Considerations (Table from Hansen et al. 2009).

River Basin	Key Fish	Geomorphic Considerations	Other Considerations
Great Lakes	chinook salmon lake trout	high gradient cobble beds	fall spawning
Upper Mississippi	walleye bass northern pike	moderate gradient sand/gravel bed	spring spawning
Minnesota River	catfish smallmouth bass	low gradient sand/fines bed	spring spawning
St. Croix River	smallmouth bass sturgeon	moderate gradient	spring spawning
Lower Mississippi	brook trout brown trout smallmouth bass	high gradient tributaries low-gradient Mississippi R.	spring and fall spawning
Red River	sturgeon northern pike	low gradient	agriculture spring spawning
Rainy River	lake trout smallmouth bass walleye	moderate gradient gravel bed	BWCAW forestry spring and fall spawning
Missouri River	Topeka shiner	prairie streams	federally endangered Topeka shiner

Along with velocity considerations, the seasonality of fish migration can strongly affect AOP concerns as well. Many fish in Minnesota migrate in the spring and early summer as described by Leete (2014). Culvert installation or replacement work in streams is restricted by the Minnesota DNR in certain

perennial streams in the state during the spawning season. Refer to Section 6.8.2 for resources and more information regarding timing of work.

B.2. OTHER AQUATIC ORGANISMS

Other aquatic life forms occurring in streams include benthic macroinvertebrates such as insects, crustaceans, mollusks, and worms. In general, less research has been done on the life cycles of aquatic organisms other than game fish species (e.g. walleye, salmon, trout) and some threatened or endangered species such as the Blanding's turtle. Passage issues for some organisms are summarized in Table B.3.

Many insects have larval forms, such as mayflies and caddisflies that spend months or years on the streambed prior to hatching into an adult form that flies for a short time before mating, laying eggs and dying. Since adult forms usually fly and thus disperse the next generation they may be minimally impacted by passage at culverts. Aquatic insects may also disperse via drift in the water column in a downstream direction though travel less easily in an upstream direction (Hall et al. 1980, Wetzel 2001). However certain types of aquatic beetles, for example, do not fly and may be more dispersal-limited. They disperse as adults by swimming or walking near the water and include the insect families *Hydraenidae*, *Dryopidae* and *Corixidae* (water boatman). These families may be more likely to have their dispersal blocked by culverts although there is little or no research on these taxonomic groups.

Crustaceans include animals such as crayfish and planktonic forms such as copepods and amphipods. Crayfish (family *Cambaridae*) may leave the water and travel across uplands while planktonic organisms such as scuds are typically confined to areas of permanent water or prolonged saturation. Crayfish could be blocked by high velocities in culverts and potentially by road berms alongside the culverts although they can move overland short distances. In some cases, as with the non-native rusty crayfish (*Orconectes rusticus*), resource managers may want to prevent their spread. Foster et al. (2011) found that culvert velocities $> \sim 1$ ft/s (30 cm/s) may favor the non-native rusty crayfish over native *Orconectes* species.

The mollusk group includes snails and freshwater mussels (class *Bivalvia*). Since there are numerous threatened and endangered mussels in the United States including Minnesota, there is increasing interest in their ability to get past culverts and other barriers. Mussel larvae are transported by fish hosts in their gills and so the dispersal of mussels is ultimately linked to their fish hosts.

There are numerous aquatic worms of the *Oligochaete* class found in streams. Drewes & Cain (1999) describe the movement ability of some aquatic worm species.

Table B.3. Other types of aquatic life and passage issues.

Group - common name and taxonomic group	Notes on movement and passage	Examples	References
Insects (Phylum arthropod; Class Insecta)	Larval stages develop on stream bed; adults typically fly, some beetles and other insect types have more limited adult mobility	Mayflies (<i>Ephemoptera</i>), caddisflies (<i>Trichoptera</i>)	Hutchinson 1981; Fremling 1989
Crabs, crayfish, etc. (Phylum arthropod; Subphylum: Crustacea)	Crayfish come out of water to feed and overwinter; mobile compared to many invertebrates	Crayfish (family <i>Cambaridae</i>), scuds Crayfish (family <i>Gammaridae</i>)	McLaughlin et al. 2005.
Mollusks (Phylum: Mollusca; Class Bivalvia)	Mussels are transported by fish in their larval stages; as adults they can move very slowly	Creek heelsplitter, (<i>Lasmigona_compressa</i>), spike (<i>Elliptio dilatata</i>)	Sietman 2017
Worms (Phylum Annelida; Order: Oligochaetes)	Have some mobility; provide food supply for higher level animals	<i>Tubifex</i> worms	Drewes & Cain (1999).
Turtles (Phylum Chordata, Class: Reptilia, Order Testudinata)	Many turtles are semi-aquatic; they feed in streams and nest in sandy upland areas adjacent to stream; Movement can be blocked at road crossings by curbs, fencing or other barriers such as gaps in bank rocks placed in a culvert, or dark culverts	Blanding's, wood, painted (<i>Chrysemys picta</i>) and softshell (genus <i>Apalone</i>)	Tuttle et al. 2005; Lenhart et al. 2013; Wolz et al. 2008
Snakes (Phylum Chordata, Class: Reptilia)	There some aquatic snakes in Minnesota, mostly in the St. Croix and Mississippi Rivers and larger southeastern rivers	Water snake (<i>Nerodia sipedon</i>) and milk snake (<i>Lampropeltis Triangulum</i>)	MN DNR 2017
Salamanders (Phylum Chordata, Class: Amphibia)	Move slowly along streambed or riparian corridor. Have tendency to drift downstream over time; changes to streambed particles size / deposition can reduce mobility; some may migrate in riparian corridor	Mudpuppy (<i>Necturus maculosu</i>)	MacCulloch & Bider (1975); Bruce, R. C. (1986); Jackson 2003; Miller et al. 2007

B.2.1. Reptiles

There are many herptiles (reptiles and amphibians) that spend part or all of their life cycle in or adjacent to streams and lakes in Minnesota. In general, these have been less-well studied than game fish species though movements of some turtle species have been well-studied. Turtles need to move out of the water and onto sandbars or uplands for nesting. They may need to move seasonally for feeding, basking or overwintering. Blanding's turtle, (*Emydoidea blandingii*), a threatened species in Minnesota, is often blocked by road curbs when moving into uplands (Rowe and Moll 1991; Gibbs and Shriver 2002). Wood turtle, (*Glyptemys insculpta*), another state endangered species, is less aquatic but lateral connectivity within the floodplain is important for them to access nesting, feeding and basking sites along rivers (Tuttle et al. 2005). Softshell turtle species (*Apalone spp.*) are large-river species that are probably less likely to be impacted by culverts which are primarily located on small streams. While road mortality is often the largest problem associated with road crossings for turtles, culverts may inhibit turtles' movement in a stream. For example, darkness may possibly inhibit turtle movement through culverts, though there is little research in this area (Woltz et al. 2008).

