Minnesota Department of Transportation

RESEARCH SERVICES

Office of Policy Analysis, Research & Innovation

Performance Assessment of Oversized Culverts to Accommodate Fish Passage

John Nieber, Principal Investigator
Department of Bioproducts and Biosystems Engineering
University of Minnesota

August 2011

Research Project
Final Report 2011-19

LRRB
LOCAL ROAD RESEARCH BOARD

Your Destination...Our Priority

All agencies, departments, divisions and units that develop, use and/or purchase written materials for distribution to the public must ensure that each document contain a statement indicating that the information is available in alternative formats to individuals with disabilities upon request. Include the following statement on each document that is distributed:

To request this document in an alternative format, call Bruce Lattu at 651-366-4718 or 1-800-657-3774 (Greater Minnesota); 711 or 1-800-627-3529 (Minnesota Relay). You may also send an e-mail to bruce.lattu@state.mn.us. (Please request at least one week in advance).

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2011-19		

4. Title and Subtitle	5. Report Date
Performance Assessment of Oversized Culverts to Accommodate Fish Passage	August 2011
	6.
7. Author(s) Brad Hansen, Sara Johnson, John Nieber, Jeff Marr	8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Bioproducts and Biosystems Engineering University of Minnesota 1390 Eckles Ave St. Paul, MN 55108	10. Project/Task/Work Unit No. CTS Project #2009086 11. Contract (C) or Grant (G) No. (c) 89261 (wo) 152
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard, MS 330 St. Paul, MN 55155	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/201119.pdf

16. Abstract (Limit: 250 words)

In Minnesota there is not a standard culvert design used at road crossings to improve aquatic organism or fish passage. The design process for fish passage in Minnesota is currently based on the knowledge and experience of local county, state and DNR personnel. The design methodology attempts to maintain the natural stream dimensions, pattern and profile through the culvert crossing. If designed properly aquatic organisms and fish that can make it upstream to the culvert should be able to pass through the culvert. This research was conducted to better understand the hydraulic conditions related to the practice of recessing culverts and other fish passage design elements over a range of landscapes in Minnesota. The design elements analyzed included bankfull width, slope, channel materials, side barrels and recessed culverts. Nineteen culvert sites were survey around the state. The main criterion used to evaluate performance of the culverts was the presence or absence of adequate sediment in the recessed culvert barrel. Six of the fourteen sites with recessed barrels had no sediment accumulation. A likely reason that these culverts lack sediment was increased velocities due to improper sizing relative to bankfull channel width and the accumulation of sediment in the side barrels. Wider Rosgen "C" type channels also correlated with performance issues related to culvert design.

17. Document Analysis/Descriptors	18. Availability Statement
Culverts, Culverts design, Fish passage, Fish ladders, Culvert width, Slopes, Sediments, Channels (Waterways), Channel classification	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	92	

Performance Assessment of Oversized Culverts to Accommodate Fish Passage

Final Report

Prepared by:

Brad Hansen
John Nieber

Department of Bioproducts and Biosystems Engineering
University of Minnesota

Sara Johnson
Jeff Marr

St. Anthony Falls Laboratory
University of Minnesota

August 2011

Published by:

Minnesota Department of Transportation
Research Services Section
395 John Ireland Boulevard, Mail Stop 330
St. Paul, Minnesota 55155

Acknowledgments

The authors would like to thank the members of the Technical Advisory Panel for providing their time and expert guidance on this project:

- Jon Bergstrand, Minnesota Department of Transportation
- Nelson Cruz, Minnesota Department of Transportation (administrative liaison)
- Nicole Danielson-Bartelt, Minnesota Department of Transportation
- Petra DeWall, project manager, Minnesota Department of Transportation (technical liaison)
- Alan Forsberg, Blue Earth County engineer
- Al Goodman, Lake County engineer
- Matt Hemmila, St. Louis County engineer
- Bruce Holdhusen, Minnesota Department of Transportation
- Shae Kosmalski, Cook County engineer
- Peter Leete, Department of Natural Resources
- Brian Walters, Hancock Concrete
- Rick West, Otter Tail County engineer

We would also like to thank the following individuals for the help they provided during the project:

Danielle Dutton, formerly graduate research assistant in Forest Resources, University of Minnesota, for her Geographic Information Systems contributions; Robert Gubernick, U. S. Forest Service for his advice and expertise on culvert design; Bill Huber, Minnesota Department of Natural Resources for the recommendation of numerous sites in Southern Minnesota; Marty Rye, U.S. Forest Service, Superior National Forest for his help in locating numerous culverts on U.S. Forest Service land.

Table of Contents

List of Tables

List of Figures

Executive Summary

In Minnesota there is not a standard culvert design used at road crossings to improve aquatic organism or fish passage. The design process for fish passage in Minnesota is currently based on the knowledge and experience of local county, state and DNR personnel. The design methods in place are some combination of matching channel parameters to culvert dimensions and reducing velocities through placement of rock in culverts. This research was conducted to better understand the hydraulic conditions related to the practice of recessing culverts and other fish passage design elements over a range of landscapes in Minnesota.

The practice of recessing culverts is frequently implemented to provide for improved fish passage through a culvert. The culvert invert is placed below the streambed elevation, allowing the sediment carried by the stream to accumulate in the recessed portion of the culvert to an elevation equal to the streambed elevation. Alternately, sediment or rocks may be placed in the culvert at the time of installation. If designed properly, this technique should increase roughness and reduce velocities through the culvert that more closely match the stream velocity. The word "oversizing" is used to reference the need to increase the culvert size to compensate for the portion of the culvert recessed below the streambed elevation. It does not mean the culvert is oversized for a given flow or bankfull width calculation. Rather, the design process begins with sizing a culvert based on the stream bankfull width or to match a calculated hydraulic capacity. The initially designed culvert size is maintained above the stream bed elevation and the added or oversized portion of the culvert is buried below the streambed to accommodate for the recessed depth. Due to the ambiguity of the "oversized" term and tendency for it to be misunderstood, the term "recessed" will be used throughout this report.

Burying or recessing culverts is not normally a standalone design but is only one of the parameters used in designing culverts to accommodate fish or aquatic organism passage. This research did not measure any actual fish or other aquatic organism passage. The analysis looked at the geomorphic and hydrologic functions of the stream and determined how well the design elements used to improve culvert function and fish passage were applied to the culvert crossing. The culvert design elements analyzed in this report are listed below.

- Matching culvert width to bankfull stream width
- Setting culvert slope equal to stream slope
- Multiple culverts
- Aligning the culvert with the stream channel
- Head cutting potential

Nineteen total sites were chosen for assessment in the Northeast, North-central, South-central and Southeast regions of the state. These regions covered the major geographic conditions around the state and also represented areas of importance in terms of fish population.

The main criterion used to determine if a culvert designed using fish passage elements was functioning properly was the presence or absence of sediment in the recessed culvert barrel. If properly designed, the recessed barrel should have accumulated sediments that increase roughness and reduce velocities through the culvert as compared to a clean barrel. A clean barrel

could produce excess velocities that would also possibly prohibit aquatic organism passage. It is not a direct measure of fish passage potential but a failure of the design methodology.

Thirteen of the 19 sites surveyed had a recessed culvert as part of the design. Based on the criterion mentioned above, six of the thirteen sites surveyed were not functioning properly due to lack of sediment in the recessed culvert barrel. A number of different factors were identified that could affect the sediment accumulation in a recessed culvert. Four of the scenarios – large flow event prior to the survey, culvert not in place long enough to accumulate sediment, culvert slope steeper than channel bed, and a lack of transportable sediment or immobile bed – are ruled out as possible factors. Improperly sized culvert widths as compared to the bankfull channel width and side barrel sediment accumulation were identified as possible reasons for the lack of sediment accumulation in recessed barrels. At thirteen sites, the recessed culvert width was less than the bankfull channel width, including all six of the sites with no sediment in the recessed culvert. Eight of the sites had a total culvert width less than channel width. The combination of insufficient width (compared to channel bank full width) and limited access to side barrels could be sufficient to raise velocities through the recessed barrel high enough to limit the ability of sediment to accumulate.

One of the possible explanations for the insufficient culvert widths at these sites may be found in the analysis of the stream types (based on Rosgen classification) associated with the culvert locations. Of the 19 sites surveyed, seventeen sites are B, E or C channels, with C and E channels equally represented at eight sites each. The predominate bed materials ranged from sand to cobbles. These are very common stream types found in Minnesota. Seven of the eight C channels had no sediment accumulated in the main culvert barrel including five of the six recessed culverts with no sediment accumulation. A likely reason for this correlation is that C channels have a greater width to depth ratio than E channels (which made up eight of the 19 total sites) and that greater bankfull width is more difficult and expensive to match with the total culvert width.

Possible solutions to this problem would be:

- A better understanding of stream and site data collection needs prior to culvert design to ensure the design more closely matches the local stream channel conditions
- An improved procedure for placing sediment or anchoring it to the culvert bottom to protect against excess velocities washing sediment out of the culvert
- A different or improved culvert design methodology that better addresses the challenges of wider channels and floodplains commonly found in Minnesota

Chapter 1 Introduction

The importance of aquatic organism passage through road crossings was first brought to light on the west coast of the United States where road crossings were restricting the passage of salmon. This triggered a push to produce new guidelines and designs for road crossings that would reduce the impacts both to aquatic organisms and stream stability. There are a number of designs that have been developed to address the various conditions encountered at road crossings related to slope, bed material, stream alignment, fish species, and hydraulic conveyance requirements [1], [2]. These newer designs and guidelines stress that the environmental concerns of fish passage and stream continuity are as important a consideration in road crossing design as hydraulic conveyance and flood capacity.

The main concept of designing a culvert for aquatic organism or fish passage is to match the culvert width, slope and bed material closely to that of the natural stream, thereby creating a velocity through the culvert that would not be significantly greater than the stream velocity. If these design principles are properly executed and installed, theory suggests that the majority of aquatic organisms that can navigate up the stream to the location of the crossing will also be able to pass through the culvert.

In Minnesota, these environmentally-friendly designs have been used sporadically around the state for the last ten to fifteen years. Most of the installations are concentrated in areas of the state where fishing and tourism are popular. These regions include the North-central lakes region and both the Northeast and Southeast corners of the state where streams and trout fishing are popular. Prior to this project, no evaluation had been done to determine if these installations were matching their intended function of matching stream parameters and hydraulic conditions through the culvert.

To insure proper function, these newer designs also require additional data collection and expertise in stream geomorphology, fish species, habitat assessment, and stream biology, thereby making culvert design a multi-agency function. The Minnesota Department of Transportation (MnDOT) is currently facing the challenges of keeping pace with the additional data requirements and weighing the benefits of improved stream continuity against the additional cost many of these structures require. The additional upfront costs are related to the need for more data collection, design, training, and education. Construction and materials costs can also be higher because of the possible need for placement of rock and/or stream sediment in the culvert and, at most road crossings, the need for larger structures to accommodate the loss of capacity due to the recessing of the culvert below the flow line elevation of the stream. The larger structures can add 10 to 30 percent to the overall cost of the culvert [3]. Because of the additional upfront and installation costs, it is important that the effectiveness of these practices be evaluated both from an economic and ecological standpoint.

The main goal of this research was to assess the practice of recessing culverts and other design parameters used in Minnesota to design for improved fish passage. If designed properly, a recessed culvert should allow natural stream sediments to accumulate in the culvert, increase roughness and thereby reduce velocity such that it more closely matches the stream velocity. Recessed culverts are initially designed to match hydraulic flow conditions or bankfull width. Additional culvert height is then added to the initial design to accommodate for the recessed depth. A rectangular culvert sized at 10 feet wide and 10 feet high to accommodate the calculated hydraulic flow would become 10 feet wide and 12 feet high if the culvert were to be recessed two feet below the streambed elevation. Recessing culverts is not normally a standalone design but is one of the parameters used in designing culverts to accommodate fish or aquatic organism passage. The research presented here examines culvert function by incorporating a number of other parameters used to design culverts for fish passage in Minnesota. A list of other design elements analyzed in this report includes:

- Matching culvert width to bankfull stream width
- Setting culvert slope equal to stream slope
- Multiple barrel culverts
- Aligning the culvert with the stream channel
- Head cutting potential.

Currently there is no standardized crossing design method used to promote fish passage in Minnesota. Current design approaches typically incorporate some combination of the design elements listed above and are based on specific site characteristics and the expertise of the county, state, or federal personnel involved in the design. There were 19 culvert sites surveyed for this report. Because there is no standardized methodology recognized or used exclusively in Minnesota it is unlikely all 19 sites used the same design approach. However, all of them were designed with the idea of improving or promoting fish passage and used some or all of the fish passage design elements. With this in mind our study sites will be referred to in this report as "culverts designed using fish passage elements" and not a specific design methodology.

The four research objectives developed to achieve the goal of assessing culverts designed using fish passage elements in Minnesota were:

1. Understand the hydraulics of recessed culverts and the possible impacts they have on adjoining stream characteristics.
2. Develop or adopt a culvert assessment protocol to assess the performance of culverts designed using fish passage elements
3. Assess the effectiveness of culverts designed using fish passage elements over a range of different geographical conditions within Minnesota, accounting for variability in stream geomorphic conditions.
4. Identify the stream morphologic and hydraulic conditions introduced by culverts designed using fish passage elements that may negatively affect fish passage.

The structure of this report will follow the main tasks of the original work plan. The four objectives listed above will be explained in more detail as they are incorporated into the task that best represents the objective. The main tasks of this report were:

Task 1. Literature Review The research team conducted a survey of relevant literature pertaining to alternative culvert designs to accommodate fish passage and any evaluation of the designs. This is covered in Chapter 2 of the report.

Task 2. Site Surveys and Selection

To measure the effectiveness of culverts designed using fish passage elements over different geographical regions of the state, study culvert sites were selected in Northeast, Southeast, North-central forested and South-central Minnesota. A total of 19 sites were chosen for field surveys. The details of the site survey and selection approach and results are described in Chapter 3 of this report and in Appendix B.

Task 3. Field Surveys

Field surveys of each site included:

- Elevation survey of the upstream, culvert, and downstream reaches of the stream including cross sections, , and water-surface profile
- Measurement of sediment depths inside the culvert(s)
- Bed material samples or pebble counts taken from the sediment in the culvert and in the adjacent streambed
- Velocity profiles both in the culvert and in the stream at the time of the site visit
- Measurement of the culvert dimensions, slope, and alignment
- Survey of any scour holes at the upstream or downstream ends of the culvert
- Photographic documentation of the site including any details of unique aspects of the design
- Stream stability analyses

The details of the field survey methods/approaches and a summary of results are described in Chapter 4 of this report.

Task 4. Evaluation of data

Using guidance information from the literature review and data from the site and field surveys, the research team developed a summary evaluation of the hydraulic and geomorphic parameters associated with culverts designed using fish passage elements

This research did not measure any actual aquatic organism passage. The analysis examined the geomorphic and hydrologic functions of the stream and determined how well the design considerations listed above were applied to the culvert crossing of the stream. If the stream geomorphology and hydrology were maintained through the culvert, fish passage was assumed to be favorable.

The methods for accomplishing this task and the results are described in Chapter 5 of this report. Chapter 6 provides the conclusions for the project.

Chapter 2 Literature Review

A substantial body of work exists for design and implementation of culverts designed for fish passage, mainly from coastal areas of the United States. The first task of the project focused on a review of state-of-knowledge for hydraulics of culverts designed for fish passage and the impacts they have on fish passage and adjoining stream characteristics through a review of the current literature. The review sought to examine all published literature on the topic and focuses on different design methods and approaches. A summary of the findings from the literature review is provided below.

2.1 Impacts of Conventional Culverts

Road culverts have a variety of impacts on fish habitat and obstruction to movement as described by Bates et al. in the Washington Fish & Wildlife Department (WDFW) guide to fish passage at culverts [1]. They describe the following seven major categories of impacts:

1. Direct habitat loss by eliminating areas of channel habitat in the immediate culvert area. Road expansion or installation of new, larger culverts results in direct loss of stream habitat.
2. Water quality degradation as a result of road crossings creating an entry point for road-runoff pollutants. Some culverts are coated with asphalt to prevent degradation. In agricultural settings, road culverts are often the entry point for road-side ditches and subsurface tile drainage outlets.
3. Upstream and downstream channel impacts caused by scour, aggradation, and associated habitat impacts.
4. Ecological connectivity may be reduced by blocking access to upstream or downstream stream segments for fish and other aquatic organisms.
5. Channel maintenance costs may be increased by inducing aggradation at oversized or under-sloped road crossings. Dredging of channel is often required at road crossings and is very damaging to stream habitat.
6. Construction impacts include possible release of sediment or pollutants, temporary fish passage barrier during construction, removal of streambank vegetation, impeding flow or stranding fish above or below the culvert. Most impacts are short term but slugs of sediment could persist in streams for months or years.
7. Risk of culvert failure although infrequent, culvert collapse can cause ecological damage, flooding and/or road maintenance problems. Safety concerns must be addressed in all culvert projects.

Culverts may block fish passage in a variety of ways. The WDFW describes five ways in which fish passage is blocked [4]:

- Excess drop at the culvert outlet
- High velocity within the culvert barrel
- Inadequate depth within the culvert barrel
- Turbulence within the culvert
- Debris and sediment accumulation at the culvert inlet or internally

Another common cause of blockage is excessive length of culvert without sufficient resting area for fish.

In summary, culverts can limit or remove the ability of fish and other organisms through the stream corridor and this is mostly due to high velocities, low water volume, or barriers to passage. The design solution to these problems focuses on fixing excess velocity and outlet drop issues.

2.2 Fish Passage Issues at Culverts

Most of the published research on fish passage through culverts has focused on salmon and trout in the Western United States. Fish passage techniques were originally developed on the west and east coast of the United States to improve salmonids (salmon and trout species) passage around large dams. Fish passage in coastal areas of the US focused on *anadromous* fish, i.e. species that migrate between the ocean and freshwater rivers. More recently, it has been recognized that many fish species migrate on seasonal and daily timescales. This includes eels and lampreys, which migrate in reverse from rivers to oceans, and freshwater fish which migrate seasonally or daily for feeding, shelter, and spawning. Therefore, fish passage efforts have spread to include all *diadromous* fish (a broader category of fish migration). Also, motivation for providing fish passage for inland and warm water fish has increased and some research is available for these regions as well. Below is a summary of design approaches utilized throughout the United States.

2.3 Design

The majority of the literature available on fish passage design targets methods for improving fish passage for a certain fish species, stream types, or crossing types. Bates et al. and the design manual by the WDFW both describe three major culvert designs to accommodate fish passage: 1) the hydraulic design method, 2) the no-slope design method, and 3) the stream simulation method [1], [4]. Three other methods are described in addition to these three main approaches.

2.3.1 Hydraulic Design Option

The hydraulic design option involves designing for a target velocity and depth that is required for specific species of fish at a specific life stage. The range of velocities or allowable turbulence for the specific fish and age of that fish must be determined as part of the design. The length of the culvert is factored into design and comes into the analysis through the swim time required for the fish to pass the culvert under design velocities. For example, when longer culverts are necessary, the design velocity may be required to be lowered to accommodate the fish's endurance. After determining the design hydrograph for the stream at the crossing, the culvert shape is selected and sized to provide flows within design velocity and depth thresholds 90% of the time.

2.3.2 No-Slope Design Option

The no-slope design option involves burying an oversized culvert below the river bed and assumes that sediment will deposit in the culvert and set its own slope. The width of the culvert installed must be at least equal to the width of the stream. The downstream end must be buried at least 20% of the diameter of the culvert but the upstream end can be countersunk a maximum of 40% of that distance. The no-slope design option can be used when the culvert is short enough so that the difference in height of the sloped sediment in the culvert from the upstream end to the downstream end is low enough as to not impede the flow at any given point on the hydrograph. This design is generally applicable in low slope regions (less than 3%). This design is meant to pass all fish and other aquatic organisms occurring in the stream.

2.3.3 Stream Simulation Design Option

The stream simulation design is used to create completely natural conditions in the culvert concurrent with conditions upstream and downstream. The culvert must be oversized by 120% of the width of the stream plus 2 feet. This allows for stream banks or dry stream borders to exist within the culvert, which guarantees shallow areas that can be important to the passage of juveniles as well as dry areas that can pass other organisms. The slope of the culvert can be no more than 125% of the slope of the stream to fit within the design guidelines. Special consideration is given to the culvert fill material in different ranges of slope, and this fill must be arranged to mimic channel conditions. This design has proven to be successful in much steeper streams than the previous two methods.

