TRANSPORTATION RESEARCH SYNTHESIS

Minnesota Department of Transportation
Office of Policy Analysis, Research & Innovation
Research Services Section
(651) 366-3780
www.research.dot.state.mn.us

TRS1302
Published March 2013

CULVERT DESIGNS FOR AQUATIC ORGANISM PASSAGE: CULVERT DESIGN PRACTICES INCORPORATING SEDIMENT TRANSPORT

Introduction

The design of culverts to accommodate aquatic organism passage (AOP) requires an understanding of organism habitat requirements, swimming ability and migration needs, as well as an understanding of how a culvert design will perform in a specific geomorphic context. This report documents existing reports on culvert design for AOP in Minnesota and nationally.

The following review is designed to build upon the work of Hansen et al. 2009 and 2011 to: 1) summarize current aquatic organism passage practices, 2) summarize aquatic organism passage needs for Minnesota species, 3) discuss the importance of roughness or streambed sediment within a culvert in different systems (high, medium, or low slope) in single and multiple barrel systems, and 4) summarize physical experiments of sediment transport and geomorphic processes through culverts.

Culvert Design Practices for Aquatic Organism Passage

Much of the existing fish and aquatic organism research has been conducted in coastal regions of the U.S. addressing the fish passage requirements of salmonids. Two recent studies funded by Mn/DOT and the Local Road Research Board (LRRB) evaluated the cost and performance of alternative culvert installations in Minnesota (Hansen et al. 2009 and 2011).

Hansen et al. (2009) conducted a literature review to determine how knowledge obtained from fish passage studies in other parts of the country translated to the Midwest. They found the following differences and similarities between the Midwest and the West coast:

Differences:

1. Fish species and community composition
2. Stream geomorphology
3. Hydrology

Similar fish passage issues:

1. Perched outlets
2. High in-pipe velocity or turbulence
3. Inadequate water depth
4. Excessive pipe length without resting space
5. Debris or sediment accumulation in-pipe

To develop a statewide picture of fish passage concerns related to road crossings in public waters, statewide general and county permits were reviewed and a survey of local and regional hydrologists and engineers was conducted to compile information about the knowledge and use of alternative culvert practices. Based on the findings of this survey, culverts were typically designed for hydraulic conveyance with alternative designs accounting for less than 30% of the total. Alternative designs for culverts in Minnesota included: 1. weirs, 2. roughened channels, 3. baffles, and 4. MESBOAC (a form of embedded culvert design). MESBOAC is a culvert design procedure incorporating geomorphic simulation used most commonly in the northern forested region of Minnesota (MN DNR 2011; http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html).

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

Key findings of the survey include a general lack of: a regional or statewide ranking or prioritization system for fish passage; evaluation of existing alternative designs; understanding outside of the Minnesota Department of Natural Resources (MN DNR) of alternative culvert practices; and knowledge about the effects of culverts on fish passage and sediment transport. A cost analysis of the four listed alternative culverts, based on materials alone (and not accounting for longevity, etc.) found that weirs increased installation costs by 15.1 %; roughened channel increased costs by 10%, baffles increased costs by 12.5 %, and MESBOAC designs ranged from -5% to 33% greater costs over the traditional culvert design.

Hansen et al. (2011) conducted a field evaluation of 19 culverts in four regions of Minnesota to assess their performance for fish passage. Based on the geomorphic and hydrologic performance assessment of those culverts,

1. There is no standard aquatic organism passage (AOP) or fish passage culvert design in Minnesota.
2. The design process for fish passage is based on knowledge and experience of local county, state, and DNR personnel.
3. Methodologies include: matching culvert dimensions to channel parameters, reducing velocities through placement of rock in culverts, and recessing culverts.

Recessed culverts are installed below the bed elevation to allow natural sediment transport to continue through the culvert. The goal is to maintain streambed characteristics through the culvert. Additional roughness may be added to reduce culvert velocities and maintain sediment characteristics through the culvert.

Hansen et al. (2011) evaluates culvert performance primarily by the presence or absence of sediment in recessed culvert barrels. Of 13 recessed culverts examined, six had a lack of sediment in the culvert barrel. Four potential reasons for lack of sedimentation were listed as: a large flow event prior to the survey, culvert too new for sediment to accumulate, culvert slope steeper than channel bed, and lack of transportable sediment or bed load. In addition, improperly sized culvert width and side barrel sediment accumulation were determined to be potential causes of lack of culvert performance. At all 13 sites, the recessed culvert width was less than the recommended bankfull channel width. The authors identified possible solutions to the problem, including a better understanding of stream and site data, improved procedure for placing sediment or anchoring sediment to the culvert, and different designs that work better with the wider channels and floodplains found more commonly in Minnesota. Similar evaluations have been conducted in Ohio and North Carolina and the general consensus is that culverts with adequate cross sectional area and low slopes (<1%) exhibited more stable stream and culvert conditions (Roberts 2009; Tumeo and Pavlick 2011). In Ohio, embedded culverts with slopes greater than 1% had no sediment present inside recessed culverts that were expected to maintain a continuous streambed. These studies identify a need to understand the physical processes that drive sediment transport into and through embedded culverts over a range of geomorphic characteristics (slope and grain size).

After the completion of the projects evaluating Minnesota alternative culvert practices, updates have been made to both state and regional culvert designs for aquatic organism passage. In Minnesota, the general permit issued by the Minnesota Department of Natural Resources to Mn/DOT in 2004 is still in effect and valid until November 30, 2013 (MN DNR 2004; available at http://www.dnr.state.mn.us/waters/forms.html), but the supporting documentation for the permit was updated in

May 2011 (MN DNR 2011; available at http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html). The general permit has the following requirements for fish passage:

> *Bridges, culverts and other crossings shall provide for fish movement unless the structure is intended to impede rough fish movement or the stream has negligible fisheries value as determined by the Transportation Hydrologist or Area Hydrologist in consultation with the Area Fisheries Manager. The accepted practices for achieving these conditions include:*
>
> *A. Where possible a single culvert or bridge shall span the natural bankfull width adequate to allow for debris and sediment transport rates to closely resemble those of upstream and downstream conditions.*
>
> - *A single culvert shall be recessed in order to pass bedload and sediment load.*
> - *Additional culvert inlets should be set at a higher elevation.*
> - *All culverts should match the alignment and slope of the natural stream channel and extend through the toe of the road side slope.*
>
> *Where possible means that other conditions may exist and could take precedence, such as unsuitable substrates, natural slope and background velocities, bedrock, flood control, 100yr flood elevations, wetland/lake control elevations, local ditch elevation and other adjacent features.*
>
> *B. Rock Rapids or other structures may be used to retrofit crossings to mimic natural conditions.*

Chapter 2 of The Best Practices for Meeting DNR GP 2001-0001 manual, updated in May 2011, is entitled “Hydraulic and Hydrologic Recommendations” and provides information relevant to fish passage through culverts for Minnesota (MN DNR 2011; available at http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html). Culvert design approaches to address fish passage in Minnesota addressed in this document include:

> ***Open bottom span**: Open bottom structures are not considered as restricting flow or impinging upon the channel cross sectional area. These structures are not considered an impediment to fish movement.*
> ***Conventional Design**: Culverts sized to pass a specified design storm (e. g. 10 yr peak flow) with no consideration to fish passage needs.*
>
> ***Hydraulic Design**: Techniques that create water depths and velocities to meet the swimming abilities of target fish populations. This approach considers the flow requirements (e.g. maximum velocity, sustained velocity, flow depth, etc.) needed by specific species. The goal is to keep the velocity below a set of thresholds corresponding to a fish’s maximum swim speed, sustained swim speed and related measures. This is a common method for meeting the frequent DNR requirement of: “Velocities of the 20yr. 24 hr. event shall not exceed 2 ft/s.”*
>
> ***Hydraulic Simulation**: Design approaches that simulate natural hydraulics of streams by adding rock or roughness elements to simulate natural hydraulic variation within or adjacent to the culvert. Typically these include placement of rock on the floor of the culvert or placement of rock rapids below the outlet to create pools and riffles, etc. This is an intermediate design method (between geomorphic simulation and hydraulic design).*
>
> ***Geomorphic Simulation**: Design approaches that simulate natural channel morphology and sediment transport. In Minnesota this technique is commonly referred to as “MESBOAC”. It was developed in the northern forested region of Minnesota for the US Forest Service and is based on principles of fluvial geomorphology rather than individual fish swimming ability (see Gubernick and Bates 2003 and Gubernick et al. 2003 for more information on the USFS methodology).*

The rest of this document focuses on MESBOAC design considerations as well as design considerations for floodplain culverts and rock weirs and rapids. Specific guidelines include:

- Width: minimum of bankfull channel width (adjust to nearest standard culvert size)
- Height: 1/3 of bankfull width
- Slope: Same as channel riffle slope

- Embedded depth: 1/6 of bankfull width (up to two feet), or 1/5 bankfull width for steeper streams with cobble substrate
- Multiple culverts: additional culverts one foot higher than thalweg culvert (can also be one foot less in height to ensure the top elevations match.)
- Alignment: align with stream channel
- Channel stability: check for headcut potential/provide grade control

National AOP Guidelines and Models

A number of national guidelines on fish and aquatic organism passage have been developed in recent years following a synthesis report published by the Federal Highway Administration in 2007 (Hotchkiss and Frei 2007; for a full review of alternative culvert practices see Hansen et al. 2009). This document divides design techniques into four general categories similar to those described above by the MN DNR. The Technical Supplement 14N published by the National Resource Conservation Service (NRCS) in the National Engineering Handbook Part 654 focuses primarily on hydraulic design and hydraulic simulation approaches, but includes guidance for the incorporation of geomorphic simulation and no slope designs (NRCS 2007).

National guidance on fish passage has generally moved away from targeting individual fish species toward a geomorphic design that is assumed to provide uninhibited passage to a range of aquatic organisms. Two methods that incorporate bed sediment characteristics included HEC-26 (Kilgore et al. 2010) and the USFS stream simulation design (FSSWG 2008). New “Hydraulic Design of Highway Culverts” guidelines published by the Federal Highway Administration in 2012 (HDS-5; Schall et al. 2012) includes many references to design for aquatic organism passage (AOP) and a full chapter illustrating the HEC-26 and USFS stream simulation approaches. The differences between these approach center around which stream bed sediment characteristics are simulated. HEC-26 uses streambed sediment behavior as a surrogate parameter. The assumption is that if the culvert design does not alter the forces on the streambed, than it can be presumed not to alter the forces experienced by aquatic organisms (i.e. the design goal is for the streambed material within the culvert to be the same as the material upstream and downstream of the culvert). This design approach should maintain natural sediment transport through the culvert without aggradation or scour. The HEC-26 methodology does not use the channel width as a measure of culvert width (as in MESBOAC or the USFS stream simulation approach), rather, culvert width is determined based on sediment transport calculations. The USFS stream simulation approach differs in that it attempts to account for the spatial and temporal variability of sediment transport processes a stream is subject to by simulating the full geomorphic characteristics of a reference reach through a culvert. This approach takes into account pool and riffle spacing, bank roughness, bed armoring and subsurface flow, and grain size distributions representing the full range of in-stream habitat conditions an organism may experience at a road crossing.

Traditional culvert design software typically does not account for aquatic organism passage or sediment transport, with the exception of outlet scour calculations. The HY-8 Culvert Analysis Program (HY-8 Version 7.3; 2012) is a revision of HY-8 developed by the Environmental Modeling Research Lab at Brigham Young University (BYU) and provided to the Federal Highway Administration (FHWA) for distribution. Versions 7.0 and above provide a Windows-based graphical user interface (GUI) for the same hydraulic calculations provided in previous versions with the following additions:

1. Energy dissipation calculators
2. A new culvert shape/coefficient database
3. The ability to model buried (embedded) culverts
4. The Utah State University exit loss equation was added as an option when computing outlet losses
5. Modeling of plastic pipes
6. Research was conducted relating to sequent depth computations for hydraulic jump computations
7. Several improvements and fixes were made to the HY-8 report generation tools.
8. Section property matrix of 10 points for interpolation was replaced with direct computation of section properties for each discharge.
9. The program computation code was rewritten to increase program stability and efficiency.
10. Capability was added to model hydraulic jumps and their length in culverts
11. Capability was added to model broken back culverts and hydraulic jump locations/lengths in broken back culverts
12. Ability to model horizontal and adverse slopes was added
13. Two new culvert types were added to the culvert shape/coefficient database: Concrete open-bottom arch (CON/SPAN) and South Dakota fabricated reinforced concrete box culverts.

The software includes multiple barrel culvert analysis, but all calculations are steady state for a various design flows. Sediment in embedded culverts is represented as an immobile (steady-state) Mannings n roughness coefficient. This treatment of roughness in embedded culverts requires an understanding of sediment structure within the culvert to determine an appropriate roughness value. Similarly, FishXing (2006; available at http://stream.fs.fed.us/fishxing/) developed by the USFS, provides a screening-level tool to assess the ability of various fish species to pass a culvert under specific design flows. Hydraulic calculations are based on steady state calculations with a single channel roughness coefficient and fish passage is based on a database of fish swimming ability. To account for unsteady flows and a more realistic representation of reduced velocity zones within a culvert, Vasconcelos et al. (2011) developed a post-processing tool similar to FishXing, but utilizing the unsteady culvert calculations in HEC-RAS 4.1.

In summary, current AOP guidelines based on geomorphic simulation are based on the assumption that that if the culvert adequately mimics the geomorphic or sediment transport characteristics of the stream, fish passage (and other aquatic organism passage) will occur without a barrier. Studies in Minnesota, North Carolina, and Ohio (Hansen et al. 2011; Roberst 2011; Tumeo et al. 2011) have indicated that embedded culverts do not always perform as intended and this seems to be a function of culvert dimensions (specifically width) or slope. There is a need to understand sediment transport through embedded culverts with various site characteristics (i.e. slope and grain size) to inform design guidelines for Minnesota AOP culverts.

Aquatic Organism Passage in Minnesota

Many fish species common in MN, such as northern pike, are weaker swimmers than salmonids (Figure 1), but require passage through culverts for spawning during typical high-flow periods in the early spring (Figure 2). The current Best Practices manual for Meeting DNR GP 2004-0001 (MN DNR 2011; available at available at http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html) includes a summary of spawning and migration behavior of MN fish species including Topeka Shiner, a federally endangered fish present in the Missouri River Basin. In addition, this document includes regional work exclusion dates broken down into trout/non-trout stream and lakes designed to protect spawning and migration of MN fish. These dates provide a rough guideline for periods of the year when fish passage is of particular importance in MN streams (Figures 2 and 3). Some MN fish species can travel large distances in spring (e.g. walleye: 150 mi, lake sturgeon: 200-750 mi, American eel > 1000 mi; Aadland 2010).