Snakes are not very common in most small Minnesota streams though they are present in larger rivers in eastern Minnesota (MN DNR 2017). Because of their limited extent and high mobility they are not likely a passage concern in most culvert situations in Minnesota.

B.2.2. Amphibians

The movement of frogs and salamanders may be affected by road crossings. For example, salamander populations were found to be influenced by the gradual downstream drift of young that exceeds upstream movement of the adults (Bruce 1986). Since they tend to have very slow movement and "swimming" speed on the bottom of streambeds (Anderson et al. 2014), if they are eliminated from an upstream area it may be very difficult for them to move back upstream. Salamanders utilize the spaces between gravel, rock and plants to move forward so that a natural streambed may be necessary for their upstream movement (Ward et al. 2008). They often use the riparian corridor for migration so floodplain connectivity at road crossings may be important for free movement of salamanders and other amphibians and reptiles. Constructed banks through culverts may facilitate movement in some cases.

B.3. STREAM CONNECTIVITY AND STABILITY AT CULVERTS

AOP may be affected by stream stability near culverts by reducing connectivity or making conditions that are unfavorable for movement through the road crossing. Stream stability is often defined by a balance between erosion and deposition over time or more simply by the lack of excessive rates of erosion or deposition. At road crossings, however there is little leeway for lateral or vertical channel movement so stability is more focused on localized bed erosion (scour) or excessive deposition that can inhibit AOP.

B.3.1. Problems from bed erosion or scour

Bed scour is most commonly found on the downstream end of a culvert where high velocity out of the culvert creates excessive shear forces on the downstream end, scouring out a hole or scour pool. This creates an excessive jump height that is impassable to most aquatic life in the upstream direction, exemplified in Figure B.1. Scour around the sides of the culvert can lead to local instabilities and undermine the structure (Johnson and Niezgodá 2004).



Figure B.1. Excessive jump at culvert outlet at tributary to Seven Mile Creek, Minnesota (C. Lenhart photo).

In many streams, increases in flow from development, land-cover change, deforestation or climate changes have downcut the channel in a system-wide manner (Castro 2003). Culverts often function to arrest the upstream migration of headcuts in these channels. As a consequence when the culvert is removed during the replacement process, a headcut can propagate upstream creating further incision and reduced connection to the floodplain. Aside from flow increases, Castro (2003) notes that removal of wood jams or beaver dams for maintenance of channels near road crossings can propagate headcutting upstream as well. Castro and Beavers (2016) describe analyses that can be done to identify channel incision, since it is not always simple to detect in the field.

Other factors that can lead to instability at culverts include removal of riparian vegetation or a change in vegetation type that has less resistance to bank erosion; constrictions at culvert and steepening of the gradient can lead to local channel instabilities. Concentration of flow by the alignment of roads and associated ditches can increase local flow rates, velocity and shear forces (Dutton 2012).

The Montana Department of Natural Resources and Conservation (Montana DNRC 2017) describe some of the major issues associated with stability and connectivity in streams with high bedload (typically gravel and larger size particles transported along the bed). The issues include:

- Reduced cross-sectional area and flow capacity with deposits of gravel or cobble.
- Reduced conveyance of bedload.
- Possible changes in the alignment of the channel as it migrates or erodes upstream and downstream of the culvert area.
- Jams caused by ice blockages or woody debris can cause localized erosion and deposition that can cause channel adjustment around the culvert.

Floodplain disconnection is created by culverts in their local vicinity (Manciola et al. 2015). This tends to increase flows downstream as floodplain storage is reduced in the area of the culvert.

B.3.2. Stability issues associated with reduced stream power, excessive deposition or shallow flow

At low flow, deposition at the upstream end of the culvert can create reduced flow depths or directly block AOP. Deposition and low flow blockages can be created in a variety of ways. Intermittent streams particularly in arid to semi-arid regions have great variability in sediment transport and deposition (Tooth 2000). Intermittent streams are more likely to have episodic deposits that are not mobilized again for months or years creating channel instability and AOP blockage. Given that most stream miles are ephemeral or intermittent, particularly in the southern and western parts of Minnesota, the episodic nature of flow and sediment delivery is problematic for culvert maintenance, channel stability and AOP across the state.

Streams with high bedload also contribute to deposition (Montana DNRC 2017) and may create local instabilities and/or AOP blockages at culverts. These situations would call for the use of geomorphic simulation and/or bottomless culverts to help to alleviate blockages from excess bed deposition.

Deposition can also be created by a low slope or even a reverse slope, slowing down the flow and promoting sediment accumulation on the upstream end of the culvert. Wargo and Weisman (2006) found that single culverts often are over-sized promoting shallow depths at low flow and deposition within the pipe. Double- or multiple-barrel culvert installations where one barrel is designed to convey low flows can alleviate some of the sedimentation issues by increasing the low flow depth while still providing flow capacity at the higher flows through offset culverts. However, multiple barrels raise concerns for catching large debris.

Rowley and Hotchkiss (2014) showed that deposition occurred at the downstream end of a culvert following a 2-year flood in a simulation study. The occurrence of deposition both above and below the culvert under different flow conditions demonstrates the complexity of hydraulics and sediment transport occurring at culverts.

The presence of debris jams on the upstream end of culverts can cause instabilities as well. Debris jams often cause backwater effects and subsequent deposition in those areas (Montana DNRC 2017) which may act as an AOP blockage.