2.3.4 The Vermont Low-Slope Design Option

The Vermont Department of Fish and Wildlife named an additional design that uses much the same principle as the no-slope design but instead suggests a slight slope to increase the hydraulic effectiveness of the culvert and decrease the risk of flow blockage at the upstream end [5]. The guideline states that the culvert bottom must be between 20% and 40% buried, as does the no-slope option, but allowing a slight culvert slope in addition facilitates a greater range of slope applicability.

2.3.5 Manual for Hydrologic and Hydraulic Design for Maryland Streams

Chapter 13 from the Manual for Hydrologic and Hydraulic Design for Maryland streams provides an additional design approach [6]. This guide recommends using the Rosgen classification of natural rivers [15] and the consideration of bankfull flows to determine the proper design. The designs describe using main channel culverts buried at a minimum of 20% of the diameter and floodplain culverts to convey high flows without concentrating flow into the main channel culvert alone. Beyond this basic framework, plans are based on the stream classifications and include outlet basins, riprap, or other special features.

2.3.6 MESBOAC

In Minnesota, a form of a stream simulation design (MESBOAC) has been used for the last 10 years by county engineers in Itasca County [12]. The county has reported few problems associated with this design and are using it whenever the design is appropriate for new or replacement culverts at road crossings. MESBOAC is an acronym that stands for:

- Matching culvert width to bankfull stream width
- Extending culvert length through the side slope of the road.
- Setting culvert slope equal to stream slope.
- Bury Culvert 1/6th bankfull stream width
- Offsetting multiple culverts.
- Aligning the culvert with the stream channel.
- Consider potential head cuts and cutoffs.

2.4 Assessment of Performance

All the work done on assessment of recessed culverts has been done under the arena of aquatic organism passage. Information specific to recessed culverts for reasons *not* related to fish passage was difficult to find. Information on the effectiveness of culverts designed for fish passage is just starting to become available. In many parts of the country, fish passage design culverts have not been around long enough to determine their effectiveness. Some of the newer multidisciplinary designs such as stream simulation culverts were first reported by Bates et al. [1]. Since then, a number of publications and reports have been written on techniques developed to measure how well the fish passage culvert designs are matching the natural channel conditions and allowing fish passage. The techniques outlined in these documents will work well for measuring the conditions present at recessed culverts in our study. These documents and techniques are outlined below.

The U.S. Department of Agriculture Forest Service produced a document entitled, "National Inventory and Assessment Procedure for Identifying Barriers to Aquatic Organism Passage at Road-stream Crossings, U.S." in 2005 [7]. It was produced to provide a nationally applicable, consistent method of identifying crossings that impede passage of aquatic organisms in or along streams. It is a how-to manual for approaching answers to two questions: "How and where does the road system restrict the migration and movement of aquatic organisms and what aquatic species are affected and to what extent?" This document contains information on what to look for at culverts to quickly determine if fish passage is a problem.

Beavers et al. developed a training manual in 2008 for the Utah Department of Transportation [8]. This manual provides assessment guidelines for measuring culvert parameters as well as the natural stream conditions near the culvert.

In 2009, the USDA and Inter-Fluve published a report entitled, "Culvert Scour Assessment" [9]. The assessment techniques measured the structure controls on channel beds, footing scour and the effectiveness of aquatic organism passage by comparing channel characteristics within the crossing structure to reference channel conditions not influenced by the structure.

The three references above use basically the same field measurements to do the culvert assessment. These measurements included: a description of the culverts shape, dimensions and materials, configuration of the apron, inlet and outlet controls, inlet and outlet tailwater conditions, channel bed material, longitudinal profile through the culvert, bankfull channel width and general site description.

As mentioned earlier, the results of culvert assessments are limited. Barnard did a similar study in Washington in 2003 comparing conditions in stream simulation design culverts with that of the natural channel [10]. Barnard was the first to look at the function of stream simulation culvert designs. This study looked at 19 of the 50 stream simulation design culverts that had been installed in Washington. The oldest of the sites was built in 1995. The conclusion of the study showed that at 14 of the 19 sites, the conditions in the culvert matched that of the channel in acceptable ranges for width and slope. Heller did an assessment of a number of road crossings in the Pacific Northwest in 2007 [11]. He looked at both the cost and durability of stream simulation designs and developed the following conclusions:

- Stream simulation and hydraulic designs are about the same initial cost on small streams with gradients of <3%.
- The initial cost of stream simulation design exceeds those of hydraulic design on large streams and those >3% gradient.
- Stream simulation designs appear to be more effective and durable than hydraulic designs.
- Stream simulation designs are more likely to pass juveniles and other aquatic organisms.

2.5 Prioritization

In Minnesota, fish passage through culverts is usually addressed when a new culvert is installed or an old culvert replaced. In the western states where fish passage has proven to be a significant problem, culverts are being replaced just to address fish passage. To best utilize the limited funds available for culvert replacement, some work has been done to identify the most problematic culverts. Beavers et al. developed a GIS-based prioritization model for the state of Utah that took into consideration fish species, habitat, ranges, hydraulic conditions in the culvert, and flow regime [8]. The GIS data was supplemented with a rapid culvert assessment that identified specific problems such as perching and backwater or critical flow conditions. Work done by Diebel et al. in Wisconsin developed a methodology that ranked culvert replacement based on stream connectivity and how much stream habitat would become available if the blocked crossing was improved [13].

2.6 Summary of Technology Review

The existing literature identifies limitations to conventional culvert design within a watershed-wide viewpoint. Culverts designed for local hydraulics alone can create barriers or flow conditions that prevent movement of fish and other organisms through the stream corridor. There are also a range of design methodologies and modes of prioritizing implementation of oversized culvert work. For this project, which focuses on Minnesota culverts and watersheds, the literature review helps to provide a context for field work, data collection and analysis.

Chapter 3 Preliminary Site Surveys and Site Selection

The goal of the site selection process was to identify culverts that would provide a sufficient dataset to assess the effectiveness of culverts designed using fish passage elements. Because Minnesota has a diverse landscape and variable fish populations, culverts were selected over a range of different geographical conditions within Minnesota, accounting for variability in fish species and stream/watershed hydrologic conditions. A goal was set by the research team and Technical Advisory Panel for selection of twenty sites which would be representative of the state and could be sampled in one season.

3.1 Range of Minnesota Stream Environments

Figure 3.1 shows the diversity of landscapes in Minnesota and how slopes are distributed within each ecoregion. Each ecoregion of the state, with the exception of the Red River Valley, has a range of low to steep slopes with geomorphic features unique to that region. Because of this diversity in landscapes a decision was made to select a small number of sites in a number of eco-regions to cover the main landscape features in the state.

Figure 3.1. Map of Minnesota showing the slope gradient in each ecoregion. The slope increases as the colors change from green to red.

3.2 Culvert Distribution

The distribution of culverts was also considered in the selection process. The southern half of Minnesota has the highest density of culverts, especially focused in the southwest and southeast (Figure 3.2). These areas of the state have two things in common; a large number of streams and high road density. The Red River Valley region and the strip of road infrastructure along the North Shore also have high concentrations of culverts.

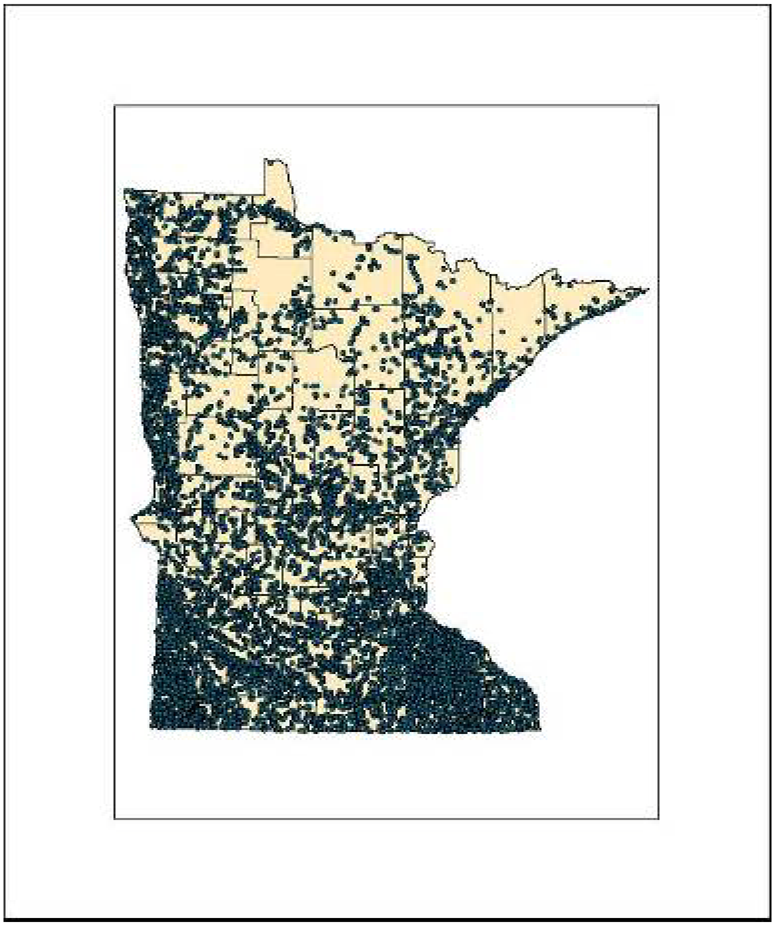


Figure 3.2. Map of Minnesota showing the locations of culverts on public waters.

3.3 Fish Populations

Fish populations are important in Minnesota for sport, food, recreation, economic and ecological reasons. Abundant fish populations can be found in the Northeast including Lake Superior, and the many Northshore streams, the Southeast corner is prized for its many trout fishing opportunities and the North-central region is covered with lakes, rivers and stream abundantly populated with a number of fish species.

3.4 Site Selection

Based on the variability of landscapes, culvert densities, and fisheries resources, the decision was made to divide the state up into the following four regions:

- Southeast
- Northeast
- North-central
- South-central

The Southeast region was chosen because of the high density of culverts and the importance of the trout fishery in this area. The steep topographic landscape and the occurrence of karst topography are other unique characteristics that play a part in the function of culverts in this region. The Northeast region provides a unique subset of streams because of the steep gradients, bedrock topography, scant soils, and interactions with the shore of Lake Superior The North-central region of the state does not have a high density of culverts, comparatively, but fishing and fish migration are important to the stakeholders in this region. In addition, the mild slopes and wetland and lake storage in this area have a unique effect on the hydrology of the landscape, thereby creating a distinct set of conditions at road crossings. The South-central sites represent the regions of the state with low gradients and high intensity of agricultural land use, that is, the South-central itself, the Southwest and the Red River Valley. Fish are not of the same importance in these regions as they are in other parts of the state but the high density of culverts, high-intensity agricultural land-use, and dynamic nature of the land (including a great deal of channel alteration) justify including these areas in the study.

Possible sites were identified by talking to MnDOT and county engineers and regional Department of Natural Resources (DNR) fisheries offices. This process generated a preliminary list of 135 sites.

To narrow down this list of potential sites and determine our final selection, many culverts were visited for a brief site evaluation. The criteria that were identified as necessary for a culvert to be incorporated in the study included:

- Good accessibility for surveying
- Recessed below the flow line elevation
- Perennial stream (flowing year round)
- Age of the culvert: having been in place at least three years to allow for accumulation of sediment in the culvert over a range of flows.

That selection was further broken down by the following characteristics:

- Range of channel substrates from sand to cobble
- Culvert configuration and size
- Stream size
- Presence of weirs: a number of sites around the state had concrete weirs to reduce the culvert slope and protect the upstream channel from incising

- Drainage area

The list was pared down to a total of 19 sites. The general characteristics of these sites are shown in Table 3.1 and the locations are mapped in Figure 3.3.

Table 3.1. Site characteristics of the 19 sites selected for detailed assessments.

Site Characteristics					
Region	County	Stream	Design	Year installed	drainage area (sq. mi)
NE	St. Louis	Stanley Creek	Recessed (rocks)	2008	2.1
NE	Lake	East Br. Beaver River D/S	Recessed (rocks)	2007	28
NE	Lake	East Br. Beaver River U/S	Recessed (rocks)	2007	24
NE	Lake	West Br. Knife River	Recessed (rocks)	2001	4.4
NE	Cook	Kimball Creek	Recessed (rocks)	2009	11.1
NC	Itasca	Splithand Creek	Recessed	2004?	7.8
NC	Itasca	Unnamed at Rearing Pond Rd.	Recessed	2006	6.84
NC	Cass	Shingobee Creek	Recessed	2001	15
NC	Mille Lacs	Bogus Brook	Recessed	2007	24.2
NC	Benton	Stoney Brook	Weir	2000	
SC	Nobles	Trib. to Little Rock	Not recessed	1996	13.5
SC	LeSueur	LeSueur Creek	Not recessed	1999	38.5
SC	Blue Earth	Trib. to LeSueur (ditch)	Bank full bench (ditch)	2000	2.7
SC	Nobles	Trib. To Champepadan	Bank full bench	2002	1.2
SE	Fillmore	Donaldson Creek	Recessed	2007	9.2
SE	Goodhue	Clear Creek	Recessed	2003	2.1
SE	Fillmore	Duschee Creek	Recessed	2004	17.4
SE	Omsted	Bear Creek	Recessed	2000	21.6
SE	Wabasha	Gorman Creek	Recessed	1994	15

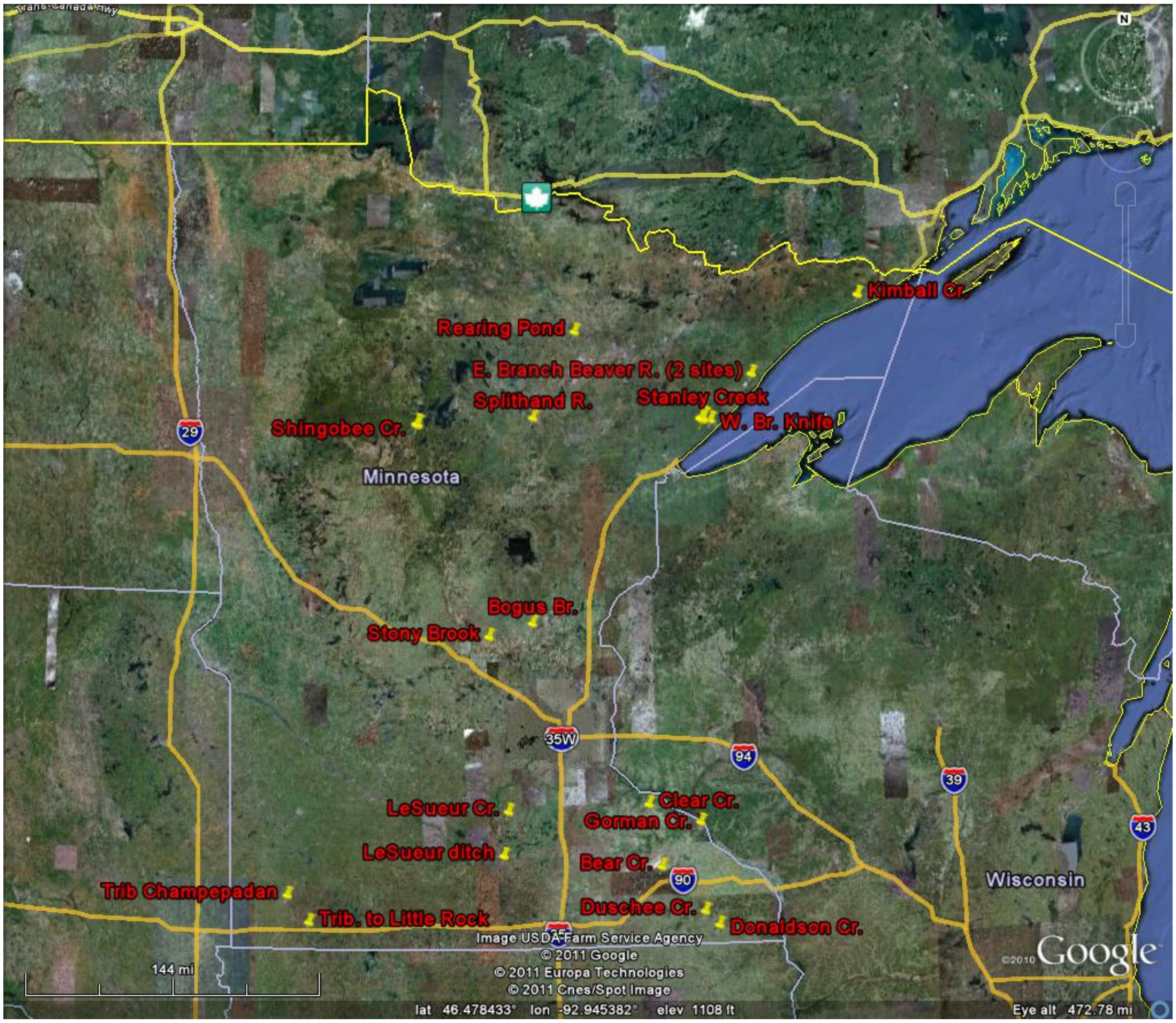


Figure 3.3. Map of Minnesota showing the location of the 19 culvert sites included in this study. Courtesy of Google Maps. Locations are: Rearing Pond, Kimball Creek, East Branch Beaver River (2 sites), Shingobee Creek, Splithand River, West Branch Knife River, Stanley Creek, Stony Brook, Bogus Brook, Le Sueur Creek, Le Sueur ditch, Tributary to Champepadan Creek, Tributary to Little Rock River, Clear Creek, Gorman Creek, Bear Creek, Duschee Creek, Donaldson Creek.

The total number of sites selected based on the aforementioned criteria was 19. These sites are described by region below, and photos and individual site descriptions can be found in Appendix B. Of those 19 surveyed sites, thirteen were recessed, two had bankfull benches built into the culverts, two sites identified as recessed prior to a detailed survey turned out not to be recessed, and two sites had concrete weirs placed at the upstream end of the culvert. The recessed depths ranged from 0.2 feet to 2.5 feet in depth. It was unclear from the work plan if either of the two sites with benches built through the culvert were recessed below the streambed.

3.4.1 Sites Selected for Southeast Minnesota
Culverts in Southeast Minnesota have the most variability to consider. The sites selected represent each of the three following variables: Head cut potential, channel substrate ranging from sand bed to channels with large gravel and cobble, and watershed size.

3.4.2 Sites Selected for North-Central Minnesota
This region is dominated by low gradient streams, abundant storage in lakes and wetlands, and a wide variety of fish. The dominant substrate in this region ranged from sand to medium gravel. A number of sites are located in Itasca County where culverts designed using fish passage elements have been in place for the last ten years.

3.4.3 Sites Selected for Northeast Minnesota
The culverts near the shore of Lake Superior were mainly on channels with larger substrate and steeper slopes. Most culverts had some type of rock placed in them to reduce velocities.

3.4.4 Sites Selected for South-Central Minnesota
Culvert sites in the region are mostly on low gradient streams and ditches. Fish passage is not considered a factor in culvert design as frequently in this region. Many counties contacted did not have any recessed culverts which made it more difficult to locate sites matching the selection criteria.

Chapter 4 Culvert Surveying Methodology

The methodology used for surveying culvert sites was developed from a number of different sources. Field surveying techniques were modeled after the Harrelson publication, and culvert assessment techniques were adopted with guidance from Beavers and Inter-Fluve [14], [8], [9]. The following is a description of each metric measured at the culvert survey sites.

Longitudinal profile: The longitudinal profile was recorded to compare channel slope upstream, downstream and through the culvert. It was also used to identify existing head cuts or the potential for future head cuts. The longitudinal profile was measured with a laser level to record elevation and a tape measure to denote the distance. Water surface and streambed elevation along the thalweg were both recorded.

Cross-section: The profile of a cross-section that represents the average channel dimensions was measured at a stream riffle as explained in the Rosgen methodology [15]. This cross-section was used to define the channel bankfull width to compare to the existing culvert width and also provided data to classify the stream using the Rosgen classification system [15].