The vast majority of culverts in Minnesota and the Midwest were not designed to accommodate fish passage and little information exists to evaluate the effect of culverts on aquatic organism communities these areas. Based on the results of Hansen et al. (2009), awareness of potential fish passage issues is low amongst the general public and engineers working on road projects. The studies on fish passage in the Midwest that have been conducted, however, indicate that fish passage is a likely issue. A survey referenced by Hansen et al. (2009) of surveyed road crossings in the Pine-Popple watershed in the forested northeast portion of Wisconsin and found that 67% of the crossings partially or totally blocked fish passage. Rayamajhi et al. (2012) conducted a screening level assessment of 55 culverts in Northeast Ohio and found that none of the selected fish species (all fish species found in MN: golden shiner, white sucker, northern pike, greenside darter, pumpkinseed, longear sunfish, smallmouth bass, largemouth bass, golden shiner, and blacknose dace) were able to pass upstream through any of the culverts during the 2-yr flood. This analysis utilized FishXing as a screening level tool similar to the Utah fish passage prioritization tool used by Beavers et al. (2008). Only two fish species (greenside darter and gold shiner) were able to pass on average 3% of the culverts during the maximum average monthly flow and two fish species (greenside darter and blacknose dace) were able to pass 25% of the culverts during the minimum average monthly flow. The most common barriers for fish passage were excessive water velocity, length of culvert, and depth of water in the culvert. To evaluate the effect of lower flow near the culvert boundaries, further analysis on a single culvert was conducted using a post-processing tool for the unsteady flow calculations in HEC-RAS (Vasconcelos et al. 2011). After accounting for low flow areas near culvert boundaries, two of the fish species passed this culvert all of the time, two were never able to pass, and the remaining three species passed some of the time. The barriers under this analysis were excessive velocity and insufficient water depth. Of the 55 culverts, only 18 were able to pass any fish during the four flows tested (max. monthly, min. monthly, typical low flow, 2-yr flow). Combined, these studies provide some evidence of the scale of fish passage issues in the Midwest. The major limitation of extending these studies is the limited information that exists for fish swimming abilities for many Midwest fish species.

In Minnesota, the only federally endangered fish is the Topeka shiner. There are, however, a number of federal- and state-listed mussel species that rely on uninhibited fish passage for dispersal to new habitat areas. The Topeka shiner is found in a relatively limited range in the Missouri River watershed (Figure 4). A study conducted in Eastern South Dakota examined the ability of Topeka shiner and other warm water species to cross a variety of road crossings including box culverts and corrugated culverts (Blank et al. 2011). General results indicated that culverts impeded fish movement for warm water species, but channel spanning embedded concrete box culverts minimized fish passage impedance compared to other structure configurations. An experimental study conducted in Kansas found that road crossings acted as semipermeable barriers to Topeka shiner and other great plains fish for velocities up to 3.6 ft/s (through a 6 ft simulated stream; Bouska and Paukert 2010). Increased water velocity affected the proportional upstream movement of Topeka shiners (but not green sunfish, red shiners or southern redbelly dace). Box culverts had less of an effect than low-water crossings; however, this experimental stream was short compared to many culverts. In addition to the Topeka shiner, there are a number of fish species of special concern in MN listed by Hansen et al. (2009) in Table B.2 that may need to be considered for specific fish passage culverts.

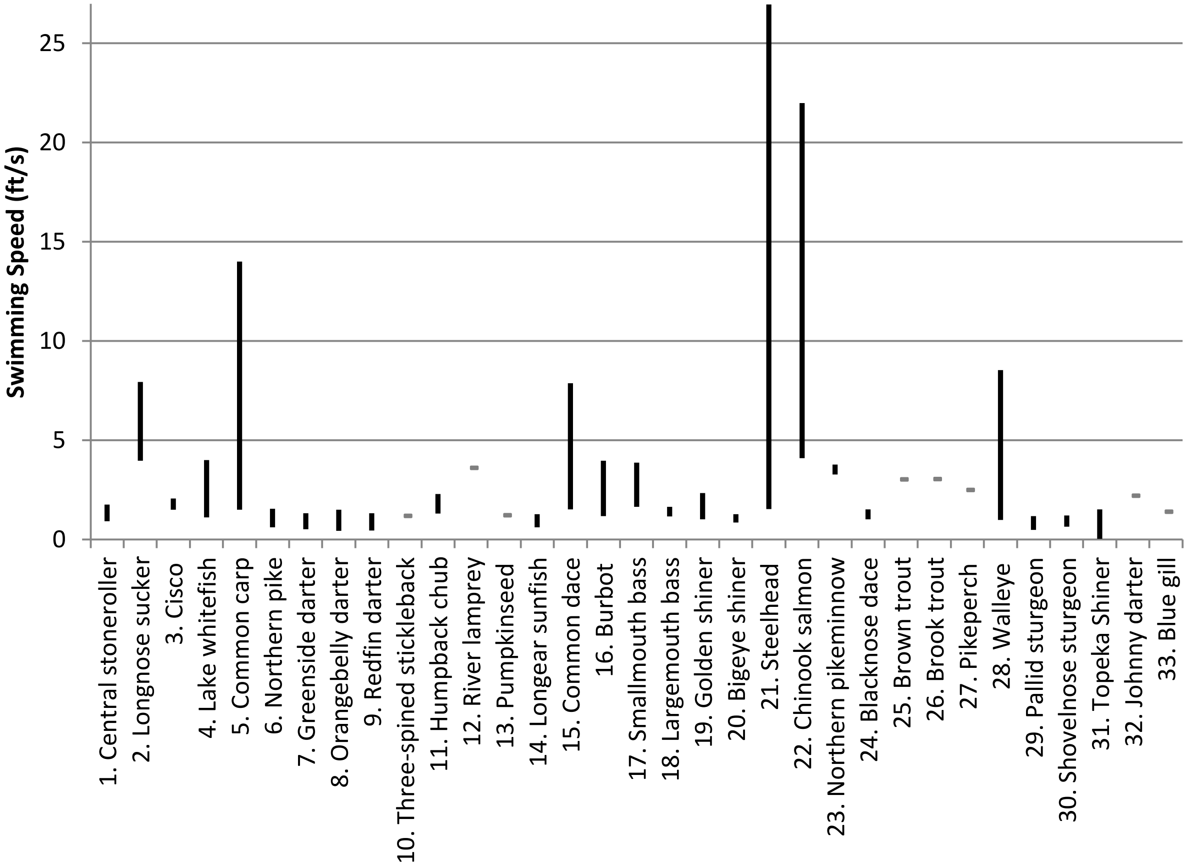

Figure 1: Swimming speeds of Minnesota fish species, including a range of maximum swimming speeds where available. Grey dashes indicate average swim speed. (1-30: Hansen et al. 2009, FishXing 2006; 31: Blank et al. 2011; 32-33: Gardner 2006). Note: swimming ability varies with fish size, life stage, measurement conditions, etc. This figure is a general compilation the range of measured swimming ability of Minnesota fish species to illustrate the relative swimming ability of Minnesota fish species to the general Minnesota requirement of "velocities of the 2-yr 24 hr event shall not exceed 2 ft/s." (MN DNR 2011).