APPENDIX C: WEB AND GIS DATA LINKS

Geographical and Water Resources Data (also see GIS Links)

DNR Public Waters Inventory Maps	http://www.dnr.state.mn.us/waters/watermgmt_section/pwi/maps.html
USGS Stream Stats for Minnesota	https://streamstats.usgs.gov/ss/
USGS Water Resources Maps	https://water.usgs.gov/maps.html
MnDOT Geographic Information and Mapping	http://www.dot.state.mn.us/maps/gdma/cart-products.html
NRCS Web soil survey	https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

Selected Organizations

MN Board of Soil and Water Resources (BSWR)	http://www.bwsr.state.mn.us/planning/data.html
MN Watershed Districts	http://www.mnwatershed.org/
MN Association of Soil and Watershed Conservation Districts	http://www.maswcd.org/
MN DNR Rivers and Streams	http://www.dnr.state.mn.us/rivers_streams/index.html

Regulations and Definitions

MnDOT Project Planning, See “Stream or Water Body Modification”	http://www.dot.state.mn.us/planning/hpdp/index.html
Ordinary High Water Level	http://www.dnr.state.mn.us/waters/surfacewater_section/hydrographics/ohw.html
DNR Water Laws	http://www.dnr.state.mn.us/waters/law.html
MN PCA Public Drainage Manual (regarding public ditches)	https://drainage.pca.state.mn.us/index.php/Main_Page
Wetlands Regulation in Minnesota	http://www.bwsr.state.mn.us/wetlands/
Topeka Shiner (federally endangered fish)	https://www.fws.gov/midwest/endangered/fishes/TopekaShiner/tosh_mn.html
MN Rare Species (state endangered, threatened, and special concern)	http://www.dnr.state.mn.us/ets/index.html

Selected GIS Data Links

Minnesota Geospatial Commons (MN GIS Data)	https://gisdata.mn.gov/
MN LiDAR Data	http://www.mngeo.state.mn.us/chouse/elevation/lidar.html
LIDAR-derived 1m digital elevation model	https://gisdata.mn.gov/dataset/elev-dig-surf-model
FEMA Digital Flood Rate Insurance Maps (DFIRM), Minnesota	https://gisdata.mn.gov/dataset/water-dnr-fema-dfirm

Agro-eco regions, associated with a specific combination of soil types, landscape and climatic features, and landuse	https://gisdata.mn.gov/dataset/agri-agroecoregions
Buffer Protection Map, Minnesota	https://gisdata.mn.gov/dataset/env-buffer-protection-mn
Land Cover	https://gisdata.mn.gov/dataset/biota-landcover-mlccs
Designated Trout Streams	https://gisdata.mn.gov/dataset/env-trout-stream-designations
Trout Stream Designation by PLS Sections	https://gisdata.mn.gov/dataset/water-trout-streams-pls-sections
MNDNR Hydrography	https://gisdata.mn.gov/dataset/water-dnr-hydrography
MNDNR Watershed Suite - collection of watershed delineations at various levels, flow network lines, and pour points.	https://gisdata.mn.gov/dataset/geos-dnr-watersheds
GIS for Rivers and Streams – many layers	http://www.mngeo.state.mn.us/chouse/water_rivers.html
Public Waters (PW) Basin and Watercourse Delineations	https://gisdata.mn.gov/dataset/water-mn-public-waters
Stream Routes with Strahler Stream Order	https://gisdata.mn.gov/dataset/water-strahler-stream-order
Statewide Altered Watercourse Project	https://gisdata.mn.gov/dataset/water-altered-watercourse
Surface Water from National Hydrography Database	https://gisdata.mn.gov/dataset/water-national-hydrography-data
National Wetland Inventory Update for Minnesota	https://gisdata.mn.gov/dataset/water-nat-wetlands-inv-2009-2014
DNR Hydrography - Fisheries Surveyed Lakes	https://gisdata.mn.gov/dataset/env-lakes-surveyed-by-mndnr
State Aquatic Management Areas	https://gisdata.mn.gov/dataset/plan-mndnr-fisheries-acquisition
Public Water Access Sites in Minnesota	https://gisdata.mn.gov/dataset/loc-water-access-sites
Aquatic Invasive Species Observations	https://gisdata.mn.gov/dataset/env-invasive-aquatic-obs
DNR Hydrography - Listed Infested Waters	https://gisdata.mn.gov/dataset/env-designated-infested-waters
Minnesota Roads (2012)	https://gisdata.mn.gov/dataset/trans-roads-mndot-tis
High Potential Interaction, between aquifers and surface waters	https://gisdata.mn.gov/dataset/us-mn-state-metc-water-high-potential-interaction

APPENDIX D: REGULATORY INFORMATION

D.1. REGULATORY AGENCIES

Some or all of the following agencies may be involved in any particular project within Minnesota that, “... affect[s] the course, current and cross-section of lakes, wetlands, rivers and streams.”

Federal-level agencies:

- US Department of Transportation (US DOT), Federal Highway Administration (FHWA)
- US Army Corps of Engineers (USACE)
- US Environmental Protection Agency (USEPA)
- US Fish and Wildlife Service (USFWS)
- US Forest Service (USFS)
- Federal Emergency Management Agency (FEMA)
- Tribal governments

State agencies:

- Minnesota Department of Transportation (MnDOT)
- Minnesota Department of Natural Resources (MN DNR)
- Board of Soil and Water Resources (BSWR)
- Minnesota Pollution Control Agency (MPCA)

Local agencies:

- Drainage districts or ditch authorities, often at the County level
- County, city, or township Zoning regulations
- Watershed districts
- Soil and water conservation districts

A good review of federal legislation and regulations potentially affecting culvert construction may be found in Appendix B of FHWA HEC 26 (Kilgore et al. 2010).