Channel substrate: To measure the ability of the recessed culvert to naturally recruit sediment sizes similar to those of the natural channel, the particle size composition of the natural channel and any sediment that accumulated in the culvert was measured.

Velocity: To measure the effect of the culvert on stream velocity, an Acoustic Doppler Profiler (ADV), was used to measure velocities both in the channel (near the culvert) and inside the culvert. Velocities were not measured at sites where the culvert was too small to access.

Sediment depth: The depth of sediment was measured in the main recessed barrel and also in any offset barrels.

Pfankuch Stability Index: This rating is comprised of a number of scores for various channel features that are determined according to their respective stability. A final score is calculated to give a stability index for the stream channel. This index was used to assess any possible influences channel stability may have on the function of recessed culverts [16].

Rosgen stream classification [15]: Each stream reach was classified to see if any particular stream type had an influence on culverts designed using fish passage elements.

Original work plan: Work plans were obtained for all of the study site culverts. They were used to obtain data on culvert dimensions, date of installation, drainage area, recessed depth and design culvert slope. Not all work plans had all of this information.

Photos: A number photos were taken at each surveyed site to record notable features of the channel or culvert.

Data was tabulated and plotted using software developed by Mecklenburg in 1999 [17]. It includes tabs for cross-sections, longitudinal profiles, bed materials and a summary. Each culvert site has its own spreadsheet. An example of each tab is given below (Figure 4.1, Figure 4.2, and

Figure 4.3). If you wish to view all field survey data in the spreadsheet format please contact the MnDOT Bridge Hydraulics Unit at 651-366-4500.

Cross Section

section:	**2+50 upstream riffle**
	Riffle Kimball ---
description:	
height of instrument (ft):	**98.55**

notes	omit pt.	distance (ft)	FS (ft)	elevation
	☐	**0**	**3.4**	95.15
	☐	**4**	**4**	94.55
	☐	**4.5**	**5.13**	93.42
	☐	**7**	**5.5**	93.05
	☐	**10**	**5.75**	92.8
	☐	**13**	**5.67**	92.88
	☐	**17**	**5.86**	92.69
	☐	**19.8**	**5.7**	92.85
	☐	**20.4**	**5.14**	93.41
	☐	**21**	**4.2**	94.35
	☐	**22**	**3.9**	94.65
	☐	**26**	**3.2**	95.35
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			
	☐			

FS bankfull	FS top of bank	W fpa (ft)	channel slope (%)	Manning's "n"
4			**1.170**	
94.55	---			

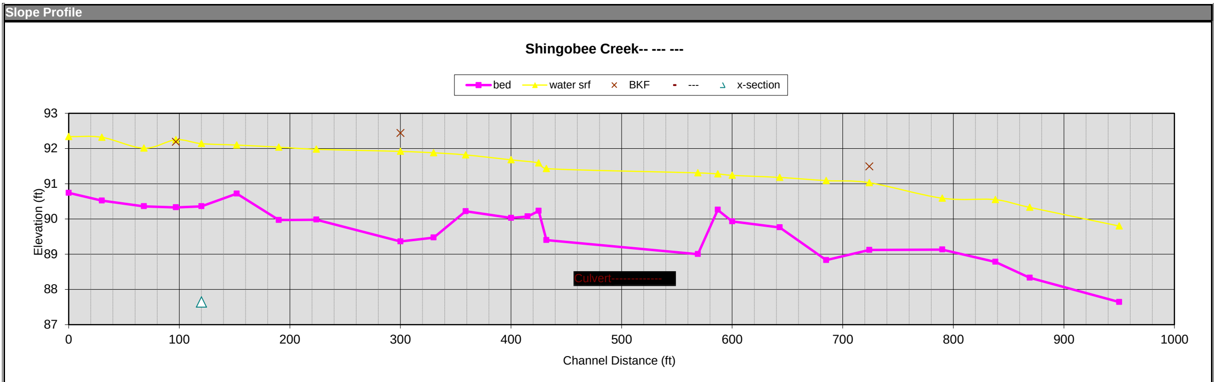
dimensions			
26.9	x-section area	1.5	d mean
17.7	width	19.2	wet P
1.9	d max	1.4	hyd radi
0.0	bank ht	11.6	w/d ratio
0.0	W flood prone area	0.0	ent ratio

hydraulics	
0.0	velocity (ft/sec)
0.0	discharge rate, Q (cfs)
1.02	shear stress ((lbs/ft sq)
0.73	shear velocity (ft/sec)
0.000	unit stream power (lbs/ft/sec)
0.00	Froude number
0.0	friction factor u/u*
75.9	threshold grain size (mm)

check from channel material			
135	measured D84 (mm)		
3.4	relative roughness	5.9	fric. factor
0.047	Manning's n from channel material		

Figure 4.1. Screenshot including table and line graph. Line graph shows the cross-sectional outline of the river channel at Kimball Creek.

Slope Profile



		continuous data			100	:Elevation BM													
notes	cross section	station		BS	HI	FS TP	FS bed	depth water	FS WS	FS BKF	FS Sediment	FS	AZ azimuth	ELEV bed	ELEV water srf	ELEV WS	ELEV BKF	ELEV Sediment	ELEV ---
					100														
Riffle		0			100		9.26	1.6						90.74	92.34				
Riffle		30			100		9.48	1.8						90.52	92.32				
Run		68			100		9.64	1.65						90.36	92.01				
Run		97			100		9.67	1.92		7.81				90.33	92.25		92.19		
Run	CS1	120			100		9.64	1.78						90.36	92.14				
Run		152			100		9.28	1.38						90.72	92.1				
Run		190			100		10.03	2.07						89.97	92.04				
Run		224			100		10.02	2						89.98	91.98				
Pool		300			100		10.64	2.56		7.56				89.36	91.92		92.44		
					100	7.56													
				5.7	98.14														
Pool		330			98.14		8.67	2.41						89.47	91.88				
Gage		359			98.14		7.92	1.6						90.22	91.82				
Riffle		400			98.14		8.11	1.65						90.03	91.68				
Rocks		415			98.14		8.07							90.07					
		425			98.14		7.91	1.36						90.23	91.59				
u/s culvert		432			98.14		8.74	2.03						89.4	91.43				
					98.14	8.74													
				6.93	96.33														
d/s culvert		569			96.33		7.33	2.31						89	91.31				
Velocity		587			96.33		6.07	1.02						90.26	91.28				
pool		600			96.33		6.4	1.31						89.93	91.24				
pool		643			96.33		6.57	1.42						89.76	91.18				
pool		685			96.33		7.5	2.26						88.83	91.09				
pool		724			96.33		7.21	1.91		4.84				89.12	91.03		91.49		
spliit		790			96.33		7.2	1.46						89.13	90.59				
split		838			96.33		7.55	1.77						88.78	90.55				
split		869			96.33		8	2						88.33	90.33				
reconnects		950			96.33		8.69	2.16						87.64	89.8				

Figure 4.2. Screenshot including table and line graph. Line graph shows the longitudinal profile of the channel bottom upstream and downstream of the culvert at Shingobee Creek.

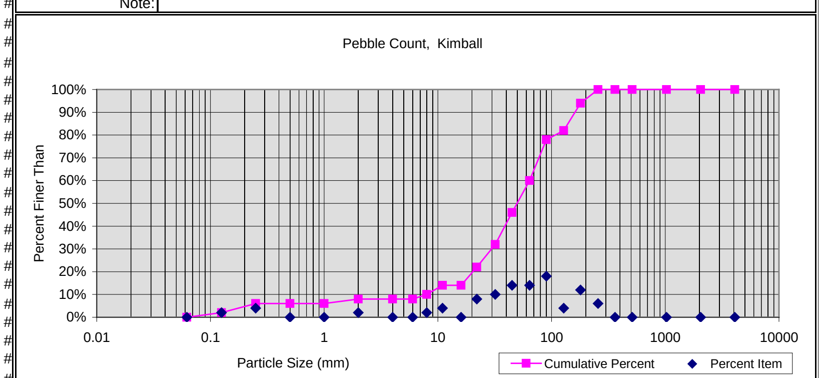
Pebble Count

Material	Size Range (mm)		Count	
silt/clay	0	0.062		# #
very fine sand	0.062	0.13	1	# #
fine sand	0.13	0.25	2	# #
medium sand	0.25	0.5		# #
coarse sand	0.5	1		# #
very coarse sand	1	2	1	# #
very fine gravel	2	4		# #
fine gravel	4	6		# #
fine gravel	6	8	1	# #
medium gravel	8	11	2	# #
medium gravel	11	16		# #
coarse gravel	16	22	4	# #
coarse gravel	22	32	5	# #
very coarse gravel	32	45	7	# #
very coarse gravel	45	64	7	# #
small cobble	64	90	9	# #
medium cobble	90	128	2	# #
large cobble	128	180	6	# #
very large cobble	180	256	3	# #
small boulder	256	362		# #
small boulder	362	512		# #
medium boulder	512	1024		# #
large boulder	1024	2048		# #
very large boulder	2048	4096		# #
bedrock				#
	Total Particle Count:		50	

Pebble Count,

	Kimball

Note:	



Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
17.326	34.43	49.8	135	191	0%	8%	52%	40%	0%	0%

Figure 4.3. Screenshot showing table and line graph. Line graph shows the particle distribution of channel sediments at Kimball Creek.

Chapter 5 Site Surveys Results and Analysis

The four research objectives developed to achieve the goal of assessing culverts designed using fish passage elements in Minnesota were:

1. Understand the hydraulics of recessed culverts and the possible impacts they have on adjoining stream characteristics
2. Develop or adopt a culvert assessment protocol to assess the performance of culverts designed using fish passage elements.
3. Assess the effectiveness of culverts designed using fish passage elements over a range of different geographical conditions within Minnesota
4. Identify the stream morphologic and hydraulic conditions introduced by culverts designed using fish passage elements that may negatively affect fish passage

Objective two was addressed in Chapter 4. Objectives one, three and four are covered in Chapter 5.

Recessing culverts is not normally a standalone design but is one of the design features employed when designing culverts to accommodate fish or aquatic organism passage. The research presented here looks at a number of other parameters used to design culverts for fish passage in Minnesota. A list of other design elements analyzed in this report includes:

- Matching culvert width to bankfull stream width
- Setting culvert slope equal to stream slope
- Multiple culverts
- Aligning the culvert with the stream channel
- Head cut potential

The analysis will first address any potential negative impacts related to the practice of recessing culverts followed by an analysis of the other culvert design parameters and their effects on culvert function.

5.1 Impacts on Stream Gradient

The main concern with the practice of recessing a culvert is the elevation drop created when the streambed is excavated to accommodate the recessed portion of the culvert. This elevation drop could lead to a head cut moving upstream. As the head cut moves up stream the streambed could lower thus increasing the stream bank height. Higher stream banks can become unstable which could lead to the bank slumping into the stream. If the head cut propagates upstream to the next grade control structure, which will most likely be a culvert, it could perch the downstream end of the culvert.

The need to protect this elevation drop created during installation of the recessed culvert was well represented in the field. The field surveys documented head cutting mitigation efforts at all but two of the recessed study sites. No evidence of head cuts moving upstream from a recessed culvert installation was observed at any of the seventeen study sites where rock had been put in place. At the two sites where no rock had been placed no head cuts had developed at the time of the survey. All mitigation study sites featured some form of rock weir or immobile rip-rap placed in the channel to serve as grade control and protect against the possibility of a head cut. Two different configurations were observed. At culvert sites with pools both upstream and downstream of the culvert, rock is placed where the channel enters the upstream pool and where the channel exits the downstream pool (Figure 5.1). At sites where the stream channel flows directly into the culvert, the rock is placed just upstream of the culvert entrance (Figure 5.2).

Figure 5.1. Photograph of rip-rap placed at upstream end of the pool to prevent the formation of a head cut developing from the recessed culvert installation.

Figure 5.2. Photograph of rock placed in the channel immediately above the culvert to protect against head cut development.

5.2 Sediment Accumulation in Recessed Culvert

Since there is not a standard fish passage culvert design used in Minnesota, designs vary across the state based on the knowledge and experience of local county, state and DNR personnel. The designs methods in place are some combination of matching channel parameters to culvert dimensions and reducing velocities through placement of rock in culverts. The main reason culverts are recessed is to allow for natural channel sediments to accumulate in the recessed portion of the culvert. These accumulated sediments usually produce a greater friction factor which should translate into reduced culvert velocities and more places to hide for aquatic organisms passing the culvert. The presence or absence of sediment in the recessed culvert barrel was used as the criteria to determine if the culvert was functioning as intended. Using that evaluation metric, six of the thirteen recessed culvert sites did not have sediment accumulated in the barrel. Table 5.1 lists culverts and bankfull widths at all sites. The sites shaded in gray had no sediment in them at the time of the survey.

Table 5.1. Channel widths at culvert site locations.

Channel Width							
Region	Stream	# of barrels	culvert size (ft. unless otherwise specified)	Sediment in recessed barrel	Overall culvert width	Recessed culvert width	Bankfull channel width
NE	Stanley Creek	2	10 x 4, 10 x 6	rip rap	20	10	9.2
NE	East Br. Beaver River D/S	2	12 x 12, 12 x 10	no	24	12	46.7
NE	East Br. Beaver River U/S	2	10 x 8, 10 x 10	no	20	10	38
NE	West Br. Knife River	1	12 x 8	no	12	12	22.6
NE	Kimball Creek	2	10 x 10, 10 x 9	yes	20	10	17.7
NC	Splithand Creek	3	arches ~10 x 5	yes	18	8.5	18.9
NC	Unnamed at Rearing Pond Rd.	2	8 x 6, 8 x 5	yes	16	8	13.2
NC	Shingobee Creek	1	12 x 8	no	12	12	24.8
NC	Bogus Brook	2	arches 157" x 97"	no	24	13	20.0
NC	Stoney Brook	2	10 x 8 weir	no	20	10	14.2
SC	Trib. to Little Rock	2	10 x 6	yes	20	10	8.7
SC	LeSueur Creek	2	12 x 10	no	24	12	48.8
SC	Trib. to LeSueur (ditch)	1	14 x 10	yes	14	14	17.4
SC	Trib. To Champepadan	3	14 x 5, 14 x 6, 14 x 5	yes	42	14	10.4
SE	Donaldson Creek	3	12 x 8, 12 x 9, 12 x 8	yes	36	12	11.8
SE	Clear Creek	2	10 x 10, 10 x 8	yes	20	10	9.4
SE	Duschee Creek	3	12 x 5, 12 x 6, 12 x 5	no	36	12	26.4
SE	Bear Creek	4	12 x 5	yes	48	12	30
SE	Gorman Creek	2	12 x 8, 12 x 9	yes	24	12	10.7

The total sites surveyed were 19. However, after the surveys were completed two of the sites Trib. To Little Rock and LeSueur Creek proved not to be recessed. Two sites Stoney Brook and Bear Creek had concrete weirs at the culvert entrance and two sites had bankfull benches installed along the culvert sides leaving thirteen sites that had been truly recessed. This left a data set of thirteen recessed culverts. Six of the thirteen recessed sites did not have sediment accumulated in the recessed barrel.

5.3 Scenarios Causing a Lack of Sediment

A lack of sediment observed in some of the recessed culvert barrels could be due to a number of scenarios:

1. A recent large flood event washed out sediment that normally would be retained in the recessed culvert under normal flow conditions.
2. The culvert has not been in place long enough for a range of flows to transport sediment into the culvert.
3. The inadequate transport of sediment due to immobile bed materials.
4. The culvert slope, width, or roughness was not properly designed, creating high velocities that wash sediments from the culvert.
5. Excessive sediment accumulated in side barrels, reducing flow capacity and increasing velocity in the main barrel.

5.3.1 Scenario 1. Possible Large Flow Event

Large flow events prior to the survey were recorded at two sites, Donaldson Creek and Bogus Brook. These sites serve as an illustration of the effect of culvert conditions on the response of in-barrel sediment to large flow events.

The Donaldson Creek site in Fillmore County experienced a rain event in the range of 2.5 to 3.5 inches the night before the survey. This site has a watershed area of 9.2 square miles, a bankfull width of 11.8 feet, and a culvert configuration consisting of three barrels for a total width of 36 feet. The center barrel was recessed one foot below the two side barrels. The site has large pools both upstream and downstream of the culvert. The upstream pool probably dissipated and distributed the high channel flow over the width of all three culverts preventing the sediment from washing out of the recessed culvert barrel. There was twelve to eighteen inches of sediment remaining in all three culvert barrels at the time of the survey.

Bogus Brook in Mille Lacs County has a drainage area of 24.2 square miles and a bankfull width of 20 feet. It is a double barrel arch culvert with both barrels 12 feet wide. The side barrel is 0.1 feet higher than the main barrel. During the first survey attempt in early Fall 2010, Bogus Brook was flowing at too high a stage to survey due to heavy rains. Two weeks later, the site was surveyed and only 20% of the recessed barrel had sediment in it. It is unclear if this culvert was washed free of sediment from the recent heavy rains or if it never maintained sediment in it. It was noted that the side barrel did have sediment in it.

All other sites were surveyed between August and November of 2010 and were not impacted by heavy rains prior to the surveys.

5.3.2 Scenario 2. Culverts in Place Long Enough to Accumulate Sediment

All culverts surveyed during this study, with the exception of the Kimball Creek crossing, had been in place at least three years. In the original selection of culverts, this three year age had been chosen as the minimum time period to allow for a range of sediment-transporting flows.

5.3.3 Scenario 3. Lack of Sediment Transport or Immobile Bed

Thirteen of the 19 surveyed sites have bed material consisting of more than 80% gravel, sand, silt and clay (see Table 5.2). In 2008, a Stream Simulation Working Group found that bed mobility is generally not a problem on most moderate to low gradient streams with gravel pool or sand bed configurations [18]. Figure 5.3 shows an example of a highly mobile bed at Gorman Creek. The other six sites have larger bed material; in these reaches cobbles and boulders make up more than 25% of the bed material. Five of the six sites with coarser bed materials are multiple barrel configurations with one culvert recessed below the flow line elevation and the other culverts at or above the flow line elevation. Sediments had not accumulated in the recessed barrel but were present (at a significant depth) in the side barrels, suggesting that sediment transport is sufficient to fill in the recessed barrel but that those sediments are not staying in place. Figure 5.4 shows a side barrel partially filled with sediment at the downstream Beaver River Site. At this site the recessed culvert was devoid of sediment (Table 5.2).

Table 5.2. Bed materials: In channel and culvert. Data were obtained by sampling via pebble count or collecting sand samples that subsequently underwent sieve analysis.

Materials Comparison								
				Materials				
Region	Stream	D84	Sample Location	Boulder 0.26 - 4.1 m	Cobble 54 - 256 mm	Gravel 2 - 64 mm	Sand 0.062 - 2 mm	Silt/Clay 0 - 0.062 mm
NE	Stanley Creek	104	Channel	4	31	38	27	0
			Culvert	Filled with rip rap				
NE	East Br. Beaver River D/S	39	Channel		3	81	15	1
			Culvert	No sediment in culvert				
NE	East Br. Beaver River U/S	209	Channel	12	54	33	2	
			Culvert	No sediment in culvert				
NE	West Br. Knife River	48	Channel		10	74	15	1
			Culvert	No sediment in culvert				
NE	Kimball Creek	135	Channel		40	52	8	0
			Culvert		11	89	0	0
NC	Splithand Creek	1	Channel			3	96	1
			Culvert			0	100	0
NC	Unnamed at Rearing Pond Rd.	0.6	Channel				100	
			Culvert				100	
NC	Shingobee Creek	24	Channel		5	48	38	5
			Culvert		0	70	30	0
NC	Bogus Brook	47	Channel		12	67	19	2
			Culvert	Sediment near ends of culvert, 10% of area				
NC	Stoney Brook	47	Channel		12	67	19	2
			Culvert	Sediment near ends of culvert, 10% of area				
SC	Trib. to Little Rock	0.4	Channel			11	80	9
			Culvert			0	76	24
SC	LeSueur Creek	43	Channel		12	62	22	4
			Culvert		0	67	24	10
SC	Trib. to LeSueur (ditch)	0.5	Channel					
			Culvert			3	89	7
SC	Trib. To Champepadan	3	Channel			32	58	10
			Culvert			5	85	10
SE	Donaldson Creek	0.2	Channel				81	19
			Culvert				16	84
SE	Clear Creek	79	Channel		29	43	17	11
			Culvert	Could not sample				
SE	Duschee Creek	156	Channel		46	54	0	1
			Culvert	No sediment in culvert				
SE	Bear Creek	37	Channel				100	
			Culvert				100	
SE	Gorman Creek	0.8	Channel			8	91	1
			Culvert			32	67	1

Figure 5.3. Photograph showing a highly mobile sand bed at Gorman Creek. Note the side culvert filled in with sediment (Goodhue County).