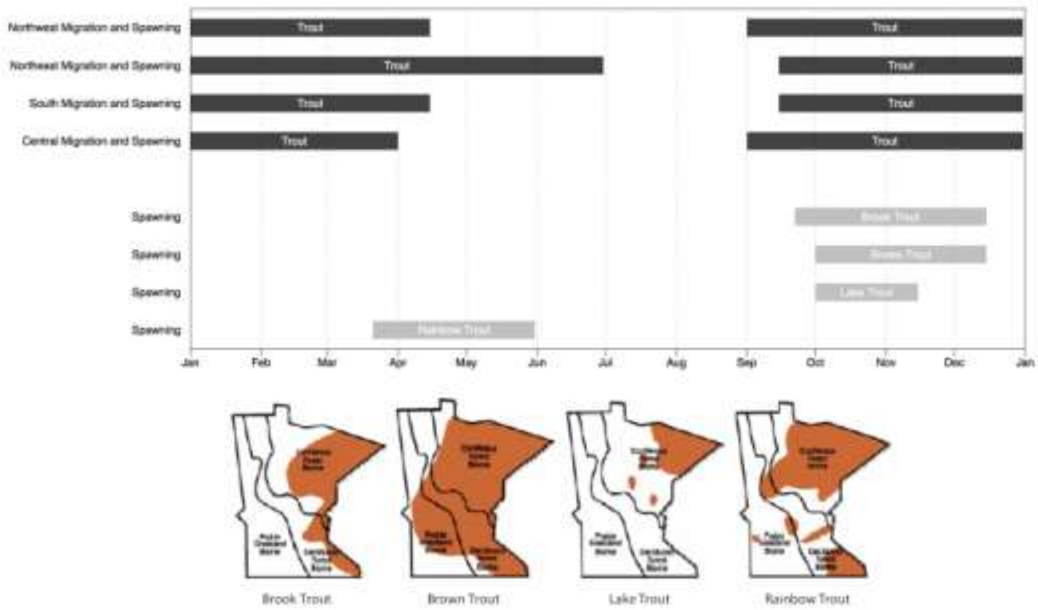

Figure 2: General range of trout in MN and timing of migration and spawning fish passage requirements by region and species (spawning dates estimated from MN DNR 2011 and UW-Extension (http://clean-water.uwex.edu/pubs/pdf/fishfriendlyculverts.pdf). Note that specific spawning dates are dependent on local characteristics such as temperature that can vary).

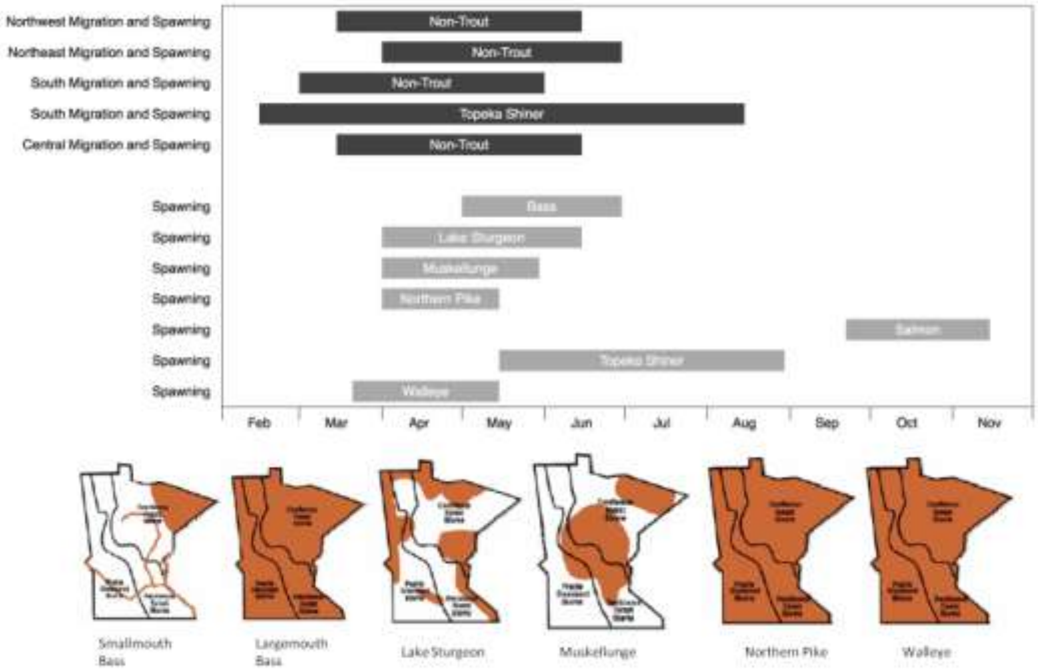

Figure 3: General range of non-trout fishes in MN and timing of migration and spawning fish passage requirements by region and species (spawning dates estimated from MN DNR 2011 and UW-Extension (http://clean-water.uwex.edu/pubs/pdf/fishfriendlyculverts.pdf). Note that specific spawning dates are dependent on local characteristics such as temperature that can vary).

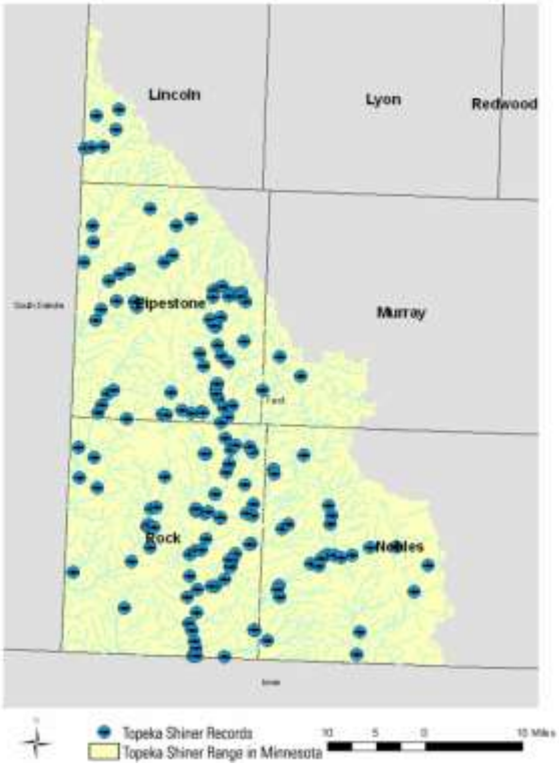

Figure 4: Topeka shiner range in MN. The Topeka shiner occurs only in the Big Sioux and Rock River watersheds where they are widespread (MN DNR June 23, 2006, USFWS 2007).