D.2. TABLE OF LAWS AND REGULATIONS APPLICABLE TO ROAD-STREAM CROSSINGS IN MINNESOTA

Federally-Administered Regulation	Responsible Agency	Notes
Section 404 of the Clean Water Act Ref: 33 U.S.C. § 1344(a), 33 C.F.R. § 320.4;	US Army Corps of Engineers	Waters of the US
Section 10 of the Rivers and Harbors Act Ref: 33 U.S.C. § 403	US Army Corps of Engineers	Waters of the US
Endangered Species Act Ref: 16 U.S.C. § 1536	US Fish & Wildlife Service	Applies to federally endangered or threatened species
National Environmental Policy Act (NEPA) Ref: 42 USC § 4321, et seq.	US Dept. of Transportation	Applies to federal actions, funding
State-Administered Regulation	Responsible Agency	Notes

DNR Public Waters Work Permit Program, including General Public Waters Work Permit GP2004-0001	MN Department of Natural Resources (DNR)	Applies to public waters, with some exceptions
MPCA Stormwater Program	MN Pollution Control Agency (MPCA)	MS4 program applies to municipalities
MPCA 401 Water Quality Certification https://www.pca.state.mn.us/water/clean-water-act-section-401-water-quality-certifications	MPCA	
Minnesota Environmental Policy Act (MEPA) Ref: Minn. Stat. ch 116D	MN Environmental Quality Board (EQB)	
Minnesota Environmental Rights Act (MERA) Ref: Minn. Stat. ch 116B	MN EQB	
Locally-Administered Regulation	Responsible Agency	Notes
Wetland Conservation Act	Local governmental unit	
Watershed District Rules Ref: Minn. Stat. ch 103D. (https://www.revisor.mn.gov/statutes/?id=103d)	Local watershed district, if present	
Shoreland and Floodplain Ordinances Ref: Minn. Stat. ch 103F. (https://www.revisor.mn.gov/statutes/?id=103F)	Local governmental unit	
Municipal Wetlands, Zoning, and other Ordinances	Varies by jurisdiction	

D.3. PERMITS FOR WORK IN PUBLIC WATERS

D.3.1. General Permit


The Public Waters Work General Permit GP2004-0001, also known as the MnDOT GP, is the main regulatory document for Minnesota Department of Transportation (MnDOT) projects involving the repair or replacement of bridges, culverts, or stormwater outfalls at locations involving Public Waters state-wide. A link to the permit is below.

http://files.dnr.state.mn.us/waters/watermgmt_section/pwpermits/General_Permit_2004-0001.pdf

Similar, but not identical, General Permits pertain to in-stream work done at the county level in several individual counties, or groups of counties within DNR administrative regions.

The MnDOT general permit – “...applies only to the replacement, reconstruction, or repair (including associated minor channel or shoreline work) of existing bridges, culverts, stormwater outfalls, or riprap in Public Waters that are designed under the supervision of a registered professional engineer” Coverage is statewide, for MnDOT projects occurring in all counties and watersheds.

Authorized activities include, “Upon notification of approval by the DNR Transportation Hydrologist or Area Hydrologist, replace or repair of bridges, culverts, riprap, or stormwater outfalls on Public Waters, where all conditions and provisions specified herein are met.” An excerpt of the General Permit is shown below (Figure D.1), which notes the purpose and authorized activities:



MINNESOTA DEPARTMENT OF NATURAL RESOURCES
Limited/Amended
Public Waters Work General
Permit
Expiration Date: 11/27/2018

General Permit Number
2004-0001

Pursuant to Minnesota Statutes, Chapter 103G, and on the basis of statements and information contained in the permit application, letters, maps, and plans submitted by the applicant and other supporting data, all of which are made part hereof by reference, **PERMISSION IS HEREBY GRANTED** to the applicant to perform actions as authorized below. This permit supersedes the original permit and all previous amendments.

Project Name: MNDOT Statewide General Permit	County: All counties in Minnesota	Watershed: All watersheds in Minnesota	Resource: All waters shown on the Public Waters Inventory	
Purpose of Permit: Bridge, culvert, or stormwater outfall repair or replacement.		Authorized Action: Upon notification of approval by the DNR Transportation Hydrologist or Area Hydrologist, replace or repair of bridges, culverts, riprap, or stormwater outfalls on Public Waters, where all conditions and provisions specified herein are met.		
Permittee: MN DEPARTMENT OF TRANSPORTATION CONTACT: CLARKOWSKI, LYNN, (651) 366-3602 OFFICE OF ENVIRONMENTAL STEWARDSHIP 395 JOHN IRELAND BLVD, MS 620 ST. PAUL, MN 55155 (651) 366-3600		Authorized Agent: N/A		
Property Description (land owned or leased or where work will be conducted): The Permittee or its authorized agent must own, control, or have permission to access and use all lands affected by the project.				
Authorized Issuer: Tom Hovey	Title: Water Regulations Unit Supervisor	Issued Date: 11/27/2013	Effective Date: 11/27/2013	Expiration Date: 11/27/2018

Figure D.1. A portion of General Permit 2004-0001 showing the purpose and application of the permit. This and other general permits are updated periodically.

To aid in application of the general permit, Peter Leete, the DNR Transportation Hydrologist and liaison to MnDOT, has assembled a document of Best Practices for Meeting DNR Public Waters Work Permit GP 2004-001, Version 4 (Leete 2014), which is referenced in the permit language, and may be found at the following website:

http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html

As stated in the Best Practices document, “The DNR anticipates that transportation projects will use practices in this document as a guide to address DNR Public Waters regulations associated with the protection of our water resources for fisheries, wildlife, rare features, invasive species, ecological connectivity, and recreational opportunity as identified in GP2004-0001.” Note that this document is referenced within the MnDNR Public Waters General Work Permit itself, but contains a wealth of information useful even in situations where the General Permit does not apply. Best Practices for Meeting DNR Public Waters Work Permit GP2004-0001 focuses on ways to better manage areas where ecological and water resources intersect with transportation systems (bridges, culverts, roadsides, etc.). It is divided into three main categories: species protection, hydraulic and hydrologic connections, and methods of in-water construction. Species protection covers fish spawning and fish passage timing and related strategies for avoiding impacts. It also covers wildlife passage including passage benches under road crossings and techniques for minimizing impacts to native plant communities and restoring them, where appropriate. The second chapter on hydraulics and hydrology describes conditions for improved AOP at culverts and broader related issues such as wood and ice jams at culverts. Appendix A of this document is on the MESBOAC method and provides a nine page overview of the method. Chapter 3 covers methods for erosion control, sediment management and other strategies for minimizing impacts to streams, rivers and lakes during construction of bridges and other projects that require in-water work.

D.3.2. Individual Permit

An individual permit from DNR is required for projects outside of the scope of a General Permit or projects that, according to the General Permit language, “...the DNR identifies as having the potential for significant resource impacts”.

If an Individual Permit is required, Minnesota has an online Permitting and Reporting System, which acts as a central location for information needed for state, federal, local permitting.