Figure 5.4. Photograph showing gravel and small cobble accumulating in the side barrel at Beaver River site (St. Louis County).

5.3.4 Scenario 4. The Culvert Slope, Width, or Velocity Not Matching the Respective Channel Parameters

Matching the culvert design width to the bankfull channel width and matching the culvert slope to the channel slope will help maintain sediment in the culvert and keep velocities low enough to allow aquatic organism passage. It is generally recommended to size the culvert 1 to 1.2 times the bankfull channel width [18]. If extra capacity or width is needed for wide flood plains or additional flood capacity, the design calls for multiple barrels, resulting in a total culvert width that is normally wider than the channel bankfull width. In general, the design methodologies suggest that, as long as the recessed culvert is sized to bankfull and the side barrels are accessible to higher flows, the recessed culvert velocities should still be in the range of the channel velocities. For these flow conditions the recess culvert should maintain sediment to the proper depth and the velocities through the culvert should be compatible for fish passage.

Figure 5.5 shows the ratio of the recessed culvert width compared to the bankfull channel width for the thirteen sites with recessed culverts. At nine of the thirteen sites the recessed culvert width is less than the bankfull width, including five of the six sites with no sediment in the recessed culvert. Of the six sites that had no sediment accumulated in the recessed barrel two were single barrel culverts and the remaining four were double barrel culverts. The single barreled culverts had ratios of 0.40 and 0.52 which suggests the culverts are undersized and sediment accumulation could be a problem because of higher culvert velocities compared to the channel. The four double barrel culverts had sediment accumulated in the side barrels which suggests enough sediment is moving downstream to accumulate in the recessed barrel. However, it may be accumulated in the side barrels to a depth that forces more flow through the recessed barrel which may explain why no sediment had accumulated in the recessed barrel.

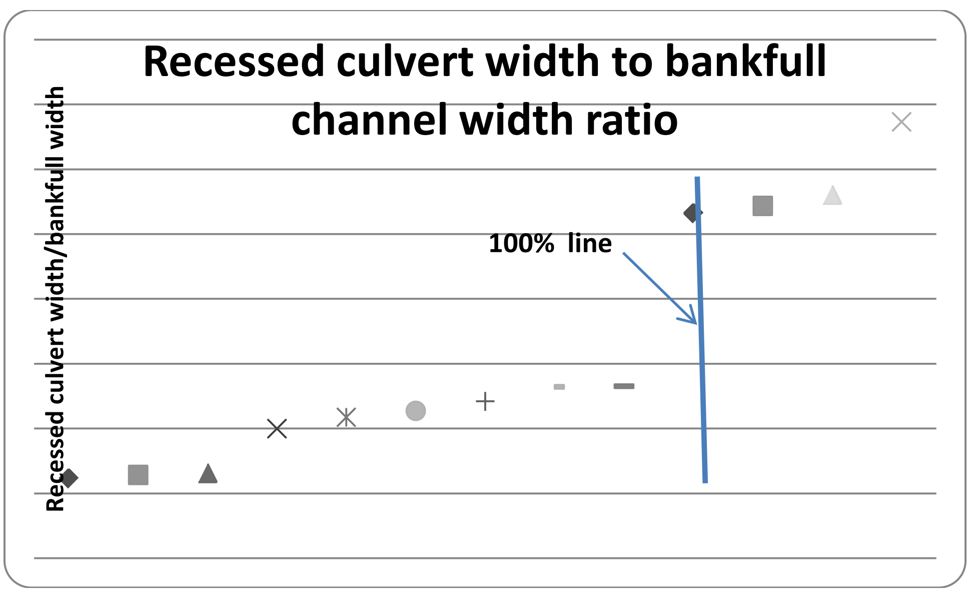


Figure 5.5. Graph showing the ratio of recessed culvert width and the bankfull channel width for the thirteen recessed culvert sites. The graph shows that at nine sites recessed culvert width was less than bankfull width.

Figure 5.6 shows the ratio of total culvert width (all barrels) to the bankfull channel width for all 19 sites. Eight of the 19 sites have a total culvert width less than the channel width.

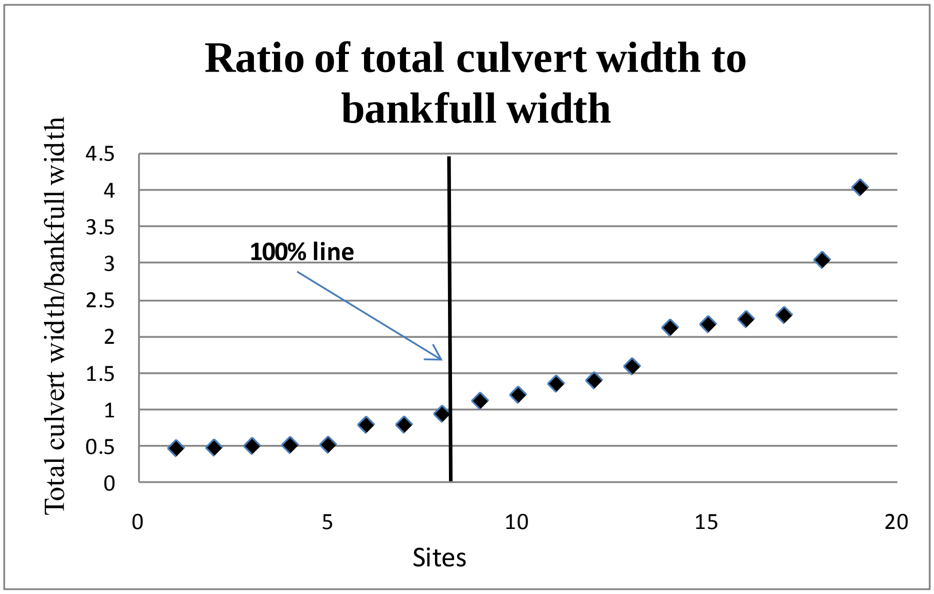


Figure 5.6. Graph of the ratio of total culvert width compared to the bankfull channel width. Eight of the sites had a total culvert width that was less than the bankfull channel width.

Longitudinal profiles were run at all 19 sites to measure overall slope, capture any slope changes, identify possible head cuts and to compare channel slope to culvert slope. Field survey data collection involved surveying the stream's thalweg over a distance that could accurately capture slope changes over the reach. Table 5.3shows the channel slope upstream and downstream of the culvert, the percent change between upstream and downstream slope, the culvert slope and the percent change between upstream channel slope and the culvert slope. The percent change was calculated according to the equations:

$$\%\ change\,\frac{DS}{UP} = \left(1 - \frac{Downstream\ slope}{Upstream\ slope}\right) * 100$$

$$\%\ change\ CS/US = \left(1 - \frac{Culvert\ slope}{Upstream\ slope}\right) * 100$$

A negative change indicates an increase in slope moving downstream and a positive change indicates a decrease in slope moving downstream. Four sites Rearing pond (-823), Trib. to Little Rock (-342), Shingobee (-306), and Trib. To LeSueur (-813) had significant increases in channel slope downstream of the culvert as compared to upstream slope. The steeper slope downstream of the culvert at the Trib. to the LeSueur site was due to natural slope change as the channel dropped down the valley walls of the main branch of the LeSueur River. It was not clear from the data why there was a significant change in slope at the other three sites. The increase in downstream slope could be the result of the culvert acting as grade control for the channel which would allow natural channel incision below the culvert and sediment accumulation above the culvert. Or it could be a natural change in slope. There was no data that suggested the change in slope was due to the practice of recessing the culvert at any of the locations.

Figure 5.7 is a graphical representation of the slope comparison between upstream and downstream. Any sites with steeper downstream gradients should be carefully analyzed to ensure that the culvert is recessed to a depth adequate to prevent perching of the downstream culvert outlet.

Table 5.3. Slopes: upstream, in culvert, and downstream at the culvert site locations.

Slope Comparison						
Region	Stream	Measured U/S slope	Measured D/S slope	Percent change U/S vs. D/S	Culvert slope	Percent change U/S vs. culvert
NE	Stanley Creek	0.021	0.0042	80.0	0.0067	68.3
NE	East Br. Beaver River D/S	0.004	0.0027	22.9	0.0075	-114
NE	East Br. Beaver River U/S	0.016	0.012	25.0	0.015	6.25
NE	West Br. Knife River	0.023	0.017	26.1	0.017	24.6
NE	Kimball Creek	0.010	0.013	-30.0	0.010	-1.72
NC	Splithand Creek	0.00022	0.00021	4.55	0	100
NC	Unnamed at Rearing Pond Rd.	0.00039	0.0036	-823	0	100
NC	Shingobee Creek	0.0016	0.0065	-306	0.0029	-81.3
NC	Bogus Brook	0.0027	0.0008	71.5	0	100
NC	Stoney Brook	0.0019	0.0010	47.4	0.0024	-26.3
SC	Trib. to Little Rock	0.00043	0.0019	-342	0.0021	-390
SC	LeSueur Creek	0.0021		100	0.0017	20.6
SC	Trib. to LeSueur (ditch)	0.00023	0.0021	-813	0.0046	-1900
SC	Trib. To Champepadan	0.0019	0.0018	4.26	0	100
SE	Donaldson Creek	0.00067			0.0022	-224
SE	Clear Creek	0.011	0.0016	85.5	0.0035	68.2
SE	Duschee Creek	0.0048	0.0066	-37.5	0.0031	34.9
SE	Bear Creek	0.0018	0.0028	-55.6	0.0024	-35.5
SE	Gorman Creek	0.0070	0.0070	0	0.016	-123

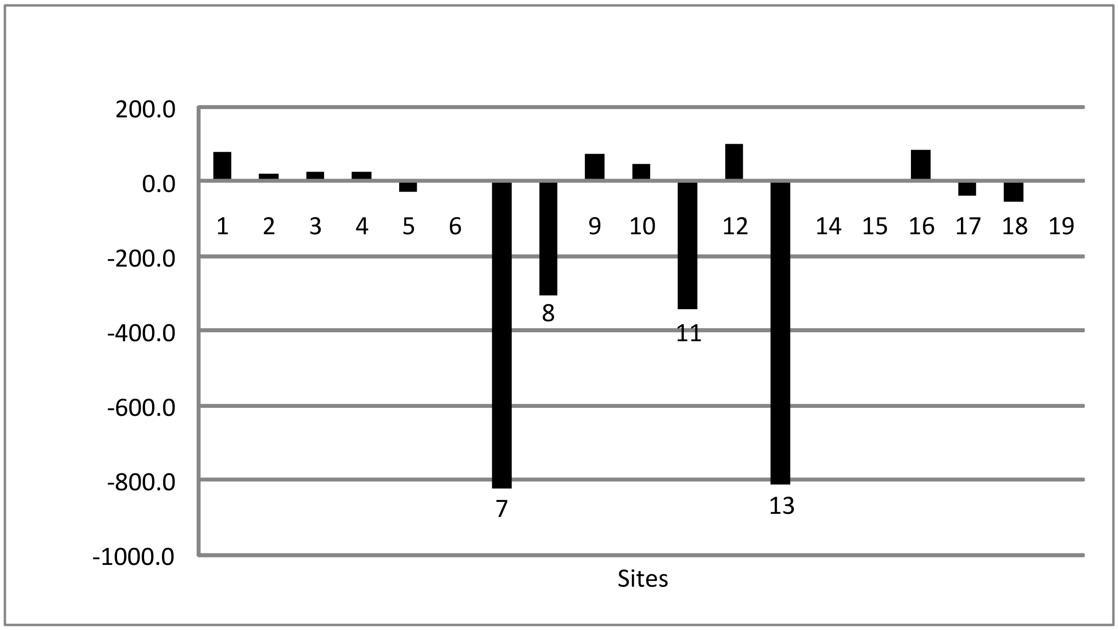


Figure 5.7. Graph comparing the upstream channel slope to the downstream channel slope. Four sites have greater downstream slope as compared to upstream slope.

Figure 5.8 compares the upstream slope to the culvert slope. Six sites have culvert slopes that are greater than the upstream slopes. Steeper culvert slopes can result in higher culvert velocities as compared to channel velocities. However, in this data set there is no correlation between higher culvert slope and a lack of accumulated sediments in the recessed culvert. Nor was there a correlation between the practice of recessing culverts and the difference in slope between upstream and downstream segments.

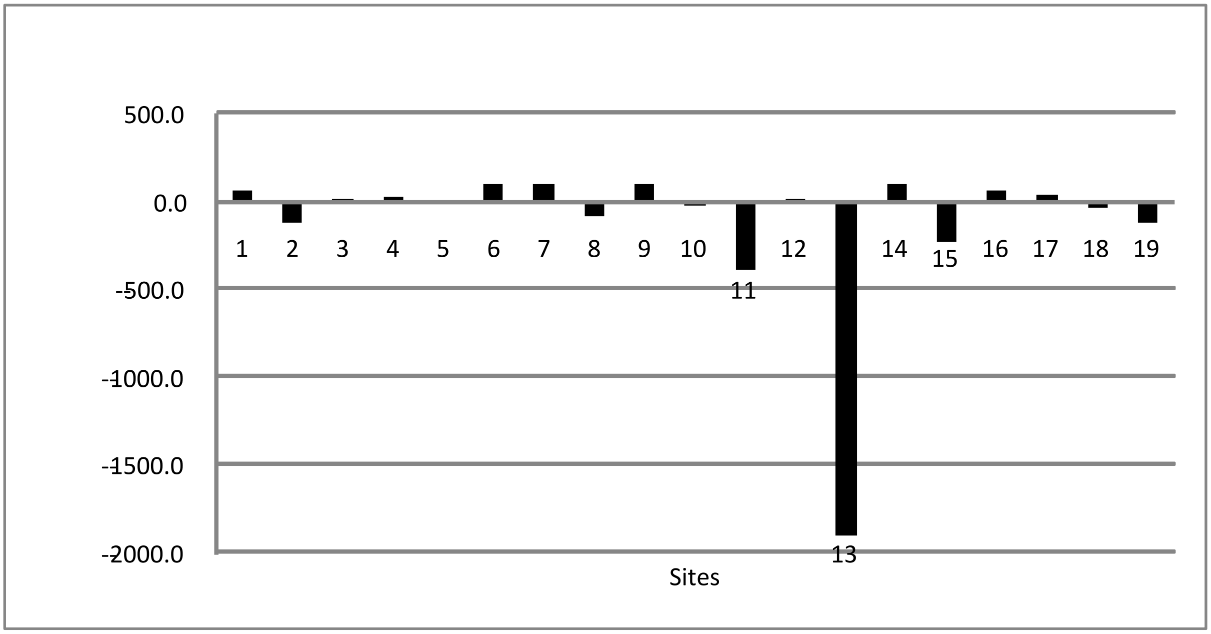


Figure 5.8. Graph showing the culvert slope compared to the upstream channel slope. Five culvert sites have greater culvert slope than upstream channel slope.

Velocities were measured at the time of the survey, both in the stream channel and the culvert, at fifteen of the 19 sites (Table 5.4). No velocity data were collected at four of the sites due to either low water conditions at the time of the survey, or else the culvert was too low to be able to access the culvert for velocity measurement. The maximum velocities measured in the culverts ranged between 0.2 and 1.8 ft/sec. The maximum velocities in the channel ranged from 0.17 to 1.7 ft/sec. No meaningful conclusions are drawn from the velocity data because of the differences in cross-sectional area between the channel and the culvert and the varied and low flows at the time of the surveys. Hydraulic modeling of the culvert sites to determine stage and flow characteristics at higher flows would be complex due to the multiple barrel configurations, varying sediment depths in the side barrels, and downstream influences of rock weirs and pools that were present at most of the sites.

Table 5.4. Channel and culvert velocities and cross-sectional (XS) areas.

Channel and Culvert Velocities										
Region	Stream	XS area culvert (ft^2)	XS area channel (ft^2)	average vel. culvert (ft/s)	avg. vel. channel (ft/s)	max. vel. culvert (ft/s)	max. vel. channel (ft/s)	min. vel. culvert (ft/s)	min. vel. channel (ft/s)	Discharge (ft^3/s)
NE	Stanley Creek	11.3	1.93	0.123	0.827	0.202	0.983	0.0560	0.277	1.25
NE	East Br. Beaver River D/S	29.6	15.6	0.210	0.880	0.500	1.73	-0.0700	-0.0300	12.8
NE	East Br. Beaver River U/S	32.6	18.8	0.515	0.615	0.678	1.28	0.414	-0.0450	16.8
NE	West Br. Knife River									
NE	Kimball Creek	4.78	5.93	0.660	0.619	0.901	0.977	0.174	0.0830	3.36
NC	Splithand Creek	19.0	31.9	0.483	0.318	0.657	0.601	0.184	0.00200	9.52
NC	Unnamed at Rearing Pond Rd.	23.6	19.4	0.180	0.276	0.247	0.610	0.112	0.0160	4.61
NC	Shingobee Creek	30.5	21.4	0.791	1.06	1.11	1.69	0.362	0.263	23.2
NC	Bogus Brook	34.8	8.80	0.250	1.09	0.550	1.64	0.020	0.200	8.69
NC	Stoney Brook	21.6	12.4	0.283	0.540	0.391	1.18	0.0860	0.0140	6.58
SC	Trib. to Little Rock									
SC	LeSueur Creek	18.2	9.80	0.573	0.996	0.646	1.16	0.467	0.646	10.6
SC	Trib. to LeSueur (ditch)	13.5	9.60	0.141	0.090	0.190	0.169	0.102	0.00800	1.82
SC	Trib. To Champepadan									
SE	Donaldson Creek		16.0		0.980		1.29		0.240	
SE	Clear Creek									
SE	Duschee Creek	13.2	11.3	0.800	0.680	1.37	1.12	0.0400	0	10.1
SE	Bear Creek	9.40 / 14.1	11.4	0.792	1.17	1.82	1.63	-0.400	0.628	9.19
SE	Gorman Creek	2.9	2.50	1.21	1.00	1.81	1.48	0.602	0.00200	3.74

5.3.5 Scenario 5. Sediment Accumulation in Side Barrels

The last factor that could affect the accumulation of sediment in the recessed culvert on multiple barrel configurations is the accessibility of the side culverts to higher flows. If the side culverts are initially placed at too high of an elevation relative to the recessed culvert or sediment has accumulated in the side barrel to a depth that limits flow access to the side barrel, excess flow could be forced through the recessed barrel possibly creating excess velocities. In

Table 5.5, column B shows the difference in sediment elevation in the side barrels relative to the recessed barrel elevation. The values in column B are then compared to bankfull depths from the channel shown in Column C to give an indication of how accessible the side barrels are to flows as they approach the bankfull stage. Positive values in Column D indicate the flow depth would need to exceed the bankfull stage before it will start to flow through the side culvert. Seven sites highlighted in column D have side barrel elevations greater than the bankfull depth of the channel. At these seven sites, bankfull flow is forced through the recessed barrel at depths higher than bankfull, thereby creating higher velocities. Four of these sites match up with sites that contain no sediment in the recessed barrel. Of the three remaining sites, Stanley Creek has rip–rap placed in the recessed barrel, the unnamed creek at Rearing Pond Road did have sediment accumulated in the bottom but very little with an average depth of 0.15 feet, and Gorman Creek has a recessed culvert barrel wider than bankfull which probably keeps the velocities low enough to maintain sediment in the recessed barrel. Why sediment was accumulating in side barrels to depths that would divert water into the recessed barrel under higher flows was not determined. One possible scenario is the culvert alignment might be such that the flow favors one side barrel over the other (in the case where there are two side barrels), leading to lower flows in the other barrel, resulting in excessive sediment deposition in that side barrel.

Table 5.5. Comparison of side barrel sediment depth to bankfull channel depth.