Additional information on fish passage:

- Fish Passage Resource Library
  Stream.fs.fed.us/fishxing/fplibrary.html
- Joint EWRI-AFS Fish Passage Reference Database
  http://scholarworks.umass.edu/fishpassage/
- http://www.nwrc.usgs.gov/publications/specindex.htm
- http://www.fishbase.org

Stream Morphology for Aquatic Organism Passage

The design of culverts for fish passage has typically been constrained by simple variables such as a maximum velocity or depth based on fish swimming ability. Studies have shown that these constraints alone are overly simplistic to allow for the natural fish passage through culverts for daily scavenging as well as seasonal migrations (Clark 2011). These constraints can be flawed for several reasons, including: failing to account for juvenile fish that do not have the swimming abilities of the typical migrating adult, or oversimplifying the diversity of flow rates experienced by a fish within a culvert. A one-dimensional (1-D) velocity limit will not account for slower flows near culvert boundaries (i.e. Vasconcelos et al. 2011; Gardner 2006).

Figure 5: Bluegill and redbreast sunfish swimming in arc pattern (photo from Gardner 2006).

Roughness affects both flow rate and turbulence and both of these variables can be quantified as discussed below. A common way of accounting for channel roughness is by the Manning coefficient for roughness, n, used to calculate steady flow based on the Manning equation:

$$Q = \left(\frac{1.49}{n}\right) R^{\left(\frac{2}{3}\right)} S^{\left(\frac{1}{2}\right)}$$

where Q is flow rate (ft/s), n is the roughness coefficient, R is the hydraulic radius (ft), and S is the channel slope (ft/ft). This calculation of roughness is used by FishXing (2006); however, this equation assumes uniform flow. As discussed above, different organisms need different paths for different purposes to perform their daily foraging and migrations. Thus while the roughness coefficient helps to determine whether the bulk stream flow is too great for fish passage, it is still too simplistic to predict actual fish movement through culverts based on complex and unsteady flow patterns.

Many fish passage culvert studies focused on salmonids on the west coast because they are important game and commercial fish and have large migration distances interrupted by dams and road crossings (Hansen et al. 2009). However, since the 1980s, biologists have begun to realize the importance of the ability of all aquatic species to pass through culverts at all life stages in a wide range of flows (Cenderelli et al. 2011). Similar studies are being conducted in the Midwest to accommodate native fish species as well as other aquatic organisms. To translate these studies and apply the information to the Midwest, we must take into account that many Midwest fish are non-anadromous and live in streams with lower gradients and turbulence. Additionally, many Midwestern fish species must navigate among lakes and rivers for feeding and overwintering and all need a relatively large navigable stream section for daily foraging (Hansen et al. 2009).

The general anatomy of fish offers two mechanisms for movement: the white and red muscle systems. The aerobic, red muscle system is used for low intensity travel while the anaerobic, white muscle system is used for high intensity travel (NRCS 2007). Too much use of the white muscle system, which is not designed for prolonged use, will result in severe fatigue of the fish and the fish will need to find refuge to rest. In order to maintain its natural movement habits, a fish needs to be able to use its regular combinations of muscle groups and an optimal culvert will provide flow patterns that encourage the fish to do so. For example, although artificial obstacles such as baffles set in a culvert will reduce the average velocity, they increase turbulence. To navigate through this turbulence, the fish will need to use their white muscle groups to reach bursting speed, and if the culvert is too long, the fish will be unable to sustain this activity and will not be successful at passing through it. Thus, the best solution for a wide range of aquatic organism ages and abilities is to maintain a variety of roughness similar to the natural stream.

Table 1: Description of Different Fish Movement Types (Excerpt from Kilgore et al. 2010).

	Description	**Muscle System**	**Period**
Sustained	Used for long periods of travel at low speeds. Normal functions without fatigue.	Red (purely aerobic)	Hours or days
Prolonged	Short periods of travel at high speeds resulting in fatigue	Red and White	0.25 to 200 minutes
Burst	Maximum swimming speed or jumping, inducing fatigue.	White (purely anaerobic)	0 to 15 seconds

In addition, some fish species specialize in different types of movements as a result of their daily foraging habits. Benthic swimmers take advantage of the slower, near-boundary water. These fish will swim at slower speeds near a roughened boundary for prolonged periods of time. Midstream swimmers, on the other hand, are less comfortable swimming at the boundary layer but are capable of darting into and through areas of higher velocity water (Esplin and Hotchkiss 2011). These midstream swimmers will tire quickly and thus need rest places to avoid sever fatigue. The different types of fish habits again show the importance for a variety of roughness.

Fish passage needs to account for the daily foraging and migration of juvenile fish as well as adult migration patterns. Juvenile fish are not as strong of swimmers as adult fish, which is especially apparent in turbulence. Turbulence is a natural effect the interaction of the flow with bedforms and grain roughness in the boundary layer in streams and can be created by artificial roughness as well. Juvenile fish in their natural habitat need paths of lower turbulence to move through the stream (Bates 1999). AOP approaches such as geomorphic simulation consider natural sediment transport and distribution of roughness elements such as boulders, pools, riffles, and bank variation.

Baffle and weir systems are a part of the hydraulic design approach. Although baffles can create the desired average velocity by adding a significant amount of backflow and creating paths and resting places through the culvert, they also add a significant amount of turbulence (Bates 1999). Placing larger elements of roughness such as boulders or cylinders throughout the channel is another method designed to add roughness and flow diversity within a culvert. Cylinders add turbulence, but also create holding zones where fish can rest; directly behind the cylinders will be areas of lower velocity. It was shown experimentally that while midstream swimmers will be able to use bursting speed to swim upstream through a path of low velocity created by the cylinders, benthic swimmers will not be able to take advantage of the flow paths around the obstacles (Esplin and Hotchkiss 2011).

Roughness can be added to the bottom of the culvert with the placement of sediments. A roughened boundary layer will extend the low-velocity boundary zone to create a large enough zone for benthic organisms to navigate. Even for midstream swimmers who can swim upstream through the cylinders using bursting speeds, the sediment is important to encourage daily foraging and natural movement through the stream (Esplin and Hotchkiss 2011). This illustrates how multiple scales and dimensions of roughness are important for aquatic organism passage. Geomorphic simulation approaches aim to promote a variety of movement and species by maintaining a natural channel inside the culvert (Bates 2003). This natural channel can be created by assessing and mimicking a number of characteristics of the original stream. Some important bed and channel features to pay attention to are (Cenderelli et al. 2011):

- Range of channel gradients
- Type and stability of grade controls
- Range of pool scour depths and controls on pool formation (bend, obstruction, plunge,etc)
- Spacing and length of channel units
- Potential aggradation surfaces upstream and downstream of the crossing

These authors show how roughness is an important feature to add in the design of culverts for both biological and geomorphological reasons. In addition, to swimming performance through the culvert barrel, roughness within the culvert barrel can assist in mitigating culvert outlet scour which is a common barrier to upstream aquatic organism passage. The energy dissipation factor (EDF) (Bates 2003) has been utilized to evaluate turbulent energy dissipation (quantified by the energy that is dissipated in a unit volume of water). Ideally, a roughened channel culvert will dissipate energy through the culvert and be left with no excess kinetic energy at the base of the culvert. Excess energy can result in faster transport rates which will cause the culvert channel to become nonalluvial and scoured and lead to downstream degradation (scour hole at culvert outlet).

It is important to consider the anatomy and capabilities of the target fish species and other aquatic organisms and match the stream characteristics on the inside of the culvert as close as possible to the rest of the stream. There are various approaches utilized to create favorable conditions within a culvert with different roughness forms; however, although often represented as such, roughness and its effects on fish passage are not one-dimensional. To maintain ecological connectivity, all aquatic organisms and all movement purposes must be considered in AOP design.