<http://www.dnr.state.mn.us/mpars/index.html>

A pdf copy of the current (dated February 2014, accessed November 2018) form may be found here:

http://www.bwsr.state.mn.us/wetlands/forms/MN_joint_appl_form.pdf

D.3.3. No permit required

No DNR permit is required for several cases categorized under Structures in Stream. For culverts, the regulation makes the following exemption:

To Construct A Bridge or Culvert, or to Fill or Excavate the Bed of a Public Watercourse Having a Total Drainage Area, at its Mouth, of Less Than 5 Square Miles (3,200 Acres) - A DNR Public Waters Work Permit is not required, provided:

1. County zoning officials and local Soil and Water Conservation District are given at least 7 days prior notice to determine that the project will not result in downstream erosion or sedimentation;
2. The project will not divert water to a different watershed;
3. The project will not impound water by damming the watercourse; and
4. The watercourse is not an officially designated trout stream.

Source: http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/requirements.html

D.3.4. Exception: Culvert replacement in-kind

Culvert replacement in-kind (replacing with the culvert of same size and elevation) is exempted from permit coverage in certain situations by the following Exception:

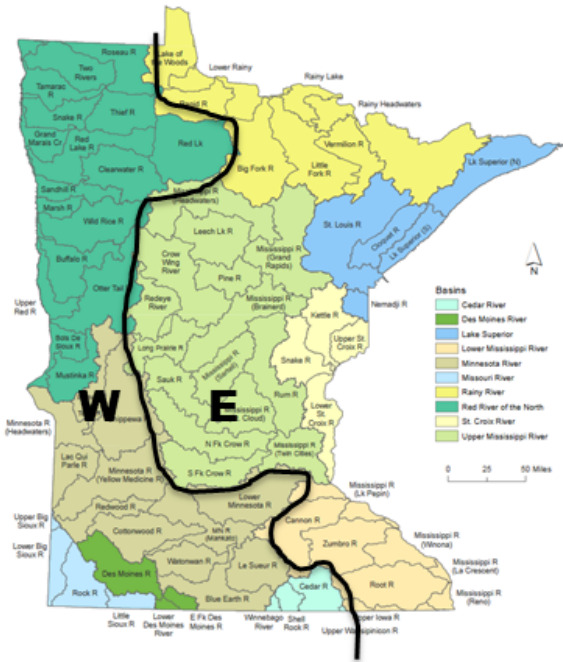
Exceptions. Under Minnesota Statue 103G.245, Subdivision 2, a public waters work permit is not required for,

- (1) work in altered natural watercourses that are part of drainage systems established under chapter 103D or 103E if the work in the waters is undertaken according to chapter 103D or 103E;
- (2) a drainage project for a drainage system established under chapter 103E that does not substantially affect public waters; or
- (3) culvert restoration or replacement of the same size and elevation, if the restoration or replacement does not impact a designated trout stream.

Despite the legality of this exemption for in-kind replacement, the Minnesota DNR Culvert Permitting Fact Sheet advises that Replacing culverts 'in-kind' (same size and elevations), "... may not be in the best interests of the environment or of the project proposer. Flood elevations, fish passage, ecological connectivity, lake and wetland control elevation, road safety and fiscal responsibility are all factors to consider when a crossing is to be replaced. The DNR encourages the correcting of ecological and hydraulic deficiencies of existing culverts to prevent replicating poor design." (DNR culvert permitting fact sheet September 8, 2015). http://files.dnr.state.mn.us/waters/publications/culvert-permitting_fact-sheet_101615.pdf

APPENDIX E: REGIONAL CURVES

Basins and Major Watersheds in Minnesota



How to Use:

Locate watershed in west or east area. Enter charts with drainage area in square miles for estimates of bankfull width, depth, and cross sectional area.

Important Note:

Regional regressions should not be used as the sole source for channel dimensions, but can be helpful as a check of field-measured values. The type of channel and setting strongly influences dimensions. Refer to Chapter 3 for more information.

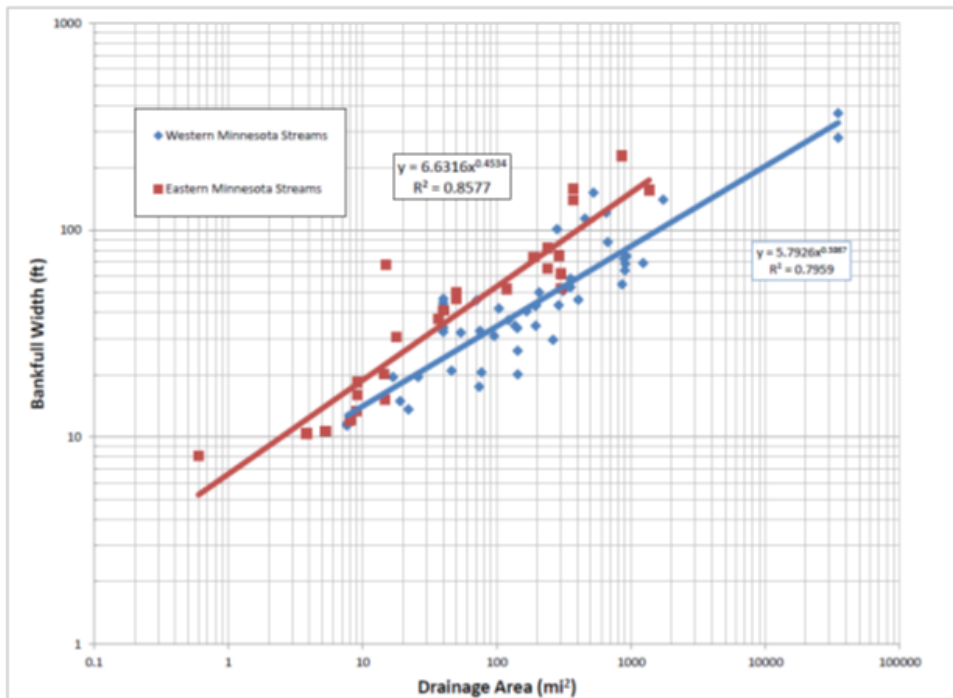
References:

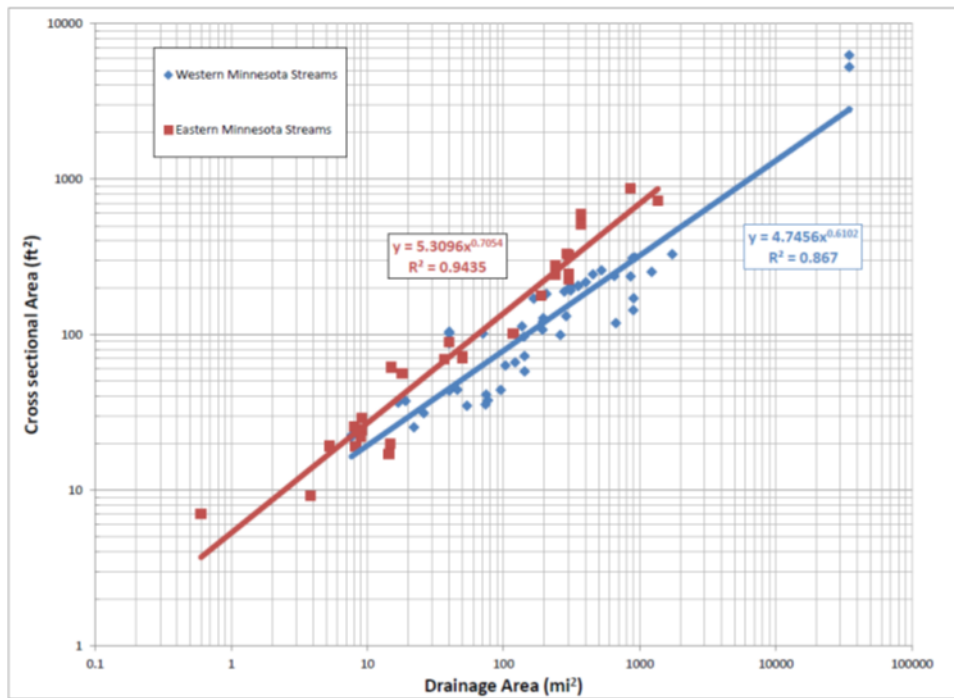
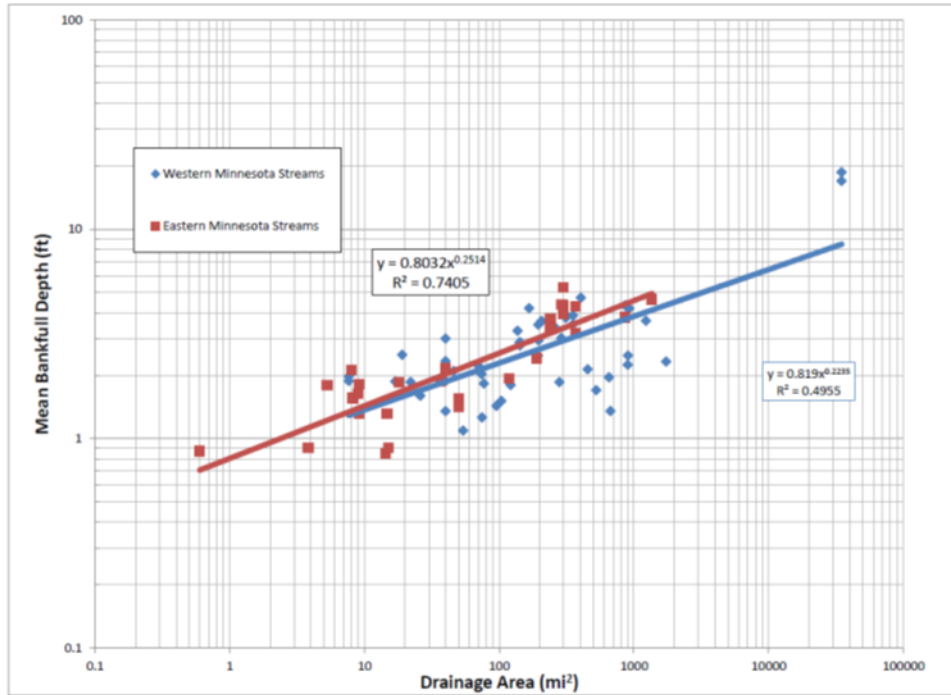
Hillman, A. 2015. Stream Crossing Inventory and Ranking Guidelines.

<http://www.dnr.state.mn.us/eco/streamhab/about.htm>

Basins figure:

<https://www.pca.state.mn.us/sites/default/files/wq-ws1-01.pdf>





Regional regression figures from Hillman (2015), also found at:
<http://files.dnr.state.mn.us/eco/streamhab/geomorphology/width.pdf>
<http://files.dnr.state.mn.us/eco/streamhab/geomorphology/depth.pdf>
<http://files.dnr.state.mn.us/eco/streamhab/geomorphology/cross-section.pdf>

APPENDIX F: STREAM SLOPES IN MINNESOTA

The significant role that stream slope or gradient plays in how a stream functions warrants some understanding of what slopes are likely to be encountered in Minnesota.

In the 2010 report, Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on data through water year 2005: U.S. Geological Survey Scientific Investigations Report 2009–5250, by Lorenz, Sanocki, and Kocian, (Lorenz et al. 2010), the authors report main channel slope for 330 streams within six hydrologic regions in Minnesota shown in Figure 3.1.2 (refer to Section 3.1.2 for further discussion).

Table F.1 identifies the maximum, average (geometric mean), and minimum main channel slope of the 330 streams used in the analysis. Assuming these streams are representative of Minnesota as a whole, one observation is that there can be a large variation in slope in different regions. With exception of hydrologic region C (the North Shore of Lake Superior), mean stream channel slopes are in the range of 0.11% - 0.37%.