Region	Stream	Elevation of sediment in recessed barrel (ft) A	Elevation of sediment in side barrel (ft B	Elevation difference column B-A C	Channel bankfull depth (ft) D	Columns C-D E	Overall culvert width	Recessed culvert width	Bankfull channel width
NE	Stanley Creek	101	102.5	1.5	1.3	0.2	20	10	9.2
NE	East Br. Beaver River D/S	100	102.5	2.5	2	0.5	24	12	46.7
NE	East Br. Beaver River U/S	100	102.5	2.5	2.1	0.4	20	10	38
NE	West Br. Knife River	100	100	0			12	12	22.6
NE	Kimball Creek	100	102	2	1.5	0.5	20	10	17.7
NC	Splithand Creek	101.5	101.75	0.25	2.1	-1.85	18	8.5	18.9
NC	Rearing Pond	100.15	102.55	2.4	1.7	0.7	16	8	13.2
NC	Shingobee Creek	100	100	0			12	12	24.8
NC	Bogus Brook	100	100.5	0.5	1.9	-1.4	24	13	20
NC	Stoney Brook	100	104.65	4.65	2.3	2.35	20	10	14.2
SC	Trib to Little Rock	100.15	101.15	1	1.6	-0.6	20	10	8.7
SC	LeSueur Creek	100	102.5	2.5	2.6	-0.1	24	12	48.8
SC	Trib to LeSueur (ditch)	101	101	0			14	14	17.4
SC	Trib. To Champepadan	100.5	101	0.5	1.5	-1	42	14	10.4
SE	Donaldson	101.9	101.9	0	2.9	-2.9	36	12	11.8
SE	Clear Creek	101.25	103.55	2.3	2.7	-0.4	20	10	9.4
SE	Duschee	100	101.7	1.7	2.3	-0.6	36	12	26.4
SE	Bear Creek	102	103	1	2.4	-1.4	48	12	30
SE	Gorman Creek	100.4	103.9	3.5	1.4	2.1	24	12	10.7

The analysis of the field data determined that six of the thirteen recessed culvert sites had no sediment accumulation. The results of the analysis identify scenarios four and five as the probable reasons for improper culvert function resulting in lack of sediment in the recessed barrel. The conclusion drawn from analysis of these culvert and channel parameters suggests the combination of insufficient culvert width (compared to channel bankfull width) and limited access to side barrels can be enough to raise velocities through the recessed barrel high enough to limit the ability of accumulated sediment to remain in the recessed barrel.

5.4 Influences of Channel Stability, Type and Region on Recessed Culverts

To assess the effect of culverts designed using fish passage elements over a range of geographical conditions in Minnesota (objective 3) each study site was classified by stream type both above and below the culvert. It is difficult to compare culvert function between stream reaches without a system of classification because of the diversity in stream reaches over many different landscapes. The classification system we used is based on procedures outlined by Rosgen [15]. This system integrates stream channel geometry, valley types and shapes, slopes, and channel materials into a classification system. Stream reaches are grouped together to form eight individual categories. At each field site, data were collected to calculate the following ratios used to classify the stream reach: entrenchment ratio, width/depth ratio, and sinuosity, slope, and dominant channel materials. Rosgen's system reduces the variability and allows comparisons to be formulated between stream type and river function. A detailed description of the classification methods is not provided here but the reader is directed to the reference itself for more information.

5.5 Pfankuch Stability Assessment

In order to draw realistic comparisons between stream reaches and stream stability, a higher level of analysis is needed. To assess river stability, the *Pfankuch Stream Reach Inventory and Channel Stability Evaluation* is combined with Rosgen's modified Pfankuch stability rating [16], [19]. In its original form, the Pfankuch stability rating evaluates the upper and lower stream banks and the bed for excessive erosion or deposition. Fifteen parameters are scored into one of four categories by matching a description of the parameter condition. A total score from all fifteen parameters is then summed and ranked *good, fair* or *poor* based on a numerical scale. Higher numbers represent less stable stream conditions. Rosgen's modifications did not change any of the fifteen scoring parameters but stratified them by stream type. This was done to ensure stream types were ranked on scores relative to their natural stability and not across all stream types.

Stream types and stability ratings for each site surveyed are listed in Table 5.6. The breakdown for the 19 sites is as follows:

- Stream types
  - Eight channels E3 – E5
  - Eight channels C3 – C5
  - Two channels G5 (one natural stream, one ditch)
  - One channel B3
- Pfankuch
  - 11 "Good"
  - 5 "Fair"
  - 3 "Poor"

Of the 19 sites surveyed, seventeen sites were B, E or C channels with bottom content ranging from sand to small cobbles. These are very common stream types found in Minnesota.

The stream types above and below the culverts were the same at fifteen of the sites. The difference between the upstream and downstream types at the remaining four sites was mostly just a small shift in bed materials.

The Pfankuch stability index rated eleven sites *good*, five sites *fair* and three sites *poor*. When looking at these ratings in a regional context, it is clear that they fall into categories based on land use disturbance. All sites in the Northeast region were rated *good*, and the *fair* and *poor* sites were mainly distributed between South-central and Southeast regions where agriculture and population have greater impacts on stream channels.

At six of the sites, the stability ranked higher upstream of the culvert than downstream. It is not clear from the data whether or not the lower rankings downstream are due to the culvert crossing. At a number of these sites there were land use changes between the upstream and downstream sections that impacted the ratings.

Table 5.6 overlays stream type and stability with the sites highlighted in gray that were defined as not functioning properly due to the lack of sediment accumulation in the recessed barrel. Eight of the 19 sites are C channels with the dominant bed material ranging from sand to cobble. Five of those eight C channels are among the six of the total thirteen sites that had no sediment accumulated in the main culvert barrel. A likely reason for this correlation is that C channels have a greater width to depth ratio than E channels (which made up eight of the 19 total sites) and that greater bankfull width is more difficult to match the elements used in fish passage design.

Table 5.6. Stream type and stability at the culvert site locations.

Stream Type and Stability							
Region	Stream	Stream Type u/s	Stream Type d/s	Pfankuch Stability Index u/s	Rating	Pfankuch Stability Index d/s	Rating
NE	Stanley Creek	E3/E4	E4	64	Good	72	Good
NE	East Br. Beaver River D/S	C4	C4	80.5	Good	75	Good
NE	East Br. Beaver River U/S	B3	B3	49	Good	49	Good
NE	West Br. Knife River	C4	C4	54	Good	54	Good
NE	Kimball Creek	C3/C4	C3	59	Good	59	Good
NC	Splithand Creek	E5	E5	87	Fair	87	Fair
NC	Unnamed at Rearing Pond Rd.	E5		71	Good		no channel
NC	Shingobee Creek	C4	C4	70	Good	74	Good
NC	Bogus Brook	C4	C4	55	Good	116	Poor
NC	Stoney Brook	E4	E4	93	Fair	133	Poor
SC	Trib. to Little Rock	E5	E5	103	Poor	97	Poor
SC	LeSueur Creek	C4	C4	119	Poor	123	Poor
SC	Trib. to LeSueur (ditch)	G5	G5	108	Fair	105	Fair
SC	Trib. To Champepadan	E5	E5	115	Poor	112	Poor
SE	Donaldson Creek	E5	E5	95	Fair	117	Poor
SE	Clear Creek	E4	E4	66	Good	102	Poor
SE	Duschee Creek	C3/C4	B3c	69	Good	62	Good
SE	Bear Creek	C5	C5	104	Fair	113	Poor
SE	Gorman Creek	G5	G5	106	Good	119	Poor

Table 5.7 shows the data sorted by bankfull channel width. The wider channels are grouped at the bottom of the table and overlay closely with the gray highlighted culvert sites that had no sediment in the recessed barrel.

Table 5.7. Stream stability sorted by increasing width at the culvert site locations. All dimensions are in feet.

Stream stability sorted by increasing width					
		Overall culvert width	Recessed culvert width	Bankfull channel width	Stream type U/S
SC	Trib. to Little Rock	20	10	8.7	E5
NE	Stanley Creek	20	10	9.2	E3/4
SE	Clear Creek	20	10	9.4	E4
SC	Trib. To Champepadan	42	14	10.4	E5
SE	Gorman Creek	24	12	10.7	G5
SE	Donaldson Creek	36	12	11.8	E5
NC	Unnamed at Rearing Pond Rd.	16	8	13.2	E5
NC	Stoney Brook	20	10	14.2	E4
SC	Trib. to LeSueur (ditch)	14	14	17.4	G5
NE	Kimball Creek	20	10	17.7	C3/4
NC	Splithand Creek	18	8.5	18.9	E5
NC	Bogus Brook	24	13	20	C4
NE	West Br. Knife River	12	12	22.6	C4
NC	Shingobee Creek	12	12	24.8	C4
SE	Duschee	36	12	26.4	C3/4
SE	Bear Creek	48	12	30	C5
NE	East Br. Beaver River U/S	20	10	38	B3
NE	East Br. Beaver River D/S	24	12	46.7	C4
SC	LeSueur Creek	24	12	48.8	C4

Chapter 6 Conclusions

The main goal of this research was to assess the hydraulic conditions related to the practice of recessing culverts and other fish passage design elements over a range of landscapes in Minnesota. A site selection process was used to identify culverts to conduct a field performance assessment relative to design criteria for facilitating fish passage over a range of different geographical conditions within Minnesota. A total of 19 sites were surveyed for assessment in the Northeast, North-central, South-central and Southeast regions of the state. These regions covered the major geographic conditions around the state and also represented areas of importance in terms of fish population.

One impact related to the practice of recessing culverts was the potential for head cut development due to the excavation of the stream bed below the flowline elevation. This potential for head cutting was recognized by the culvert design engineers as a potential problem and addressed in the design at all but two of the recessed study sites. At most study sites the rock protection consists of immobile rip-rap placed in the channel to serve as grade control and protect against the possibility of a head cut.

A culvert assessment methodology was developed based on similar studies conducted in other states. It consists of a description of each culvert's configuration, shape, dimensions and materials, channel and culvert bed materials, longitudinal profile through the culvert, bankfull channel dimensions, analysis of stream type and stability, velocity measurements in the channel and culvert, and general site description.

The main criterion used to determine if a culvert site designed using fish passage elements was functioning properly was the presence or absence of sediment in the recessed culvert barrel. If properly designed, the recessed barrel should accumulate sediments that increase roughness and reduce velocities through the culvert as compared to a clean barrel. A clean barrel suggests excess velocities that would also possibly prohibit aquatic organism passage. Burying or recessing culverts is not normally a standalone design but is one of the many methods employed when designing culverts to accommodate fish or aquatic organism passage. Other design elements analyzed in this study were culvert width compared to bankfull channel width, stream and culvert slope comparison, streambed and culvert bed particle size, and sediment accumulation in side barrels.

Thirteen of the 19 sites surveyed had a recessed culvert as part of the design. Based on the criterion mentioned above, six of the thirteen sites surveyed were not functioning properly due to lack of sediment in the recessed culvert barrel. A number of different factors were identified that could affect the sediment accumulation in a recessed culvert. Four of the scenarios – large flow event prior to the survey, culvert not in place long enough to accumulate sediment, culvert slope steeper than channel bed, and a lack of sediment transport or immobile bed – were ruled out as possible factors for the sites examined in this study. Improperly sized culvert width relative to channel bankfull width and side barrel sediment accumulation were identified as possible reasons for the lack of sediment accumulation in recessed barrels. At thirteen sites, the recessed culvert width is less than the bankfull channel width, including all six of the sites with no sediment in the recessed culvert. Eight of the sites have a total culvert width less than channel width. The result of the recessed culvert being undersized with respect to bankfull channel width is the creation of excess velocity through the recessed barrel, thereby changing the sediment transport with respect to stream conditions, possibly preventing sediment from accumulating in the barrel.

The reason why a larger culvert more closely matching channel bankfull width was not installed at these sites is unclear. It could be a lack of proper data, a lack of understanding of the how to identify bankfull width, or other design restrictions present at the site that prohibited the installation of a larger culvert.

One of the possible explanations for the insufficient culvert widths at these sites may be explained by looking at stream types. Of the 19 sites surveyed, seventeen sites are B, E or C channels, with C and E channels equally represented at eight sites each. The predominate bed materials ranged from sand to cobbles. These are very common stream types found in Minnesota. Seven of the eight C channels had no sediment accumulated in the main culvert barrel including five of the six recessed culverts with no sediment accumulation. A likely reason for this correlation is that C channels have a greater width to depth ratio than E channels (which made up eight of the 19 total sites) and that greater bankfull width is more difficult and expensive to match with the total culvert width for these types of channels.

The last design critierion that influences proper culvert function is the practice of offsetting multiple barrels. Sixteen of the 19 sites surveyed have more than one culvert barrel. The accessibility of the side barrels to higher flows was measured, and the depth of sediment accumulated in the side barrels was compared to the bankfull stage of the channel. Seven of the sixteen sites with multiple barrels have sediment accumulated in side barrels at a depth greater than the bankfull channel stage.

The conclusion of comparing these culvert and channel parameters suggests the combination of insufficient width (compared to channel bankfull width) and limited access to side barrels could be enough to raise velocities through the recessed barrel high enough to limit the ability of sediment to accumulate or aquatic organisms to pass. These observations suggest that improvements can be made in the design methods for Minnesota's fish passage culverts. The problem was most prevalent on wider channels suggesting it is more difficult to match natural stream conditions through a culvert on wider channels. Possible solutions to this problem would be:

- A better understanding of stream and site data collection needs prior to culvert design to ensure the design more closely matches the stream channel
- An improved procedure for placing sediment or anchoring it to the culvert bottom to protect against excess velocities washing sediment out of the culvert
- A different or improved culvert design methodology that deals better with challenges of wider channels and floodplains commonly found in Minnesota.

References

[1] K. B. Bates, B. Barnard, J. P. Heiner, P. D. Klavas, *Design of Road Culverts for Fish Passage,* Washington Department of Fish and Wildlife, Olympia, WA, 2003. Available at: http://wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf. Accessed 12/17/2007.

[2] R. S. Hotchkiss, C. M. Frei, *Design for Fish Passage at Roadway Stream Crossings: Synthesis Report,* U.S Department of Transportation, Federal Highway Administration, Office of Highway Infrastructure and Research, FHWA-HIM-07-033, Washington, D.C., 2007.

[3] B. H. Hansen, J. L. Nieber, C. Lenhart, *Cost Analysis of Alternative Culvert Installation Practices in Minnesota,* University of Minnesota, Minneapolis, MN, 2009.

[4] K. B. Bates, B. Barnard, J. P. Heiner, P. D. Klavas, *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, Olympia, WA, 1999.

[5] Vermont Department of Fish and Wildlife, *Vermont Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms,* Waterbury, VT, 2007.

[6] Maryland State Highway Administration, "Chapter 13: Culverts," *Guidelines for the Selection and Design of Culvert Installations*, Draft, Office of Bridge Development Manual for Hydrologic and Hydraulic Design, Baltimore, MD, 2006.

[7] K. A. Clarkin, A. Conner, M. Furniss, B. Gubernick, M. Love, K. Moynan, S. Wilson-Musser, *National Inventory and Assessment Procedure for Identifying Barriers to Aquatic Organism Passage at Road-stream Crossings*, U.S. Department of Agriculture Forest Service, National Technology and Development Program, San Dimas, CA, 2005.

[8] A. E. Beavers, R. H. Hotchkiss, M. C. Belk, *Fish Passage at UDOT Culverts: Prioritization and Assessment*, Utah Department of Transportation Research and Innovation Division, Salt Lake City, UT, 2008.

[9] Inter-Fluve, Inc., *Culvert Scour Assessment*, 0877-1812-SDTDC, US Forest Service, San Dimas Technology and Development Center, San Dimas, CA, 2009.

[10] B. Barnard, *Evaluation of the Stream Simulation Culvert Design Method in Western Washington, a preliminary study – Draft,* Washington Department of Fish and Wildlife, Olympia, WA, 2003.

[11] D. Heller, "A Strategic Approach for the Identification and Correction of Fish Passage on National Forest Lands for the Pacific Northwest," *Proceedings of the International Conference on Ecology and Transportation*, Little Rock, AR, 2007.

[12] MDNR, *Sustainable Soil and Water Quality Practices on Forest Land*, Michigan Department of Natural Resources, Michigan Department of Environmental Quality, Lansing, MI, 2007.

[13] M. Diebel, M. Fedora, S. Cogswel, "Prioritizing Road Crossing Improvement to Restore Stream Connectivity for Stream-Resident Fish." *Proceedings of the 2009 International Conference on Ecology and Transportation,* Center for Transportation and the Environment, North Carolina State University, Raleigh, NC, 2010, pp. 647 – 660. Available online: http://www.icoet.net/ICOET_2009/downloads/proceedings/ICOET09-Proceedings-Session411.pdf. Accessed 6/2009.

[14] C. C. Harrelson, J. P. Potyondy, C. L. Rawlins, *Stream Channel Reference Sites: An Illustrated Guide to Field Technique,* General Technical Report RM-245, U.S. Department of Agriculture, Forest Service, Fort Collins, CO, 1994.

[15] D. L. Rosgen, *Applied River Morphology,* Wildland Hydrology, Pagosa Springs, CO, 1996.

[16] D. J. Pfankuch, *Stream reach inventory and channel stability evaluation,* USDA Forest Service Northern Region, Montana, R1-75-002, Govt. Printing Office, # 696-260/200, Washington, D.C., 1975.

[17] D. Mecklenburg, *The Reference Reach Spreadsheet,* Software Version 2.1, Ohio Department of Natural Resources, Columbus, OH, 1999.

[18] Stream Simulation Working Group, S*tream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings*, U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. Washington, D.C., 2008.

[19] D. L. Rosgen, "A Stream Channel Stability Assessment Methodology," *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Vol. 2, pp. II - 18-26, March 25-29, Reno, NV, 2001.

Appendix A Task 1: Literature Review

Introduction

The research objectives of this project are to:

1. Understand the hydraulics of buried oversized culverts and the possible impacts they have on fish passage and adjoining steam characteristics.
2. Develop a methodology to assess the performance of oversized culverts with respect to fish passage.
3. Assess the effectiveness of oversized culverts in allowing fish passage over a range of different geographical conditions within Minnesota, accounting for variability in stream geomorphic conditions.
4. Identify the morphologic and hydraulic conditions introduced by over-sized culverts that may negatively affect fish passage.

In order to understand the practice of installing oversized culverts with respect to objective number one listed above, a review of the current literature was conducted. Because fish attract as much attention as they do with respect to the economics and the food and recreation industries, a great deal of concern and the bulk of the public academic and government literature on the topic of culvert stability focuses on the passage of fish. MnDOT has been in the practice of installing recessed culverts in Minnesota for many years in order to provide culvert stability and continuity of the stream ecosystem and morphology, and the relatively recent interest in fish passage provides a more thorough body of literature with which to analyze this practice.

Fish Passage Issues at Culverts

Most of the research that has been done on fish passage through culverts has focused on salmon and trout in the Western United States. Most of the designs can be modified to fit the different topography and fish species found in Minnesota. The abundance of research in the West makes it a good starting point and adaptation of principles and methods can be made when these differences are taken into consideration.

Fish passage techniques were originally developed on the west and east coast of the United States to allow salmonids (salmon and trout species) passage around large dams. Fish passage in coastal areas of the US focused on *anadromous* fish, i.e. species that migrate between the ocean and freshwater rivers. More recently, it has been recognized that many fish species migrate on seasonal and daily timescales. This includes eels and lampreys, which migrate in reverse from rivers to oceans, and freshwater fish which migrate seasonally or daily for feeding, shelter, and spawning. Therefore, fish passage efforts have spread to include all *diadromous* fish (a broader category of fish migration). With this change, the literature is now beginning to turn its focus to inland areas, and our intent is to focus this topic on Midwestern streams and in particular, Minnesota streams.