AOP Culvert Design in a Geomorphic Framework

Steeper streams are generally composed of larger substrate with more frequent pools, more turbulence, and rapid sediment transport, while a stream with a very small gradient (< .001 ft/ft) will have a lower velocity, lower turbulence, finer sediments, and slower sediment transport (Montgomery and Buffington 1998). General regional geomorphic characteristics as related to fish passage were compiled by Hansen et al. (2009). Streams in Minnesota range from high gradient cobble beds to low gradient sand/fine bedded streams. Additional information on regional geomorphic and landuse characteristics can be derived from the Level III Ecoregion descriptions (Figure 6; Table 3). Understanding the geomorphic context for a culvert design is important. For example, in low gradient streams with highly mobile sediment, placing large roughness elements or filling the culvert may not be necessary, but in steeper channels where the larger bed material is only mobile during infrequent large storms, roughness may need to be added to the culvert to create appropriate AOP.

Table 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

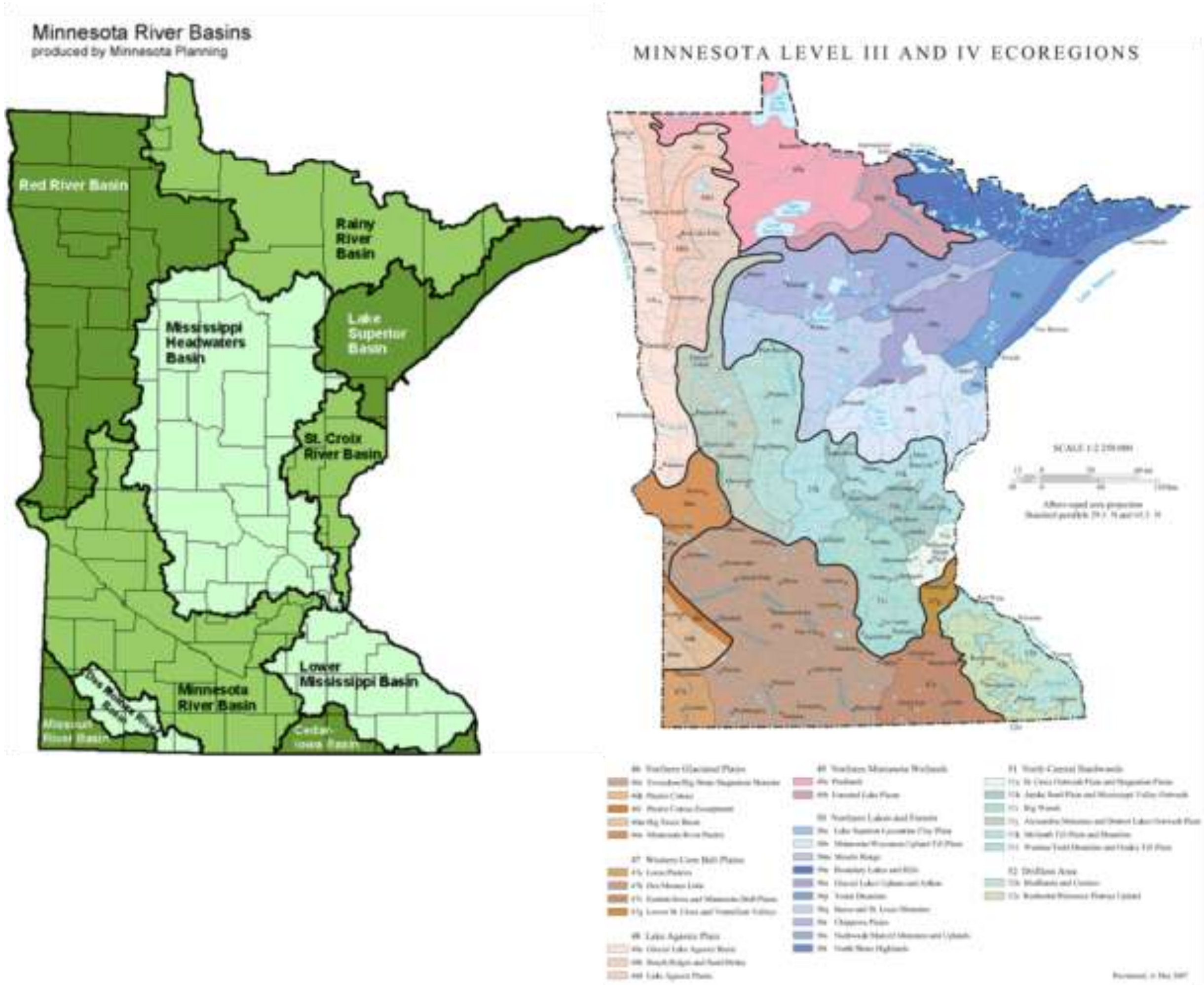

Figure 6: Major River Basins of Minnesota and Level III and IV Ecoregions of Minnesota (See Table 2 for fish passage considerations in each river basin and Table 3 for general ecoregion descriptions).

Table 3: Descriptions from the Level III Ecoregion for Minnesota.

Level III Ecoregion	Precipitation	Hydrology	Terrain	Fish	Landuse
Northern Glaciated Plains	400-610 mm	Low density of streams and rivers; high concentrations of temporary and seasonal wetlands	Flat to gently rolling plains composed of glacial till		Agriculture
Western Corn Belt Plains	610-1000 mm mainly in the growing season	Intermittent and perennial streams, many channelized; few natural lakes	Nearly level to gently rolling glaciated till plains and hilly loess plains	walleye, northern pike, bluegill, sunfish	Agriculture
Lake Agassiz Plain	450-700 mm most during growing season thunderstorms	Low density, low-gradient stream and river networks (Red River system); ditching and channelization common	Flat to low rolling plains; moraine and lacustrine deposits	perch and walleye	Agriculture
Northern Minnesota Wetlands	550-700 mm	Large wetland area, with some lakes; some low-gradient streams and eroded river channels, especially to the east	Flat plains and irregular plains; most of the flat terrain is still covered by standing water	walleye, northern pike	Forestry, recreation, hunting and fishing, minor areas of mixed farming and grazing
Northern Lakes and Forests	500-960 mm.	Moderate to low gradient perennial streams; wetland areas; numerous glacial lakes	Glaciated irregular plains and plains with hills. Undulating till plains, morainal hills, broad lacustrine basins, and extensive sandy outwash plains	walleye, northern pike, brook trout, muskellunge	Forestry, recreation, tourism, hunting and fishing, iron ore mining; minor hay and grain crops, dairy
North Central Hardwoods	600- 890 mm winters are snowy	High density of perennial streams, wetlands, and lakes	Nearly level to rolling till plains, lacustrine basins, outwash plains, and rolling to hilly moraines	northern pike, walleye, carp, sunfish	Forest land, cropland agriculture, pasture, and dairy; urban, suburban, and rural residential
Driftless Area	760- 965 mm winter snowfall is common	Many perennial streams; springs and spring-fed streams are common; few natural lakes	Hilly uplands, deeply dissected, loess-capped, bedrock dominated plateau. Gently sloping to rolling summits with steeper valley walls and bluffs.	northern pike, walleye, largemouth bass.	Pasture and cropland on flatter uplands; woodlands and forest on steeper slopes and ravines; livestock and dairy

Sediment Transport Experiments to Evaluate Culvert Performance

A literature review on physical modeling of culvert systems returns few studies focusing on modeling of stream simulation or recessed designs. Nevertheless physical models of flow, sediment transport, and scour in and around culverts have some pertinent details that can help to inform AOP design or the importance of understanding sediment transport processes under different geomorphic contexts. Table 4 gives information on various physical model studies including focus and findings.