The stream channel slope data underlying the table includes streams with contributing drainage areas of up to 2,640 square miles. These large streams warrant bridges. Practical upper limits for drainage areas of bankfull width culverts are in the range of perhaps 20 to 100 square miles, depending on region (refer to regional curves in Appendix E). A characterization of streams by slope is shown in Figure F.1 below, for all data (drainage area up to 2,640 sq mi), and three subsets (0- 20 sq mi, 20-100 sq mi., and 100- 2,640 sq mi)

Table F.1. Channel slope data at gauging stations used in development of peak flow regressions in six hydrologic regions (see Figure 3.1.2). "Average" refers to geometric mean. The main channel slope is based on the elevation change between the 10% and 85% stream length (from Table 7, Lorenz et al. 2010)

Main Channel Slope		Region A	Region B	Region C	Region D	Region E	Region F
(%)	Minimum	0.03%	0.01%	0.21%	0.03%	0.08%	0.09%
	Average	0.11%	0.15%	1.00%	0.15%	0.23%	0.37%
	Maximum	0.71%	4.51%	4.45%	1.46%	2.22%	4.34%
(feet/ mile)	Minimum	1.74	0.67	11.2	1.49	4.04	4.64
	Average	5.63	7.76	52.6	8.12	12	19.6
	Maximum	37.4	238	235	77.2	117	229

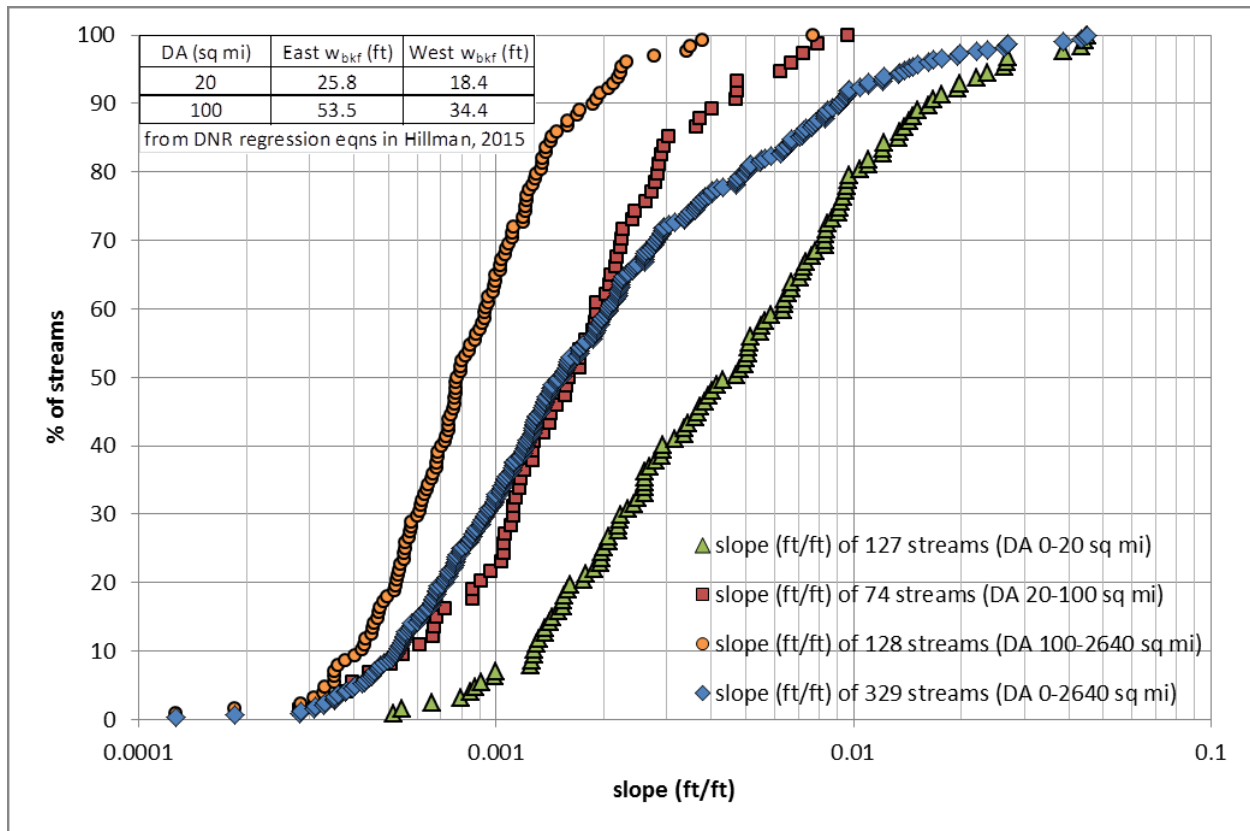


Figure F.1. Percentage of streams vs main channel slope, based on data from Table 2, Lorenz et.al. 2010. Curves for four subsets of streams, based on drainage area.

The following table (Table F.2) presents a categorization of stream channel slope data. If the dataset is representative of Minnesota as whole, the vast majority of streams have main channel slopes less than one percent. Among streams with drainage area less than 20 square miles, slopes between 0.2% and 1.0% are most common, whereas lower slopes are most common for larger streams. However, so-called high value streams such as trout streams or cold water fisheries may be among the smaller number of higher slope streams.

Table F.2. Categorization of Minnesota streams by main channel slopes. Data from Table 2 of Lorenz et al. 2010.

slope category (Section 5.1)	127 streams (DA 0-20 sq mi)	74 streams (DA 20-100 sq mi)	128 streams (DA 100-2640 sq mi)	329 streams (DA 0-2640 sq mi)
<0.2%	24%	61%	91%	59%
0.2-1.0%	55%	39%	9%	33%
1.0-3.0%	17%	0%	0%	7%
>3.0%	3%	0%	0%	1%

APPENDIX G: MNDOT STREAM SURVEY FORMS

G.1. MNDOT SURVEY REQUIREMENTS AT BRIDGE OR CULVERT CROSSINGS

Surveys are essential for an accurate hydraulic analysis. The survey information is used in the creation of hydraulic models which will analyze the bridge crossing of the subject stream. With the availability of statewide high quality lidar data, much of the overbank/floodplain topography data is readily available. The main drawback to lidar data is that it can't "see" underwater. Lidar also can't capture data of the in-place structure. The minimum data required to design bridge waterway crossings is as follows (See Figure G.1 for illustration of requirements):

- The thalweg profile of the stream, upstream and downstream of the crossing for 1000 feet or 3X the bridge opening whichever is greater. The thalweg is a line extending down a channel that follows the lowest elevation of the stream.
- The water surface elevation at each point a measurement was taken for the thalweg.
- A series of in-stream cross sections - enough to create a tin of the channel bottom, approximately every 100' measured along the channel. Cross sections should extend out to the top of bank and should be oriented perpendicular to the flow.
- Bankline profiles of both streambanks at top of bank
- Cross-section at the upstream and downstream face of the in-place Bridge opening along with the low steel
- For culverts, inlet and outlet invert elevations and top of culvert
- Existing roadway profiles

The following information should also be collected by the surveyors:

- Maximum observed high water and dates of high water event (if possible) upstream and downstream of the bridge
- Elevation of any debris lines
- Foundation elevation of the lowest property upstream that might get flooded
- Any evidence of scour should be noted
- Any evidence of ice or debris problems
- Boat passage requirements if marked or signed at the bridge opening
- Pictures
 1. Standing on the bridge deck take pictures of the upstream channel, downstream channel and of the roadways coming onto and off of the bridge.
 2. From the stream bank, take a picture of both the upstream and downstream faces of the bridge.
 3. Features of interest such as sandbars in the river, debris pile ups, beaver dams, any hydraulic control structures in the area, etc.