Road culverts have a variety of impacts on fish habitat and obstruction to movement as described by Bates et al. (2003) in the Washington Fish & Wildlife Department’s guide to fish passage at culverts. Bates et al. describe the following seven major categories of impacts:

1. Direct habitat loss by eliminating areas of channel habitat in the immediate culvert area. Road expansion or installation of new, larger culverts results in direct loss of stream habitat.
2. Water quality degradation as a result of road crossings creating an entry point for road-runoff pollutants. Some culverts are coated with asphalt to prevent degradation. In agricultural settings, road culverts are often the entry point for road-side ditches and subsurface tile drainage outlets.
3. Upstream and downstream channel impacts caused by scour, aggradation and associated habitat impacts.
4. Ecological connectivity may be reduced by blocking access to upstream or downstream stream segments for fish and other aquatic organisms.
5. Channel maintenance costs may be increased by inducing aggradation at oversized or under-sloped road crossings. Dredging of channel is often required at road crossings and is very damaging to stream habitat.
6. Construction impacts include possible release of sediment or pollutants, temporary fish passage barrier during construction, removal of streambank vegetation, impeding flow or stranding fish above or below the culvert. Most impacts are short term but slugs of sediment could persist in streams for months or years.
7. Risk of culvert failure although infrequent, culvert collapse can cause ecological damage, flooding and/or road maintenance problems. Safety concerns must be addressed in all culvert projects.

Culverts may block fish passage in a variety of ways. The Washington state manual describes five ways in which fish passage is blocked (Bates et al., 2003):

- Excess drop at the culvert outlet
- High velocity within the culvert barrel
- Inadequate depth within the culvert barrel
- Turbulence within the culvert
- Debris and sediment accumulation at the culvert inlet or internally

Another common cause of blockage is excessive length of culvert without sufficient resting area for fish.

Most work has focused on fixing excess velocity and outlet drop issues. However inadequate water depth and sediment accumulation are frequent problems, especially in low gradient streams commonly found in the Upper Midwest.

This document includes an annotated bibliography of the current and relevant literature that will be beneficial to understanding and assessing the function of recessed culverts in various environments present in the state of Minnesota, followed by a synthesis document that summarizes the findings of this literature. Finally a complete bibliography is included in the appendix.

Annotated Bibliography

Because the landscape, local environment, and fish species play such an important roll in the assessment of fish passage through culverts, the following reviewed documents have been organized by geographic area.

Pacific Northwest

Barnard, B. Stream Simulation Culverts: Culvert Sizing. Washington Department of Fish and Wildlife.

- Washington
- This design exercise to size culverts focuses on high-sloped gravel bedded rivers. This short cartoon-narrated guide details the theory and equations behind the "stream simulation" method. The clear and efficient guide is a useful introduction to the method.

Barnard, B. 2003. Evaluation of the Stream Simulation Culvert Design Method in Western Washington, a preliminary study - Draft. Washington Department of Fish and Wildlife. August 2003.

- Washington
- **Abstract:** More than 50 stream simulation culverts have been constructed in Washington State since 1995. This paper summarizes monitoring conducted on 19 of these culverts in various settings. The monitoring goal was to compare the physical characteristics of the adjoining upstream channel with those of the culvert bed. The premise of stream simulation design is that similar physical characteristics imply similar passage conditions. Field parameters included channel geometry (channel width, slope and cross section, pool spacing, and residual pool depth) and sediment size distribution. Mathematical modeling using field data compared culvert and channel hydraulic performance including inlet contraction and depth distribution (quantification of shallow water habitat). Standard statistical tests were used to evaluate individual parameters, unfortunately the sample size was too small to perform multivariate analysis. Results show that when designed and constructed according to stream simulation design criteria (Culvert bed width = 1.2(Channel width)+2 feet, and slope of culvert < 1.25(Channel slope)), stream simulation culverts are reliable and create similar passage conditions compared to the adjoining channel.
- This paper details monitoring efforts on 19 stream simulation culverts installed with goals of improving fish passage. The unique value in this paper comes from the scarcity of such monitoring efforts. A main emphasis is that healthy ecosystems depend on the dynamic nature of natural channels. The document carefully details the methods of data collection and compares width, slope, velocity, and top width ratios. Importance is placed on analysis of the stream channel characteristics and not fish passability. The equations used for designing stream simulation culverts are given and explained and the monitoring involves comparison to these original morphology goals. Interesting feedbacks are identified among channel parameters.

Bates, K., B. Barnard, B. Heiner, J. P. Klavas, P. D. Powers. 2003. Design of Road Culverts for Fish Passage. Washington Department of Fish and Wildlife. Available at: http://wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf

- Washington
- **Abstract (Preface):** The overwhelming majority of Washington's fish and wildlife species depend on aquatic and riparian ecosystems for all or part of their life cycle. This rich and diverse fauna, and the flora on which they depend are irreplaceable elements of Washington's natural resources and are the basis for much of the state's cultural heritage, economy and quality of life. Unfortunately, in our enthusiasm for enjoying and developing land surrounding these aquatic habitats, we have destroyed, degraded and fragmented many of our most precious marine, freshwater and riparian ecosystems. Over time, these adverse impacts have resulted in the federal listing of many marine, freshwater and riparian animal species as "endangered" or "threatened" under the federal Endangered Species Act, and the state of Washington's wildlife protection legislation. Of particular note is the listing of several salmon species under the ESA. In 1999, Governor Gary Locke and several Washington State agencies adopted a statewide strategy to protect and restore salmon habitat in the state. At the heart of the strategy is the hands-on involvement of landowners and other individuals. Incentives and technical assistance in salmon protection/recovery initiatives are included in the strategy to encourage such participation. In the 1999-2001 biennium, Washington State distributed nearly $50 million to more than 300 salmon protection/recovery projects sponsored by local governments, watershed groups, County Conservation Districts, Regional Fisheries Enhancement Groups, volunteer groups and individuals. For such involvement to be effective, there is an urgent need for increased technical guidance to ensure that these local efforts are strategic in approach, address the source of a problem and not just the symptoms, make the best use of limited funds and are based on the best available science that can be consistently and effectively applied across the landscape. The Aquatic Habitat Guidelines program is designed to help provide this technical assistance.

BC Ministry of Transportation and Highways. 2000. Culverts and Fish Passage Fact Sheet. October. Environment Management Section, Engineering branch. Available at: http://www.th.gov.bc.ca. Accessed January 14, 2010.

- British Columbia
- This quick reference guide gives a short introduction to the common causes of fish blockage and references design criteria including hard numbers that could not possibly apply to all stream systems. It suggests an outlet pool with tailwater control be located at the end of the culvert to ensure passage into the structure. It also details the importance of replacing/filling the disturbed areas around and inside of the culvert. Overall, it is a good general guide for non engineers/scientists.

Castro, J. 2003. Geomorphic Impacts of Culvert Replacement and Removal: Avoiding Channel Incision. US Fish and Wildlife Service, Oregon Fish and Wildlife Office, Portland, OR.

- Pacific Northwest
- **Abstract:** This technical note describes a specific methodology for determining the vertical stability of stream channels in the vicinity of existing road crossings (primarily

culverts), although the methodology is applicable along any reach of a stream. Vertical stability refers to the relative constancy over time of streambed elevation through a given stream reach. A streambed that deepens over time is referred to as “incising,” while a rising bed elevation is indicative of an “aggrading” stream channel. Streams that are incising or aggrading on a reach scale are considered to be vertically unstable. However, local variations in bed elevation are inherent in streams because of scour and fill processes, and should not be confused with vertically unstable channels. Vertical stability is of considerable interest at culverts because these structures often provide elevational control for incising stream channels. Provision of elevational control or “grade control” is important because removal of this control may allow channel incision to migrate upstream, potentially affecting habitat and impeding fish passage. Of primary concern to the U.S. Fish and Wildlife Service (Service), and hence the subject of this paper, are culvert removal or replacement projects in vertically unstable streams. Activities associated with these streams can lead to additional channel incision with a resultant loss of habitat and potential fish passage blockage. Changes to the channel profile post-project are collectively referred to as channel “regrade.”

Forest Service Stream-Simulation Working Group. 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings. 0877-1801—SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 515 p.

- Pacific Northwest
- **Abstract:** This document was produced by the USFS in response to the estimated 6,250 road crossing on forested lands in the Pacific Northwest. About 90 percent of these road crossings were estimated to pose some sort of barrier to fish passage. Ecological considerations for crossing design are discussed and explanations are given as to why aquatic species need to move, what they require to be able to move, and what the consequences of barriers to individuals, populations, and communities are. A brief overview of the planning, design, construction, and monitoring practices that can solve road-stream crossing barrier problems, including best management practices are provided. This overview is intended for land managers who participate in setting project objectives and making policy decisions that affect crossing projects. The next six chapters describe the steps or phases of a stream-simulation design project. The process is applicable to new and replacement crossings, and to crossing removals. The focus is on forest roads; however, the concepts and general approach are applicable to crossings on other parts of the transportation system such as trails, highways, and railroads. Chapters 3 through 8 are addressed to members of multidisciplinary project teams responsible for the assessment, design, and construction of road-stream crossings. Readers who are unfamiliar with stream morphology and processes can refer to appendix A for a brief introduction to geomorphic terms and concepts used throughout the assessment and design process.

Heller, David. 2007. A Strategic Approach for the Identification and Correction of Fish Passage on National Forest Lands for the Pacific Northwest. Chapter 4, ICOET Proceedings.

- Oregon and Washington

- **Abstract:** A multi-year, cooperative program for the identification, prioritization and correction of fish passage at road- stream crossings (more than 4,000 sites on a land base of 24 million acres) sites has been developed and is being implemented over the last five years. A comprehensive assessment of fish passage, at road-stream crossings, was completed for all 17 of the National Forests in the states of Oregon and Washington. The assessment took 3 years to plan and complete. More than 5,100 crossings, representing 82% of all crossings on fish bearing streams, were evaluated in the field. Initial determinations were made to identify which crossings would pass all species and life stages of fish found in the respective streams. Juvenile coho salmon were used as the target species for evaluation and a matrix integrating a variety of crossing characteristics including crossing type, crossing structure gradient, outlet drop height, a ratio of crossing structure width to bankfull width, etc. was utilized to categorize sites into three categories (passable, not passable and need further investigation). Results indicate that 68% of all road-stream crossings. (bridges included) impair, to some degree, upstream passage for at least one species/life stage of fish. Considering only culvert crossing structures, about 90% are impassable. It is estimated that more than 3,000 miles of habitat for fish is affected. This represents about 15% of the total miles of fish bearing streams on National Forest System lands of the Pacific Northwest Region. The assessment has provided the foundation for a more systematic and strategic approach to improve fish passage as part of the Regional Aquatic Restoration Program. A cooperative process to prioritize river basins and treatment sites is being used to guide selection of sites for remediation. Regional design standards have been established for replacement crossings and 2 design assistance teams have been created to improve the effectiveness and cost efficiency of new structures. More than 250 sites have been treated over the last 5 years. Increasingly, cooperative funding is being used to increase the number of sites being treated. A basic protocol for monitoring post treatment effectiveness is currently being revised to provide more quantitative results for post project monitoring. Additional research on the biological response of aquatic organisms, including non game and juvenile fish, during a full range of flows, is needed.
- An identification and prioritization system was developed for road crossing improvements within seventeen forests in the Pacific Northwest. Juvenile coho was the defined target species and results were organized in three categories: passable, not passable, and need more information. The results showed that 68% of all structures (including bridges) impair upstream passage and 90% of culverts impair. A startling finding is that 15% of the total length of fish bearing streams is affected. After the sites were identified, 250 sites have been reconstructed in the last five years. The protocol for monitoring is being revised to present quantitative results.

Love, M. 2007. Corner Baffle Design Exercise: Fish Passage Retrofit and Culvert Rehabilitation Highway 128 at John Hatt Creek. Course exercise.

- California
- This is a design exercise for retrofitting steep pipe culverts with corner baffles to help lower velocities specifically for steelhead trout. The document gives a great deal of information specific to this stream and fish species, but is not incredibly applicable to other settings. It would be a good design exercise for a stream restoration course.

Ministry of the Environment. 2007. Canimred Tributary Weir Construction 535 Road. Ministry of Water, Land and Air Protection. British Columbia, Canada: Government of British Columbia. Available at: http://www.env.gov.bc.ca. Accessed.

- British Columbia
- This one-page project summary details the installation of weirs downstream of an elevated culvert in order to raise water level below the culvert and minimize the drop.

Washington Department of Fish and Wildlife. 1999. Fish Passage Design at Road Culverts: A design manual for fish passage at road crossings. Habitat and Lands Program, Environmental Engineering Division.

- Washington
- This comprehensive design manual is similar to others presented here. It describes the processes by which fish passage is blocked and details several designs that can be installed to improve passage depending on the specifics of the road crossing.

West Central U.S.

Beavers, A.E., Hotchkiss, R.H., and Belk, M.C. (2008) Fish Passage at UDOT Culverts: Prioritization and Assessment, Utah Department of Transportation Research and Innovation Division, Salt Lake City, Utah.

- Utah
- **Abstract:** State Departments of Transportation are becoming more involved in providing Aquatic Organism Passage (AOP) at road-stream crossings. Department of Transportation (DOT) emphasis on AOP has been driven largely in response to endangered species listings, other agencies' initiatives, and the desire to restore ecosystem connectivity to watercourses. UDOT is currently responsible for approximately 47,000 culverts, but AOP is currently addressed only on an as-needed basis. Currently UDOT has no prioritization or assessment strategy procedure for AOP at UDOT road-stream crossings. Historical fish passage strategies have focused on federally listed adult anadromous salmon and trout. These are generally very large fish whose life cycle includes both fresh and salt water environs. These species have adapted to the wetter conditions prevalent in their Pacific Northwest habitat. However, Utah fish species have adapted to the arid conditions of the Great Basin, are generally much smaller, and complete their life cycle entirely within fresh water. For UDOT these differences represent a potential fundamental divergence in the approaches used for providing fish passage in Utah vs. those historically used in the Pacific Northwest. The purpose of this research was to develop a method of prioritizing culverts statewide and to modify existing culvert assessment procedures for UDOT within a Great Basin/Utah regional context. Developed as part of the research are tools to prioritize and assess culverts. A GIS database was developed to store fish passage assessment data as well as provide functions for prioritizing culverts on the state and regional level. A fish passage assessment protocol for assessing UDOT culverts was developed based on existing fish passage assessments. The culvert assessment was tailored to meet developed UDOT fish passage strategies. A training manual was also created to aid technicians on performing the several physical culvert assessments developed. Additionally, a mark and recapture

study at six UDOT culverts was performed to field verify the developed culvert assessment procedure. A step by step methodology was then created to establish critical progression for prioritizing and assessing culverts for fish passage utilizing project results.

- The purpose of this research was to develop a method of prioritizing culverts statewide and to modify existing culvert assessment procedures for UDOT within a Great Basin/Utah regional context. As part of the research, tools are developed to prioritize and assess culverts. A GIS database was developed to store fish passage assessment data as well as provide functions to aid in prioritizing culverts on a state and regional level. A fish passage assessment protocol for assessing UDOT culverts was developed based on existing fish passage assessments. The culvert assessment was tailored to meet developed UDOT fish passage strategies. A training manual was also created to aid technicians on performing the several physical culvert assessments developed. Additionally, a mark and recapture study at six UDOT culverts was performed to field verify the developed culvert assessment procedure A step by step methodology was then created to establish critical progression for prioritizing and assessing culverts for fish passage utilizing project results.

Northern U.S.

Hendrickson, S., Walker, K., Jacobson, S., Bower, F. 2008. Assessment of Aquatic Organism Passage at Road/Stream Crossings for the Northern Region of the USDA Forest Service.

- Montana, Northern Idaho, Eastern North Dakota, Eastern South Dakota
- **Abstract (Executive Summary):** The Northern Region of the USDA Forest Service completed a comprehensive survey and assessment of fish passage at road- stream crossings. The surveys were done over 3 years at a cost of $270 per site. Approximately 2900 culverts were surveyed on 50,000 miles of Forest Development Roads in Montana, northern Idaho and eastern North and South Dakota. Those surveys were assessed based on passage of adult and juvenile westslope and yellowstone cutthroat trout. Findings indicate that approximately 80% of the surveyed culverts impede passage of cutthroat at some life stage or during certain flows. Of those barriers, 576 culverts impede all fish passage and represent total barriers, thus isolating fish populations. These barriers represent a significant issue for fragmentation and viability of cutthroat populations in the Region. This assessment provides the Region with a tool to build a strategic program to improve aquatic organism passage across the Northern Region.
- This document summarizes an investigation into fish passage at crossings that was initiated due to declining numbers of bull trout, steelhead trout, Chinook salmon, westslope cutthroat trout and Yellowstone cutthroat trout in an area classified as the inter-mountain west. Included is a brief explanation of the reasons for fish passage problems and the effects on the ecosystem. The assessment aims to provide a comprehensive and broad-scale look at the barriers in this region and organizes the crossings surveyed into four categories—total barrier, partial barrier, indeterminate, and no barrier. Of 2900 culverts surveyed, 80% were considered barriers, 13% were indeterminate, and 7% allowed for free passage of the target species. In addition, 93% of culverts were found to

constrict channels to some degree and 50% constricted channels to a ratio of 0.5 or less. The "stream simulation" design was recommended to address these crossings.

Eastern U.S.

Chapter 13: Culverts. In *Guidelines for the Selection and Design of Culvert Installations*. Draft, 2006. Office of Bridge Development Manual for Hydrologic and Hydraulic Design.

- Maryland
- This chapter is a thorough guide for installing culverts based on the Rosgen Stream Classification System. The document aims to minimize the effect of culverts on the stream, and its floodplain, wetlands, and associated habitat. The culverts are to be sized according to bankfull stream widths and placed to avoid deposition or scouring of material, and it is pointed out that a culvert should be depressed a minimum of twenty percent below the existing channel bed when fish passage is a concern. The document addresses the occurrence of upstream migrating knickpoints and how they may affect the culvert placement. The document recommends riprapped outlet basins at the downstream end of a culvert; a basin that will dissipate energy and facilitate fish passage into the barrel. The basins include a grade control structure on the downstream end to maintain a pool elevation that allows fish to enter the culvert, but the structure needs a means of fish passage itself. Culverts designed differently for pool/riffle crossings.

Jackson, S., Bowden, A., and Graber, B. 2007. Protecting and Enhancing River and Stream Continuity. Chapter 4, ICOET Proceedings.

- Massachusetts
- A comparison is made between roads and streams as long linear systems that intersect one another 35,000 times in Massachusetts. When most of the culvert infrastructure was installed, the only purpose was to move water across the road. Now the River and Stream Continuity Partnership is working on the project of the same name to develop Massachusetts River and Stream Crossing Standards with the help of a team of volunteers who assess the crossings. A database has been created in which all data collected has been geo-referenced and the crossings are prioritized with A, B, or C ratings.

Vermont Department of Fish and Wildlife. 2007. Vermont Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms.

- Vermont
- **Abstract (Preface):** Stream crossings by transportation systems have had a profound influence on the movement and distribution of populations of aquatic species in Vermont. These impacts range from exclusion of species from tributaries of the White River and Connecticut River associated with the development of railroads and the interstate highway system, to highly fragmented habitats associated with town and private road development adjacent to stream networks. Vermont's Wildlife Action Plan (Vermont Department of Fish and Wildlife, 2005) identifies a large number of aquatic species threatened by such habitat fragmentation including 15 "species of greatest conservation need." The Vermont Department of Fish and Wildlife (VDFW) and the Vermont

Transportation Agency (VTrans) have formally recognized this threat in a 2005 Memorandum of Agreement. The agencies developed a common goal "*to improve accommodation of wildlife and aquatic organism movement around and through transportation systems and to minimize habitat fragmentation resulting from the presence of transportation infrastructure*". The *Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organism in Vermont* was developed by VDFW in collaboration with the Vermont Department of Environmental Conservation and VTrans as a major step toward meeting this goal. The contents of this guideline are based upon current knowledge of aquatic biology, fluvial geomorphology, hydrology and engineering and required the assistance of many experts in these areas of study. This document is presented with the intent of fostering improved design, installation, and maintenance of stream crossing structures to provide aquatic organism passage (AOP), aquatic habitat connectivity, and fluvial geomorphic functions in Vermont streams and rivers.

- This extremely thorough document provides technical guidance for design of road crossings that have been identified as challenges to fish passage as well as detailed theory on how the methods work and why they are so important to the system. The emphasis is placed on connectivity, explaining that fish can be healthy if the ecosystem is connected and processes and materials move through the system. The document details many ways that culverts disturb the natural connectivity and damage is done by undersized culverts. A three-phase design process is described: pre-design, fish passage design, and final design. A section on 'fixing' channel incision is presented, examining whether or not returning the channel to its original slope is always the best option because of possible damage to the ecosystem. Three culvert options are emphasized and detailed in the document: the "Vermont" low slope option, the stream simulation option, and the hydraulic option. Finally, in the conclusion of the document, the importance of design documentation is emphasized in order to evaluate outcomes and monitor the project.