There are numerous studies on the hydraulic analysis of fish passage design, especially as it relates to baffle or weir design. Table 4 lists a few recent studies on baffle design, but the more relevant studies are those such as Clark and Kehler (2011) who examined turbulent flow in corrugated culverts to understand the variation in flow fields within a culvert. Understanding the flow field distribution has implications for both fish and sediment transport.

Many studies focus on the inlet geometry of the culvert and how the flow enters the culvert. These studies look at the shapes of the inlet and many experiments deal with culverts running under inlet control and running full, characteristics which do not often apply to culverts designed with AOP goals, but rather the effect of extreme events on conventional culvert design. Jones et al. (2006) ran experiments at a 1:30 scale and did look at the effect of multiple barrels on the flow, determining that there was almost no difference in performance of a single barrel culvert compared to a multiple barrel culvert for unsubmerged inlet control.

A few physical models have sought to understand sediment transport through culverts. These were primarily focused on understanding potential bed degradation (and potential failure) of bottomless culverts under various configurations. There are many ways in which bottomless culverts function very differently from recessed and buried culverts. Crookston (2008) looks at sediment transport through bottomless culverts and in particular incipient motion for four sediment conditions. The experiments were performed at full scale in both a bottomless culvert and a rectangular flume. Incipient motion was studied using the Shields relation. Crookston (2008) did not avoid constriction and expansion at the culvert ends, and of note that he observed large variations in velocity and depth where flow constricted to pass into the culvert and then expanded in the tailbox. FHWA conducted experiments in 2003 that looked at flow through bottomless culverts (Kornel et al. 2003). A result of this study is a recommendation for predicting maximum scour. Limitations of the study were identified and addressed by the authors, including a lack of inflow sediment into the system. Multiple barrel culvert studies have focused on developing self-cleaning culverts. Information gained from Ho (2010) helps to inform our basis of knowledge on multiple barrel culvert hydraulics and sediment transport and reconfirms the importance of entrance conditions on culvert performance. Finally, while physical studies on stream simulation are rare, two studies, Maxwell et al. (2001) and Goodridge (2009) evaluated the effects of bedforms on culverts under different geomorphic settings. Maxwell et al. (2001) focused on step pool morphology in high-gradient streams, while Goodridge (2009) focused on the effect of sand and gravel bedforms on culvert hydraulics.

Table 4: Focus and Findings of Physical Model Studies on Culvert Performance.

Citation	Title	Parameters	Key Findings	Sediment
Hydraulic Analysis of Fish Passage Design				
Clark and Kehler 2011	Turbulent Flow Characteristics in Circular Corrugated Culverts at Mild Slopes	cross-sectional velocity and turbulence	Significant percentage of the cross-sectional flow had streamwise velocity lower than mean bulk velocity	N/A
Ead et al. 2002	Generalized Study of Hydraulics of Culvert Fishways	velocity field in culvert fishways	Recommended spacing of baffles, weir and slotted weir designs	N/A
Kerenyi 2012	Fish Passage in Large Culverts with Low Flows- ongoing	velocity distributions above and between corrugations	Local velocities and flow distributions in corrugated metal pipes; practical design method for estimating average local velocities in culverts	fixed sediment
Morrison et al. 2009	Turbulence Characteristics of Flow in a Spiral Corrugated Culvert Fitted With Baffles and Implications for Fish Passage	Velocity and turbulent kinetic energy distribution	Minor differences in turbulent distributions with different baffle types did not relate to biological fish passage tests	N/A
Knight and Sterling 2000	Boundary Shear in Circular Pipes Running Partially Full	cross-sectional velocity distributions boundary shear stress	Distribution of boundary shear stress within culvert is highly sensitive to cross-sectional shape; implications of secondary flows for sediment transport	smooth flat bed representing sediment
Inlet and Outlet Scour				
Liriano et al. 2002	Scour at Culvert Outlets as Influenced by the Turbulent Flow Structure	mean velocity turbulence intensities scour hole geometry	Fundamental understanding of scour hole formation at culvert outlet; initial formation of outlet scour hole results from mean velocity exceeding the critical velocity; further scour is associated with the turbulent flow structure	uniform gravel
Abt et al. 2007	Enhancement of the Culvert Outlet Scour Estimation Equations	Scour Geometry Drop Height	Simplified expressions in 1983 HEC-14 scour calculations; general expression relating outlet scour geometry to discharge, culvert dimensions, time, and bed material gradations	non-cohesive gradations
Emami and Schleiss 2010	Prediction of Localized Scour Hole on Natural Mobile Bed at Culvert Outlets	Scour hole geometry	dimensionless relationships between scour hole geometry with discharge and tail water depths	uniform

Citation	Title	Parameters	Key Findings	Sediment
Bottomless Culverts				
Kerenyi et al. 2007	Bottomless Culvert Scour Study Phase II Laboratory Report	inlet scour hole geometry, velocity distributions (including PIV)	Analysis of inlet and outlet scour with different bottomless culvert geometries and scour protection measures	uniform, various sizes (angular)
Crookston 2008	A Laboratory Study of Streambed Stability in Bottomless Culverts	incipient motion, scour dimensions	Angularity and gradation decrease the extent of scour inside culvert barrel; 2-D methodologies for calculating incipient motion better predictors for larger substrates than Shields relation	2 sizes of rounded and angular substrate
Bedforms in Culverts				
Maxwell et al. 2001	Step-Pool Morphology in High-Gradient Countersunk Culverts	bed morphology, bed sediment distribution, relative submergence	Relationships between step-pool morphology on flow and sediment characteristics; generic design method for streambed simulation of high-gradient countersunk culverts	3 size distributions; well-graded mixture
Goodridge 2009	Sediment Transport Impacts Upon Culvert Hydraulics	incipient motion, critical shear stress, velocity distributions	Calibrated model for culvert design incorporating sediment transport; quantifies energy consumption for four different bedforms; methodologies for determining critical shear stress and bed load	sand and gravel sizes
Flow and Sediment Transport in Multiple barrel Culverts				
Ho 2010	Investigation of Unsteady and Non-Uniform Flow and Sediment Transport Characteristics at Culvert Sites	velocity distribution, sediment transport	Self-cleaning culvert design: lateral expansion areas filled with sloping volumes of material to reduce the depth and to direct flow and sediment towards central barrel diminishing strength of secondary currents	sand
Jones et al. 2006	Effects of Inlet Geometry on Hydraulic Performance of Box Culverts	water surface slope, depth, velocity distributions (PIV)	SDDOT box culvert design including single and multiple barrel culverts	N/A
Wargo and Weisman 2006	A Comparison of Single-Cell and Multicell Culverts for Stream Crossings	outlet scour hole geometry, flow depths	Benefits of multiple barrel designs	fixed gravel roughness (not fixed at outlet)
Haderlie and Tullis 2008	Hydraulics of Multibarrel Culverts under Inlet Control	head-discharge relationships	Recommends a physical model when designing a culvert with a nonuniform approach flow condition	N/A

References

Aadland, L.P., (2010) Reconnecting Rivers: Natural Channel Design in Dam Removals and Fish Passage. Minnesota Department of Natural Resources Division of Ecological Resources Stream Habitat Program. Available at http://www.dnr.state.mn.us/eco/streamhab/reconnecting_rivers.html

Bates, K. (1999) Fish Passage Design at Road Culverts: A Design Manual for Fish Passage at Road Crossings. Washington Department of Fish and Wildlife Habitat and Lands Program: Environmental Engineering Division.