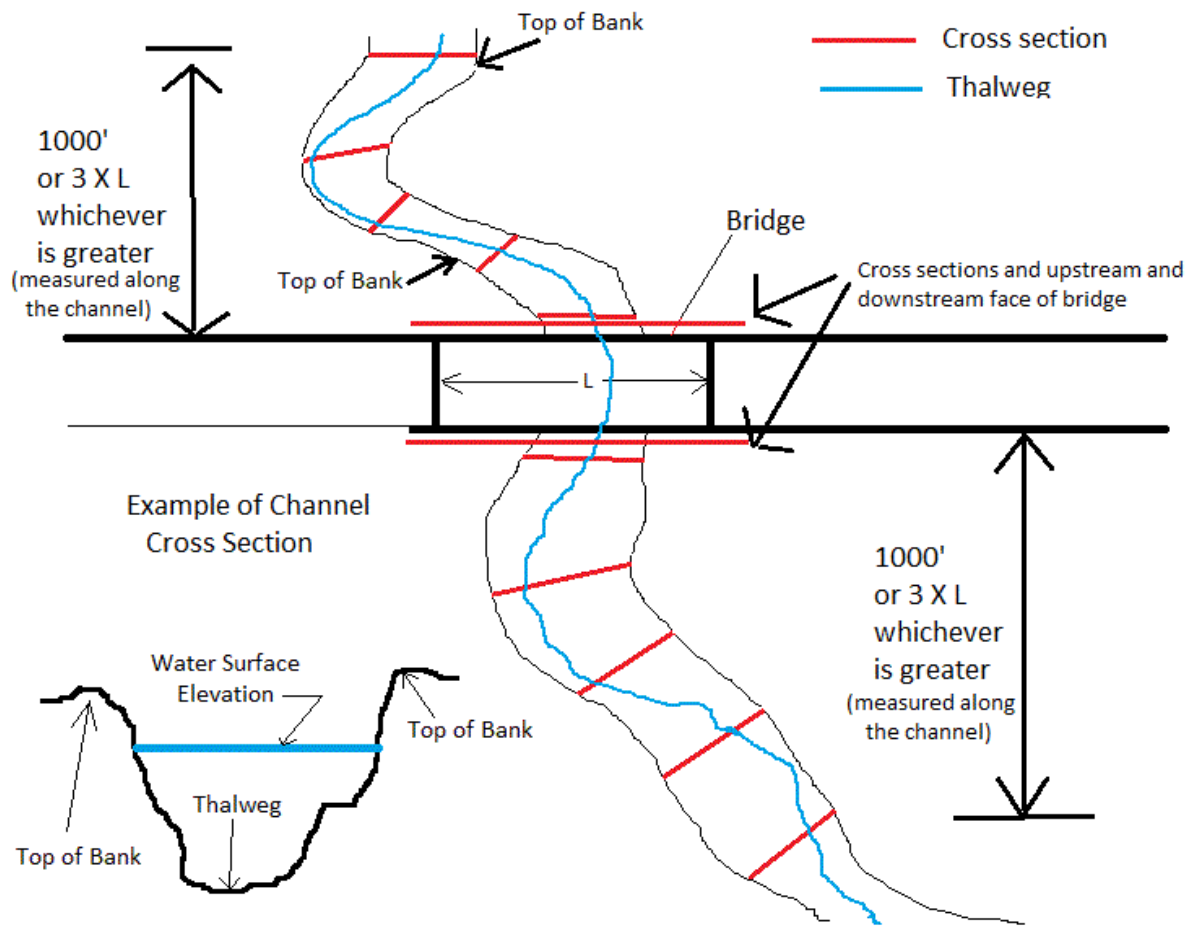


Figure G.1. Illustration of features to survey for bridge and culvert crossings (MnDOT Bridge Office, Hydraulics Unit 2015).

G.2. WOLMAN COUNT FOR RIPRAP GRADATION

Table G.1 below is the data collection table from a MnDOT spreadsheet form used for quantifying riprap gradation. The form could also be used for stream channel Wolman pebble counts (Section 3.6). This eventually will be available online as part of the Grading and Base Manual: Form G&B-109b.

Table G.1. Wolman count for riprap gradation (MnDOT Bridge Office, Hydraulics Unit 2015).

Wolman Count for Riprap Gradation							
Project No:		Tester Name:				Date:	
Sample #:		Source or Stockpile Location:					
Pay Item Number		Riprap Class		Quantity		Gradation Tests	
						Required	Attached
Particle #	Measured Intermediate Axis (inches)	Particle #	Measured Intermediate Axis (inches)	Particle #	Measured Intermediate Axis (inches)	Particle #	Measured Intermediate Axis (inches)
1		26		51		76	
2		27		52		77	
3		28		53		78	
4		29		54		79	
5		30		55		80	
6		31		56		81	
7		32		57		82	
8		33		58		83	
9		34		59		84	
10		35		60		85	
11		36		61		86	
12		37		62		87	
13		38		63		88	
14		39		64		89	
15		40		65		90	
16		41		66		91	
17		42		67		92	
18		43		68		93	
19		44		69		94	
20		45		70		95	
21		46		71		96	
22		47		72		97	
23		48		73		98	
24		49		74		99	
25		50		75		100	

Once all measurements have been recorded complete 'Wolman Grad._e-worksheet_X', for the applicable riprap class, to get gradation results. Submit this form with G&B 109b.