South Eastern U.S.

Gardner, A. N. 2006. Fish Passage Through Road Culverts. MS Thesis. Raleigh, NC: North Carolina State University, Department of Biological and Agricultural Engineering.

- North Carolina
- **Abstract:** The North Carolina Department of Transportation (NCDOT) has regulations requiring road crossings to facilitate Aquatic Organism Passage (AOP). Due to a current inability to prove that AOP will not be inhibited, acquiring permits for the design and construction of culverts has become difficult. Often, bridges costing up to three times as much must be built in their place. To improve the design of culverts and the feasibility of obtaining a permit, this study determined the maximum swimming speed that can be sustained by a fish for a period of ten minutes. This speed, known as the critical velocity, is equivalent to traversing a 100m culvert. The critical velocities were determined for the following fish species native to the piedmont of North Carolina: Nocomis leptocephalus, Lepomis auritus, Etheostoma nigrum, Lepomis macrochirus, Noturus insignis, Notropisprocne. The fish were collected by electrofishing from local streams. After resting for 12 to 18 hours the fish were placed in a flume and allowed to accommodate at a resting velocity of 20cm/s. The velocity was then increased by 10cm/s every ten

minutes, while returning to the resting velocity for five minutes between each step. The critical velocities for each species were 85.56cm/s, 43.89cm/s, 67.76cm/s, 37.05cm/s, 48.67cm/s, 61.42cm/s respectively. Based on the data collected in this experiment, it is recommended that the maximum velocity in a culvert be kept under 55cm/s for 90% of the fish migration period. A Microsoft Excel model was created based on the results. The model uses the critical velocities as guidelines for maximum flow rates in the hydrologic design of culverts. Using the model in addition to other hydrologic design models can aid in the design of culverts that do not impede fish passage.

- Design guidelines in North Carolina state that you must prove the Aquatic Organism Passage (AOP) will not be impaired by a stream crossing installation. Because this is difficult to prove, many times bridges are installed at up to three times the cost. This group performed a fairly detailed study of the recommendations nationwide and then proceeded to conduct flume experiments to determine the maximum swimming velocity of multiple species of fish and created a model whose findings help define recommendations for culvert design.

Hanson, G. J. and A. Simon. 2001. Erodibility of Cohesive Streambeds in the Loess Area of the Midwestern USA. *Hydrological Processes* 15(1): 23-38. Stillwater, OK: John Wiley and Sons.

- Mississippi
- **Abstract:** Excess stress parameters, critical shear stress (tau_c) and erodibility coefficient (kd), for degrading channels in the loess areas of the Midwestern USA are presented based on *in situ* jet-testing measurements. Critical shear stress and kd are used to define the erosion resistance of the streambed. The jet-testing apparatus applies hydraulic stresses to the bed and the resulting scour due to the impinging jet is related to the excess stress parameters. Streams tested were primarily silt-bedded in texture with low densities, which is typical of loess soils. Results indicate that there is a wide variation in the erosion resistance of streambeds, spanning six orders of magnitude for _c and four orders of magnitude for kd. Erosion resistance was observed to vary within a streambed, from streambed to streambed, and from region to region. An example of the diversity of materials within a river system is the Yalobusha River Basin in Mississippi.

The median value of tau_c for the two primary bed materials, Naheola and Porters Creek Clay Formations, was 1_31 and 256 Pa, respectively. Streambeds composed of the Naheola Formation are readily eroded over the entire range of shear stresses, whereas only the deepest flows generate boundary stresses great enough to erode streambeds composed of the Porters Creek Clay Formation. Therefore, assessing material resistance and location is essential in classifying and modelling streambed erosion processes of these streams.

- This document discusses the erodability of loess soils of the Midwest based on tests performed with a jet-testing apparatus. This guide can be useful to understand the behavior of the substrate for stream restoration in areas with this type of soil, but the document itself does not discuss culvert installation or ecosystems in this environment.

Warren, M.L., and Pardew, M.G. 1998. Road Crossings as Barriers to Small-Stream Fish Movement. Transactions of the American Fisheries Society 127:637-644.

- Arkansas

- **Abstract:** We used mark-recapture techniques to examine the effects of four types of road crossings on fish movement during spring base flows and summer low flows in small streams of the Ouachita Mountains, west-central Arkansas. We assessed movement for 21 fish species in seven families through culvert, slab, open-box, and ford crossings and through natural reaches. We detected no seasonal or directional bias in fish movement through any crossing type or the natural reaches. Overall fish movement was an order of magnitude lower through culverts than through other crossings or natural reaches, except no movement was detected through the slab crossing. In contrast, open-box and ford crossings showed little difference from natural reaches in overall movement of fishes. Numbers of species that traversed crossings and movement within three of four dominant fish families (Centrarchidae, Cyprinidae, and Fundulidae) also were reduced at culverts relative to ford and open-box crossings and natural reaches. In spring, retention of fishes was consistently highest in stream segments upstream of crossings and lowest in downstream segments for all crossing types, a response attributed to scouring associated with spring spates. Water velocity at crossings was inversely related to fish movement; culvert crossings consistently had the highest velocities and open-box crossings had the lowest. A key requirement for improving road crossing designs for small-stream fish passage will be determination of critical levels of water velocity through crossings.
- Fish movement is critical for its need to disperse for reasons of spawning, access to prey, and avoidance of predators. This movement was found to be an order of order of magnitude lower through culverts as compared to bridges in the Ouachita Mountains of Arkansas. A connection was made that the degree to which a crossing acted as a barrier was directly related to the degree of alteration of the flow.

Upper Midwest

Ashland National Fish and Wildlife Conservation Office. 2009. Planning, Design, and Construction of Fish Friendly Stream Crossings. US Fish and Wildlife Service. Webpage at: http://www.fws.gov/midwest/Fisheries/streamcrossings/index.htm

- Nationwide, program headquartered in Midwest
- The website's intent is to provide tools needed to design and execute a fish passage culvert but reminds readers to check with federal, state, and local policymakers to comply with permitting and construction regulations. This document emphasizes that not all barriers are bad; some keep out exotic species, disease, genetic mutations, and prevent channel incision. They recommend the "stream simulation" design method and detail steps of design and installation including stabilization of site soils.

Freiburger, Chris and Fulcher, Jerry. Culvert Sizing and Installation Stream Simulation. Power point presentation.

- Michigan
- This presentation offers a nice introduction to fish passage issues and gives some statistics from highly studied areas. The focus is then brought to Michigan streams and what applies there morphologically and bureaucratically. The MESBOAC concept is introduced and the discussion of the importance of bankfull flows follows.

Muste, M., Ettema, R., Ho, H-C., and Miyawaki, S. 2009. Development of Self-Cleaning Box Culvert Designs. Iowa Highway Research Board Report IHRB-TR-545.

- Iowa
- **Abstract (Summary):** The main function of a roadway culvert is to effectively convey drainage flow during normal and extreme hydrologic conditions. This function is often impaired due to the sedimentation blockage of the culvert. This research sought to understand the mechanics of sedimentation process at multi-box culverts, and develop self-cleaning systems that flush out sediment deposits using the power of drainage flows. The research entailed field observations, laboratory experiments, and numerical simulations. The specific role of each of these investigative tools is summarized below:

  a) The field observations were aimed at understanding typical sedimentation patterns and their dependence on culvert geometry and hydrodynamic conditions during normal and extreme hydrologic events.
  b) The laboratory experiments were used for modeling sedimentation process observed in situ and for testing alternative self-cleaning concepts applied to culverts. The major tasks for the initial laboratory model study were to accurately replicate the culvert performance curves and the dynamics of sedimentation process, and to provide benchmark data for numerical simulation validation.
  c) The numerical simulations enhanced the understanding of the sedimentation processes and aided in testing flow cases complementary to those conducted in the model reducing the number of (more expensive) tests to be conducted in the laboratory.

  Using the findings acquired from the laboratory and simulation works, self-cleaning culvert concepts were developed and tested for a range of flow conditions. The screening of the alternative concepts was made through experimental studies in a 1:20 scale model guided by numerical simulations. To ensure the designs are effective, performance studies were finally conducted in a 1:20 hydraulic model using the most promising design alternatives to make sure that the proposed systems operate satisfactory under closer to natural scale conditions.
- The research group is looking into the silting up of multiple barrel box-culverts during periods of low flow. The stream will concentrate its flow in one of the barrels during these periods and to maintain the low flow width and depth. The remaining barrels tend to fill with silt and grow vegetation. The concern is that the silt deposits will reduce conveyance capacity when the 50-year flood comes. A small modification to the inlet geometry has provided a means of keeping the bottoms of the box-culverts clean while maintaining the majority of the low flow focused through the main culvert. This research has a dissimilar focus from the fish passage issues that we focus on here.

Patronski, Tim, et al. 2008. Fish Passage and Stream Barrier Management in the Bad River Watershed in Northern Wisconsin. SDM Workshop December 8-12, 2008.

- Northern Wisconsin
- **Abstract (Decision Problem):** The U.S. Fish and Wildlife Service's (Service) Fish and Wildlife Conservation Office in Ashland, Wisconsin (Ashland FWCO) works with local partners to restore habitat for fish and other aquatic species within the Bad River Watershed (BRW) in northern Wisconsin. There are over 1,100 perched culverts within

the watershed and many of these are barriers to fish passage (Bad River Watershed Association 2007). The Service's restoration work in the BRW is conducted under the authority of the Great Lakes Fish and Wildlife Restoration Act (as well as other enabling federal legislation and policies) and is consistent with the culvert inventory and remediation component of the Bad River Watershed Association's Strategic Plan (Bad River Watershed Association 2008).

In general, the removal or modification of barriers to allow for fish passage has beneficial impacts to the watershed (e.g., improving connectivity, restoring hydrology, and increasing spawning access for fish). However, in certain cases, it may also be detrimental to ecosystem health (e.g., opening habitat for invasive species such as sea lamprey (*Petromyzon marinus*) and allowing passage of migratory fish with elevated contaminant levels that may subsequently impact piscivorous wildlife such as bald eagles (*Haliaeetus leucocephalus*)). In collaboration with local partners, the Ashland FWCO decides how to best manage barriers and restore fish passage within the BRW. Management options include: barrier removal, barrier replacement, barrier modification, and barrier construction. Funding proposals for barrier management activities are developed annually within the context of a ten year planning period for managing barriers within the watershed. Decisions involving the potential to increase sea lamprey spawning habitat within the watershed must include concurrence from the Service's Sea Lamprey Control Program. Decisions should also be made in collaboration with the Service's Ecological Services Program to determine the risk of upstream migration of contaminants to fish-eating wildlife. We developed an initial prototype of a decision structure for solving this multiple objective decision problem at a workshop held at the National Conservation Training Center December 8-12, 2008.

This case study considers the Great Lakes tributary fish passage and barrier management problem from the perspective of Service decision making, e.g., where best to allocate Service funds and resources. It was developed as a rapid prototype at a one-week workshop. This report illustrates a way to structure this decision analysis to help the Service find the 'best' barrier management solutions. While we chose to focus on the Service's mandates and programs, we recognize that watershed management encompasses numerous issues important to other agencies and stakeholders in the region. Fortunately, the decision structuring approach that we prototyped will be useful to all partners in Great Lakes tributary watershed management because we face a common decision-making challenge—that is, figuring out how best to balance among multiple, sometimes conflicting objectives.

- This document contains no information on culvert design or mechanics; mainly it addresses culvert management and a decision making framework for culvert replacement. The Bad River Watershed contains over 1,100 perched culverts of which many are barriers to fish passage. Generally the removal or modification of these barriers would be beneficial to the watershed, but in certain cases the ecosystem might be at risk of invasive species such as the sea lamprey or coho salmon or migratory fish with high levels of contaminants. The document details multiple decision making framework options from the perspective of the USFWS's mandates and programs while recognizing that numerous other issues exist that are important to other agencies and stakeholders in the region.

Nationwide

Clarkin, K., A. Conner, M.J. Furniss, B. Gubernik, M. Love, K. Moynan, and S. Wilson Musser (2005). National Inventory and Assessment Procedure for Identifying Barriers to Aquatic Organism Passage at Road-stream Crossings, U.S. Department of Agriculture Forest Service. National Technology and Development Program, San Dimas, CA.

- Nationwide
- **Abstract:** This document was designed to help identify problem areas for fish passage in streams nationwide. The methods are based on principles from projects undertaken in the Pacific Northwest but instruct users to develop regional screens to adapt analysis to the types of fish and streams present in that particular area. The guide names the stream simulation method as a preferred design practice, but does not go into detail on design, stating that this step requires interdisciplinary work. The document states its primary objective as determining passage ability of local species and as a secondary objective it helps the user choose and prioritize areas to assess for restoration. FishXing is the tool recommended for this exercise. Case Studies from the Pacific Northwest are described.
- The following summarizes the barrier inventory-assessment process and highlights important recommendations.

  • Build and overlay maps of streams, roads, land ownership, analysis species distributions, aquatic habitat types, and habitat quality.

  • Population and habitat information from field surveys is highly preferred because the assumptions used to estimate these variables from maps are often inaccurate.

  • Develop analysis species lists and criteria with the assistance of aquatic experts and in collaboration with a group of stakeholders including land management and regulatory agencies, as well as other interested parties (such as, tribes, Departments of Transportation).

  • Document assumptions and rationale.

  • Include crossings on all land ownerships if possible; otherwise, conduct the analysis recognizing the gaps in knowledge.

  • Collect the entire suite of variables on all crossings to permit later reevaluation if needed

  • Use interdisciplinary teams to collect and interpret the data

  • Establish the watershed context

  • Collaboratively establish criteria for regional screens

  • Conduct the field inventory

• Use regional screens for rapid field assessment of natural channel simulation and barrier category.

• Use hydraulic analysis where screens fail to determine barrier category.

• Understand the limitations of the analytic procedure, such as:

- For many species, movement capabilities and needs are unknown.
- Estimates of culvert velocity are based on imprecise roughness values and may not accurately reflect the flow conditions faced by fish.

• Set priorities for replacements aimed at maximum biological benefit in conjunction with logistical considerations.

• Collaborate with partners and other stakeholders to set priorities.

• Determine barrier category: natural channel resemblance or species-specific crossing category.

• Map barrier locations and overlay on habitat-quality maps to set priorities for restoring connectivity.

FHA (Federal Highway Administration). 2007. Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report. Publication No. FHWA-HIF-07-033. Federal Highway Administration; Office of Infrastructure Research and Development; McLean, Virginia.

- Nationwide
- **Abstract:** Cataloging and synthesizing existing methods for the design of roadway-stream crossings for fish passage began in January 2005 with an extensive literature review covering the topics of culvert design and assessment to facilitate fish passage. A survey was posted online to gather input from design professionals across the country, and a Culvert Summit Meeting was held in Denver Colorado from February 15-16, 2006, to allow presentation and discussion of state-of-practice design and assessment techniques. Following the Summit meeting, a Technical Advisory Committee was developed with individuals specifically knowledgeable in the topics of interest. Members were crucial in shaping and reviewing the direction of these guidelines.
  This document places current culvert design techniques into four categories based on design premise and objectives. These categories include: No Impedance techniques, which span the entire stream channel and floodplain; Geomorphic Simulation techniques, which create fish passage by matching natural channel conditions within the culvert crossing; Hydraulic Simulation techniques, which attempt to closely resemble hydraulic diversity found in the natural channels through the use of natural and oversized substrate; and Hydraulic Design techniques, which may utilize roughness elements such as baffles and weirs to meet species specific fish passage criteria during periods of fish movement. Preliminary chapters covering the topics of fish biology and capabilities, culverts as

barriers, fish passage hydrology, and design considerations aid in the selection of appropriate design techniques based on hydraulic, biologic, and geomorphic considerations. A further section presents examples of design techniques fitting the defined design categories. Design examples and case histories for a selection of design techniques are presented next, and are followed by a discussion on construction, maintenance, monitoring, and future research needs.

- This document presents a thorough and exhaustive look at fish passage design options. It is the result of a literature review and presents no new design options. The three types of design that dominate the discussion include geomorphic simulation, hydraulic simulation, and hydraulic design. Of note, sections on monitoring and future research need give a nice account of what can be done to further the field.

Harrelson, C.C., Rawlins, C.L., and Potyondy, J. P. (1994) Stream Channel Reference Sites: an Illustrated Guide to Field Technique, USDA Forest Service. Rocky Mountain Forest and Range Experiment Station, Ft Collins, CO.

- Nationwide
- **Abstract:** This document is a guide to establishing permanent reference sites for gathering data about the physical characteristics of streams and rivers. The minimum procedure consists of the following: (1) select a site, (2) map the site and location, (3) measure the channel cross-section, (4) survey a longitudinal profile of the channel, (5) measure stream flow, (6) measure bed material, and (7) permanently file the information with the Vigil network. The document includes basic surveying techniques, provides guidelines for identifying bankfull indicators and measuring other important stream characteristics. The object is to establish the baseline of existing physical conditions for the stream channel. With this foundation, changes in the character of streams can be quantified for monitoring purposes or to support other management decisions.
  Outlines field techniques used in measuring geomorphic features related to stream channels. Cross-sections, longitudinal profiles, bottom content, meander patterns are all covered. Field note taking as well as guidelines on the surveyed stream length needed to accurately represent the channel dimensions are described in detail.

Inter-Fluve Inc. 2009. Culvert Scour Assessment. 0877-1812-SDTDC. US Forest Service, San Dimas Technology and Development Center, San Dimas, CA, 54 p.

- Nationwide
- **Abstract:** The purpose of this study is to quantitatively analyze (1) the geomorphic and structure controls on channel-bed and footing scour at road-stream crossings, and (2) the effectiveness of aquatic organism passage (AOP) at these crossings by comparing channel characteristics within the crossing structure to reference channel conditions not influenced by the structure. From this analysis, one can determine the design, construction, stream, and channel conditions that contributed to the success or failure of the installation for AOP and scour resistance.

Normann, Jerome M., Houghtalen, Robert J., and Johnston, William J. 2001. Hydraulic Design of Highway Culverts. Hydraulic Design Series No. 5 (HDS-5), U.S. Federal Highway Administration, Publication No. FHWA-NHI-01-020.

- Nationwide
- Section VI.B.6 focuses on special considerations: fish passage. The material presented here includes the important standard ideas for stable systems that pass fish. The section does not seem to have been updated with new ideas or concepts of ecosystem continuity.

USFS, (2006). "FishXing: User Manual and Reference" Version 3.0, USDA Forest Service San Dimas Technology and Development Center, San Dimas, CA.

- Nationwide
- **Abstract:** The Forest Service has produced a software model—called FishXing—that facilitates assessing and designing stream crossings. Pronounced "Fish Crossing", this software is designed to assist engineers, hydrologists and fish biologists in the evaluation and design of culverts for fish passage. It is free and available for download at the FishXing website. FishXing models the complexities of culvert hydraulics and fish performance for a variety of species and crossing configurations. The model has proven useful in identifying culverts that impede fish passage, leading to the removal of numerous barriers. As a design tool, FishXing accommodates the iterative process of designing a new culvert to provide passage for fish and other aquatic species. FishXing is an interactive software package that integrates a culvert design and assessment model for fish passage. The software models organism capabilities against culvert hydraulics across a range of expected stream discharges. Water surface profiles can be calculated for a variety of culvert shapes using gradually varied flow equations. The program then compares the flows, velocities and leap conditions with the swimming abilities of the fish species of interest. The output includes tables and graphs summarizing the water velocities, water depths, and outlet conditions, then lists the limiting fish passage factors and flows for each culvert.

USFS (2008). "A Tutorial on Field Procedures for Inventory and Assessment of Road-Stream Crossings for Aquatic Organism Passage." http://www.stream.fs.fed.us/fishxing/PEPs.html, Accessed January 25, 2010.

- Nationwide
- Abstract: The presenters on this tutorial go over step by step the measurements needed to complete an assessment of a culvert for fish passage.