Bates, K. (2003) Design of Road Culverts for Fish Passage. Washington Department of Fish and Wildlife.

Beavers, A.E., R.H. Hotchkiss, and M.C. Belk (2008) Fish passage at UDOT culverts: prioritization and assessment. Utah Department of Transportation Research Division Report No. UT-08.08.

Blank, M., B. Bramblett, S. Kalinowski, J. Cahoon, and K. Nixon (2011) Impacts of Barriers on Topeka Shiner Populations. South Dakota Department of Transportation No. SD2006-07-F.

Bouska W.W., and C.P. Paukert (2010) Road crossing designs and their impact on fish assemblages of Great Plains streams. *Transactions of the American Fisheries Society*. 139(1): 214-222.

Brunner, G.W. (2010) HEC-RAS River Analysis System User’s Manual v. 4.1. U.S. Army Corps of Engineers, Hydrologic Engineering Center.

Cenderelli, D., K. Clarkin, R. Gubernick, and M. Weinhold (2011) Stream Simulation for Aquatic Organism Passage at Road-Stream Crossings. *Journal of the Transportation Research Board*. 2(2103): 36-45.

Clark, S.P. (2011) Turbulent Flow Characteristics in Circular Corrugated Culverts at Mild Slopes. *Journal of Hydraulic Research*. 49(5):676-684.

Clark, S.P. and N. Kehler (2011) Turbulent Flow Characteristics in Circular Corrugated Culverts at Mild Slopes. *Journal of Hydraulic Research*. 49(5):676-684.

Crookston, B.M. (2008) A laboratory study of streambed stability in bottomless culverts. Utah State University Thesis.

Esplin, L.D., and R.H. Hotchkiss (2011) Culvert Roughness Elements for Native Utah Fish Passage: Phase I. Utah Department of Transportation Research Division.

FishXing (2006) User Manual and Reference. U.S. Department of Agriculture U.S. Forest Service. Available at: http://www.fsl.orst.edu/geowater/FX3/help/FX3_Help.html

FSSWG (2008) Stream Simulation: An Ecological Approach to Road-Stream Crossings,U.S. Department of Agriculture Forest Service Stream Simulation Working Group National Technology and Development Program.

Gubernick. R. and K. Bates (2003) Designing culverts for Aquatic Organism Passage: Stream Simulation Culvert Design. International Conference of Ecology and Transportations Proceedings, Lake Placid, NY. Available at: http://www.icoet.net/downloads/03FishPassage.pdf

Gubernick. R., K. Clarkin, and M. Furniss (2003) Site Assessment and Geomorphic Considerations in Stream Simulation Culvert Design. International Conference of Ecology and Transportations Proceedings, Lake Placid, NY. Available at: http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1148&context=jmie/roadeco

Gardner, A.N. (2006) Fish passage through road culverts. North Carolina State University Thesis.

Goodridge, W.H. (2009) Sediment Transport Impacts Upon Culvert Hydraulics. Utah State University Thesis.

Hansen, B., J. Nieber, and C. Lenhart (2009) Cost Analysis of Alternative Culvert Installation Practices in Minnesota. Minnesota Department of Transportation Report no. Mn/DOT 2009-20.

Hansen, B., S. Johnson, J. Nieber, and J. Marr (2011) Performance Assessment of Oversized Culverts to Accommodate Fish Passage. Minnesota Department of Transportation Report no. Mn/DOT 2011-19.

Ho, H. (2010) Investigation of unsteady and non-uniform flow and sediment transport characteristics at culvert sites University of Iowa Thesis.

HY-8 (2012) Version 7.3. U.S. Department of Transportation Federal Highway Administration. Available at: https://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/

Jones, J.S., K. Kerenyi, and S. Stein (2006) Effects of inlet geometry on hydraulic performance of box culverts. U.S. Department of Transportation Federal Highway Administration No. FHWA-HRT-06-138.

Kilgore, R.T., B.S. Bergendahl, and R. Hotchkiss (2010) HEC-26: Culvert Design for Aquatic Organism Passage: First Edition. U.S. Department of Transportation, Federal Highway Administration Publication Number**:** HIF-11-008.

Kornel, K., J.S. Jones, and S. Stein (2003) Bottomless Culvert Scour Study: Phase I Laboratory Report. U.S. Department of Transportation Federal Highway Administration Report No. FHWA-RD-02-078.

Maxwell, A.R., A.N. Papanicolaou, R.H. Hotchkiss, M.E. Barber, and J. Schafer (2001) Step-pool morphology in high-gradient countersunk culverts. *Journal of the Transportation Research Board* 1743:49-56.

Montgomery, D.R and J.M. Buffington (1998) Channel Classification, Processes, and Response. Ecology and Management in Pacific Northwest Rivers.

MN DNR (2004) General Public Waters Work Permit GP 2004-0001. Available at: http://www.dnr.state.mn.us/waters/forms.html#generalpermits

MN DNR (2011) Best Practices for Meeting DNR General Public Waters Work Permit GP 2004-0001. Minnesota Department of Natural Resources. Available at: http://www.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_manual.html

NRCS (2007) Technical Supplement 14N: Fish Passage and Screening Design, National Engineering Handbook Part 654, National Resource Conservation Service.

Rayamajhi, B., J.G. Vasconcelos, J.P. Devkota, D. Baral, H.M. Tritico (2012) Should Fish Passage through Culverts Be a Concern for Midwest Engineers and Planners? Determining the Percentage of Culverts That Act As Barriers to Fish Passage in NE Ohio. World Environmental and Water Resources Congress ASCE.

Roberts, J.T. (2009) Field Assessment of Culvert Impacts on Stream Channel Morphology. North Carolina State University Thesis.

Schall, J.D., P.L. Thompson, S.M. Zerges, R.T. Kilgore, and J.L. Morris (2012) HDS-5: Hydraulic Design of Highway Culverts: Third Edition U.S. Department of Transportation, Federal Highway Administration Publication Number: HIF-12-026.

Tumeo, M.A. and J.A. Pavlick (2011) A Study of Bankfull Culvert Design Effectiveness. Ohio Department of Transportation Report No. FHWA/OH-2011/12.

USFWS (2007) Threatened and Endangered Species: Topeka Shiner in Minnesota. U.S. Fish and Wildlife Service Datasheet. Available at: http://www.fws.gov/midwest/endangered/fishes/pdf/tosh_mn022607.pdf

Vasconcelos, J.G., H.M. Tritico, and T.M. Hatcher (2011) A Post-Processing Tool for HEC-RAS for the Assessment of Fish Passage Conditions in Highway Culverts. World Environmental and Water Resources Congress, ASCE.