Ongoing Research—Not Published

A Collaborative Approach to Managing and Restoring a Forested Wetland, Upper St. Louis River Watershed, Minnesota

Mark A. Fedora
USDA Forest Service Eastern Region
The Nature Conservancy

Daryl Peterson
The Nature Conservancy
Northeast Minnesota Office

The headwaters of the St. Louis River system is a vast, largely undeveloped wetland complex located within the Great Lakes Basin. The area has a complex ownership pattern, with Federal, State, County and privately owned lands intermixed within the 100,000 acre patterned peatland. In 2003 The Nature Conservancy, US Forest Service, Minnesota Department of Natural Resources, Lake County and St. Louis County representatives began meeting to coordinate land management activities and accomplish restoration and management projects of mutual interest. Initial coordination efforts were limited, without comprehensive understanding of existing and historical resource uses. A small team of field specialists and scientists evaluated key issues including forest structure and composition, stream channel sensitivity to management practices, exotic species, road management, and habitat conditions of the St. Louis River. Existing conditions for each issue were analyzed in relation to reference conditions. The results identified both specific projects and gaps in knowledge. The team used the results to inform the larger collaborative group of managers and decision makers, and to set priorities for on-the-ground actions. Specific actions taken to date include:

- Replacement of three road/stream crossing structures,
- Removal of one road/stream crossing structure,
- Development of a single road/trail database to be used to develop a comprehensive access and travel management plan,
- Development of a single database of forest vegetation and planned management to coordinate future activities to achieve forest structure and composition goals, and
- Planting of long-lived conifers to move species composition toward the historic composition.

Improving Water Quality and Fish Habitat in the Bad River in Northern Wisconsin—the Work of the Bad River Watershed Association

Tom Fitz, Geoscience, Northland College, 1411 Ellis Avenue, Ashland, WI 54806, tfitz@northland.edu

Michelle Wheeler, Bad River Watershed Association, 422 Third Street West, Suite 105, Ashland, WI 54806

The Bad River drainage basin in northern Wisconsin is one the largest watersheds in the in the Lake Superior basin and is a major source of sediment flowing into the lake. The watershed is underlain primarily by clay-rich till and lake deposits that cause flashy discharge and rapid erosion. Human activity in the watershed, specifically the installation of culverts at road/stream crossings, has caused disruption of stream flows and increased erosion. Many of the 1074 road/stream crossings have culverts that are undersized or are placed too high and thus restrict water flow and act as barriers to fish passage. During high runoff events the culverts can cause erosion of road embankments. The resulting increase in turbidity and sedimentation downstream and in Lake Superior has had a negative impact on fish habitat.

The Bad River Watershed Association (BRWA), a group of citizen volunteers working in association with many federal and local government agencies has undertaken an inventory and assessment of all road/stream crossings with the goal of decreasing the impact culverts have in the watershed. Citizen volunteers, students, and agency personnel have done extensive culvert assessment and water-quality monitoring. Based on these assessments, culverts have been ranked according to their impacts on stream flow, sediment supply, and fish passage. The BRWA has worked cooperatively with local highway departments and government agencies to begin replacing the worst of the culverts. Three high-priority culverts were replaced in 2007, and two more are to be completed in 2008. Detailed studies of the streams and their fish populations are being done to assess the effects of culvert replacement. Although there is much more work to be done, the cooperation of citizens and government agencies has set the foundation for continued improvement of the water quality in the Bad River watershed and Lake Superior.

Assessment of Sculpin Movement in a 1st Order Tributary

Jason A. DeBoer1, Stephanie Ogren2, J. Marty Holtgren2, Kristofor N. Nault1, and Eric B. Snyder1. (1) Biology, Grand Valley State University, 1 Campus Drive, Allendale, MI 49401, (2) Conservation, Little River Band of Ottawa Indians, Manistee, MI 49660

We evaluated a 1st order tributary to the Big Manistee River. Following perched culvert replacement (Summer ’05), a shift in Mottled Sculpin (Cottus bairdi) distribution (upstream versus downstream) was observed. Pre-restoration, 31% of sculpin were captured upstream of the culvert. Post-restoration, 58% were captured upstream of the new bridge. 95 Sculpin were captured from eight 100m reaches (10 each from 5 downstream reaches, and ~15 each from 3 upstream reaches). Fish were measured, weighed, implanted with a PIT tag and released. 48 of 88 (7 dropped tags) individuals (54.5%) were recaptured at least once. Results indicate

individual fish moved as much as 660m. Post-restoration, several habitat variables were compared between downstream and upstream reaches, including surficial sediment composition and water depth and velocity. Significant difference was detected for key habitat variables. Surber samples were taken in the spring (3 at each of 3 up- and 3 downstream transects), 2 years pre- and 2 years post-restoration. Pre-restoration, average macroinvertebrate abundance per m2 was 149 upstream, and 286 downstream (434 total). Post restoration, the values were 254 upstream, and 189 downstream (443 total). From a management perspective, our results indicate removing undersized, perched culverts can have multiple positive impacts on fish communities.

Ecosystem Response to Restoration in Three Sand-Dominated Michigan Streams

Eric B. Snyder1, Jason A. DeBoer1, Nichol Y. De Mol1, Nicholas J. Gressick2, J. Marty Holtgren3, Kris N. Nault1, Stephanie Ogren3, and April L. Wright1. (1) Biology, Grand Valley State University, 1 Campus Drive, Allendale, MI 49401, (2) J.F. New, 600 South Beacon Blvd., Suite A, Grand Haven, MI 49417, (3) Conservation, Little River Band of Ottawa Indians, Manistee, MI 49660

Historic inputs of sediment derived from the logging era represent a ubiquitous problem in Michigan streams. This project sought to reduce continuing inputs of sediment while measuring a combination of functional and structural response variables in a BACI design. Monitoring (2 pre- and 1 year post-restoration) indicated that undersized culverts trapped fine sediments upstream while old bridges contributed to fine sediments downstream. The restoration efforts in the short term documented an increase in coarse sediments at some sites ($p<0.05$, MANOVA). The macroinvertebrate community showed positive changes in diversity and abundance metrics ($p<0.05$), but was not significantly correlated to the restoration efforts (MANOVA). The fish community showed no significant responses to restoration, except where a perched culvert was replaced (increased ($p<0.05$) potamodromous salmonids upstream). Multivariate (NMDS) analyses indicated both macroinvertebrate and fish communities were correlated to substrate, thus more time may be required to show positive restoration effects in the biotic community. In addition, an OM budget and community metabolism suggests strong links to substrate characteristics. As predicted, the habitat template plays a strong role in determining both structural and functional properties, allowing us to examine the relationship between the restoration effort and temporal and spatial patterns in biophysical improvements.

Identifying Strategic Opportunities for Road CrossingI to Benefit Stream Fishes

Matt Diebel mwdiebel@wisc.edu

Mark Ferdora Fedoramfedora@fs.fed.us

Stewart Cogswell stewart_cogswell@fws.gov

Conclusions of this study were road crossings significantly limit stream connectivity and that stream connectivity effected fish species richness. Stream order was found to be a metric for quantifying connectivity. Barriers were ranked for remediation based on the amount of habitat

that would become available if the barrier was removed. Cost of the project was also factored into the prioritization.

Synthesis of Literature Review

Design

The majority of the literature available on fish passage are guides that detail various design methods for improving fish passage for a certain fish species, stream type, or crossing type. Bates (2003) and the design manual by the Washington Department of Fish and Wildlife (1999) both describe three major culvert designs to accommodate fish passage: the hydraulic design method, the no slope design method, and the stream simulation method.

Hydraulic Design Option

The hydraulic design option does not match stream conditions upstream or downstream of the culvert location but instead involves designing for a target velocity that is required for specific species of fish for which the culvert is being designed to allow passage. This method was typical of older designs but is now mostly used in retrofits or under conditions that do not allow the other methods. The design may allow passage of a species of key importance but it does not account for other aquatic organisms or morphological continuity.

The design method for this type of culvert begins at the downstream end and works upstream. The length of the culvert must be considered such that the target species is able to traverse that entire distance under the velocities presented. When longer culverts are necessary, the velocity threshold must be lowered. The range of velocities or allowable turbulence for the specific fish and age of that fish must be determined. If juvenile fish passage is necessary at the site, the use of a hydraulic design culvert is usually limited. After determining the hydrograph, the culvert must be sized to keep flows within velocity and depth thresholds 90% of the time.

No-Slope Design Option

The no-slope design option can be used when the culvert is short enough so that the difference in height of the sloped sediment in the culvert from the upstream end to the downstream end is low enough as to not impede the flow at any given point on the hydrograph. The width of the culvert installed must be at least equal to the width of the stream. The downstream end must be buried at least 20% of the diameter of the culvert but the upstream end can be countersunk a maximum of 40% of that distance. This design is generally applicable in low slope regions (less than 3%). This design is meant to pass all fish and other aquatic organisms occurring in the stream.

Stream Simulation Design Option

The stream simulation design is used to create completely natural conditions in the culvert concurrent with conditions upstream and downstream. If a fish can make it to the culvert it should be just as able to make it through the culvert. The culvert must be oversized by 120% of the width of the stream plus 2 feet. This allows for stream banks or dry stream borders to exist within the culvert, which guarantees shallow areas that can be important to the passage of juveniles as well as dry areas that can pass other organisms.

This design has proved to be successful in much steeper streams than the previous two. The slope of the culvert can be no more than 125% of the slope of the stream to fit within the design guidelines. Special consideration is given to the culvert fill material in different ranges of slope, and this fill must be arranged to mimic channel conditions.

The Vermont Low-Slope Design
The Vermont Department of Fish and Wildlife named an additional design that uses much the same principle as the no-slope design but instead allows a slight slope to increase the effectiveness of the culvert and decrease the risk of flow blockage at the upstream end. The guideline states that the culvert bottom must be between 20% and 40% buried, as does the no-slope option, but allowing a slight culvert slope in addition allows for a greater range of slope applicability. This design would likely be useful when applied to many Minnesota streams because of the low slopes.

A last resource that takes a slightly different approach is Chapter 13 from the Manual for Hydrologic and Hydraulic Design for Maryland streams. This guide recommends using the Rosgen stream classification system and the consideration of bankfull flows to determine the proper design. The describe designs using main channel culverts buried at a minimum of 20% of the diameter and flood plain culverts to convey high flows without concentrating flow into the main channel culvert alone. Beyond this design, plans for certain stream classifications include outlet basins, riprap, or other special features.

Assessment
All the work done on assessment of recessed culverts has been done under the arena of aquatic organism passage. Information specific to recessed culverts for reasons *not* related to fish passage was difficult to find. Information on the effectiveness of culverts designed for fish passage is just starting to become available. In many parts of the country, fish passage design culverts have not been around long enough to determine their effectiveness. Some of the newer multidisciplinary designs such as stream simulation culverts were first reported in Bates et al., 2003. Since then there has been a number of publications and reports written on techniques developed to measure how well the fish passage culvert designs are matching the natural channel conditions and allowing fish passage. The techniques outlined in these documents will work well for measuring the conditions present at recessed culverts in our study.

The U.S. Department of Agriculture Forest Service produced a document titled, "National Inventory and Assessment Procedure for Identifying Barriers to Aquatic Organism Passage at Road-stream Crossings, U.S" in 2003. It was produced to provide a nationally applicable, consistent method of identifying crossings that impede passage of aquatic organisms in or along streams. It is a how-to manual for approaching answers to two questions. "How and where does the road system restrict the migration and movement of aquatic organisms and what aquatic species are affected and to what extent? This document contains information on what to look for at culverts to quickly determine if fish passage is a problem.
Beavers et al. developed a training manual in 2008 for the Utah Department of Transportation. This manual provided assessment guidelines for measuring culvert parameters as well as the natural stream conditions near the culvert.
In 2009 the USDA published a report titled "Culvert Scour Assessment." Their assessment techniques measured the structure controls on channel beds, footing scour and the effectiveness

of aquatic organism passage by comparing channel characteristics within the crossing structure to reference channel conditions not influenced by the structure.
The three references above use basically the same field measurements to do the culvert assessment. These measurements included: a description of the culverts shape, dimensions and materials, configuration of the apron, inlet and outlet controls, inlet and outlet tailwater conditions, channel bed material, longitudinal profile through the culvert, bankfull channel width and general site description. Barnard did a similar study in Washington in 2003 comparing conditions in stream simulation design culverts with that of the natural channel.

As mentioned earlier, the results of culvert assessments are limited. Barnard was the first to look at the function of stream simulation culvert designs. This study looked at 19 of the 50 stream simulation design culverts that had been in installed in Washington. The oldest of the sites was built in 1995. The conclusion of the study showed that at 14 of the 19 sites, the conditions in the culvert matched that of the channel in acceptable ranges for width and slope. Heller did an assessment of a number of road crossings in the Pacific Northwest in 2007. He looked at both the cost and durability of stream simulation designs and developed the following conclusions:

- Stream simulation and hydraulic designs are about the same initial cost on small streams with gradients of <3%.
- The initial cost of stream simulation design exceeds those of hydraulic design on large streams and those >3% gradient.
- Stream simulation designs appear to be more effective and durable than hydraulic designs.
- Stream simulation designs are more likely to pass juveniles and other aquatic organisms.

In Minnesota, a form of a stream simulation design (MESBOAC) has been used for the last 10 years by county engineers in Itasca County. The county has reported no problems associated with this design and are using it whenever the design is appropriate for new or replacement culverts at road crossings.

Prioritization

In Minnesota fish passage through culverts is usually addressed when a new culvert is installed or an old culvert replaced. In the western states were fish passage has proven to be a significant problem culverts are being replaced just to address fish passage. To best utilize the limited finds some work has been done to identifying the most problematic culverts. Beavers et. al. in 2008 developed a prioritization model for the state of Utah. It was a GIS based model that took into consideration fish species, habitat, ranges, hydraulic conditions in the culvert, and flow regime. The GIS data was supplemented with a rapid culvert assessment that identified specific problems such as; perched, backwatered or critical flow conditions. Some unpublished work done by Diebel in Wisconsin developed a methodology that ranked culvert replacement based on stream connectivity and how much stream habitat would become available if the blocked crossing was improved.

Synthesis Documents

For a more in depth look at fish passage issues and specific designs a good reference is the synthesis report produced for the FHWA by Hotchkiss in 2007. Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report. Publication No. FHWA-HIF-07-033. Federal Highway Administration.

Bibilography

Ashland National Fish and Wildlife Conservation Office. 2009. Planning, Design, and Construction of Fish Friendly Stream Crossings. US Fish and Wildlife Service. Webpage at: http://www.fws.gov/midwest/Fisheries/streamcrossings/index.htm

Barnard, B. Stream Simulation Culverts: Culvert Sizing. Washington Department of Fish and Wildlife.

Barnard, B. 2003. Evaluation of the Stream Simulation Culvert Design Method in Western Washington, a preliminary study - Draft. Washington Department of Fish and Wildlife. August 2003.

Bates, K., B. Barnard, B. Heiner, J. P. Klavas, P. D. Powers. 2003. Design of Road Culverts for Fish Passage. Washington Department of Fish and Wildlife. Available at: http://wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf

Beavers, A.E., Hotchkiss, R.H., and Belk, M.C. (2008) Fish Passage at UDOT Culverts: Prioritization and Assessment, Utah Department of Transportation Research and Innovation Division, Salt Lake City, Utah.

BC Ministry of Transportation and Highways. 2000. Culverts and Fish Passage Fact Sheet. October. Environment Management Section, Engineering branch. Available at: http://www.th.gov.bc.ca. Accessed January 14, 2010.

Castro, J. 2003. Geomorphic Impacts of Culvert Replacement and Removal: Avoiding Channel Incision. US Fish and Wildlife Service, Oregon Fish and Wildlife Office, Portland, OR.

Chapter 13: Culverts. In *Guidelines for the Selection and Design of Culvert Installations*. Draft, 2006. Office of Bridge Development Manual for Hydrologic and Hydraulic Design.

Clarkin, K., A. Conner, M.J. Furniss, B. Gubernik, M. Love, K. Moynan, and S. Wilson Musser (2005). National Inventory and Assessment Procedure for Identifying Barriers to Aquatic Organism Passage at Road-stream Crossings, U.S. Department of Agriculture Forest Service. National Technology and Development Program, San Dimas, CA.

FHA (Federal Highway Administration). 2007. Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report. Publication No. FHWA-HIF-07-033. Federal Highway Administration; Office of Infrastructure Research and Development; McLean, Virginia.

Forest Service Stream-Simulation Working Group. 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings. 0877-1801—SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 515 p.

Freiburger, Chris and Fulcher, Jerry. Culvert Sizing and Installation Stream Simulation. Power point presentation.

Gardner, A. N. 2006. Fish Passage Through Road Culverts. MS Thesis. Raleigh, NC: North Carolina State University, Department of Biological and Agricultural Engineering.

Hansen, B., Nieber, J., and Lenhart, C. 2009. Cost Analysis of Alternative Culvert Installation Practices in Minnesota.

Hanson, G. J. and A. Simon. 2001. Erodibility of Cohesive Streambeds in the Loess Area of the Midwestern USA. ***Hydrological Processes*** **15(1): 23-38. Stillwater, OK: John Wiley and Sons.**

Harrelson, C.C., Rawlins, C.L., and Potyondy, J. P. (1994) Stream Channel Reference Sites: an Illustrated Guide to Field Technique, USDA Forest Service. Rocky Mountain Forest and Range Experiment Station, Ft Collins, CO.

Heller, David. 2007. A Strategic Approach for the Identification and Correction of Fish Passage on National Forest Lands for the Pacific Northwest. Chapter 4, ICOET Proceedings.

Hendrickson, S., Walker, K., Jacobson, S., Bower, F. 2008. Assessment of Aquatic Organism Passage at Road/Stream Crossings for the Northern Region of the USDA Forest Service.

Inter-Fluve Inc. 2009. Culvert Scour Assessment. 0877-1812-SDTDC. US Forest Service, San Dimas Technology and Development Center, San Dimas, CA, 54 p.

Jackson, S., Bowden, A., and Graber, B. 2007. Protecting and Enhancing River and Stream Continuity. Chapter 4, ICOET Proceedings.

Love, M. 2007. Corner Baffle Design Exercise: Fish Passage Retrofit and Culvert Rehabilitation Highway 128 at John Hatt Creek. Course exercise.

Ministry of the Environment. 2007. Canimred Tributary Weir Construction 535 Road. Ministry of Water, Land and Air Protection. British Columbia, Canada: Government of British Columbia. Available at: http://www.env.gov.bc.ca. Accessed.

Muste, M., Ettema, R., Ho, H-C., and Miyawaki, S. 2009. Development of Self-Cleaning Box Culvert Designs. Iowa Highway Research Board Report IHRB-TR-545.

Normann, Jerome M., Houghtalen, Robert J., and Johnston, William J. 2001. Hydraulic Design of Highway Culverts. Hydraulic Design Series No. 5 (HDS-5), U.S. Federal Highway Administration, Publication No. FHWA-NHI-01-020.

Patronski, Tim, et al. 2008. Fish Passage and Stream Barrier Management in the Bad River Watershed in Northern Wisconsin. SDM Workshop December 8-12, 2008.

USFS, (2006). "FishXing: User Manual and Reference" Version 3.0, USDA Forest Service San Dimas Technology and Development Center, San Dimas, CA.

USFS (2008). "A Tutorial on Field Procedures for Inventory and Assessment of Road-Stream Crossings for Aquatic Organism Passage." http://www.stream.fs.fed.us/fishxing/PEPs.html, Accessed January 25, 2010.

Vermont Department of Fish and Wildlife. 2007. Vermont Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms.

Warren, M.L., and Pardew, M.G. 1998. Road Crossings as Barriers to Small-Stream Fish Movement. Transactions of the American Fisheries Society 127:637-644.

Washington Department of Fish and Wildlife. 1999. Fish Passage Design at Road Culverts: A design manual for fish passage at road crossings. Habitat and Lands Program, Environmental Engineering Division.

Appendix B Photos of Sites Selected for Surveys

Eighteen sites were selected at locations around the state of Minnesota. The locations are shown in Figure 1. The sites include recessed culverts in the following landscapes of Minnesota:

- Southeast, steeper slopes, trout streams
- Agricultural
- North central, with an abundance of lakes and wetlands
- Steep rocky terrain of the North Shore

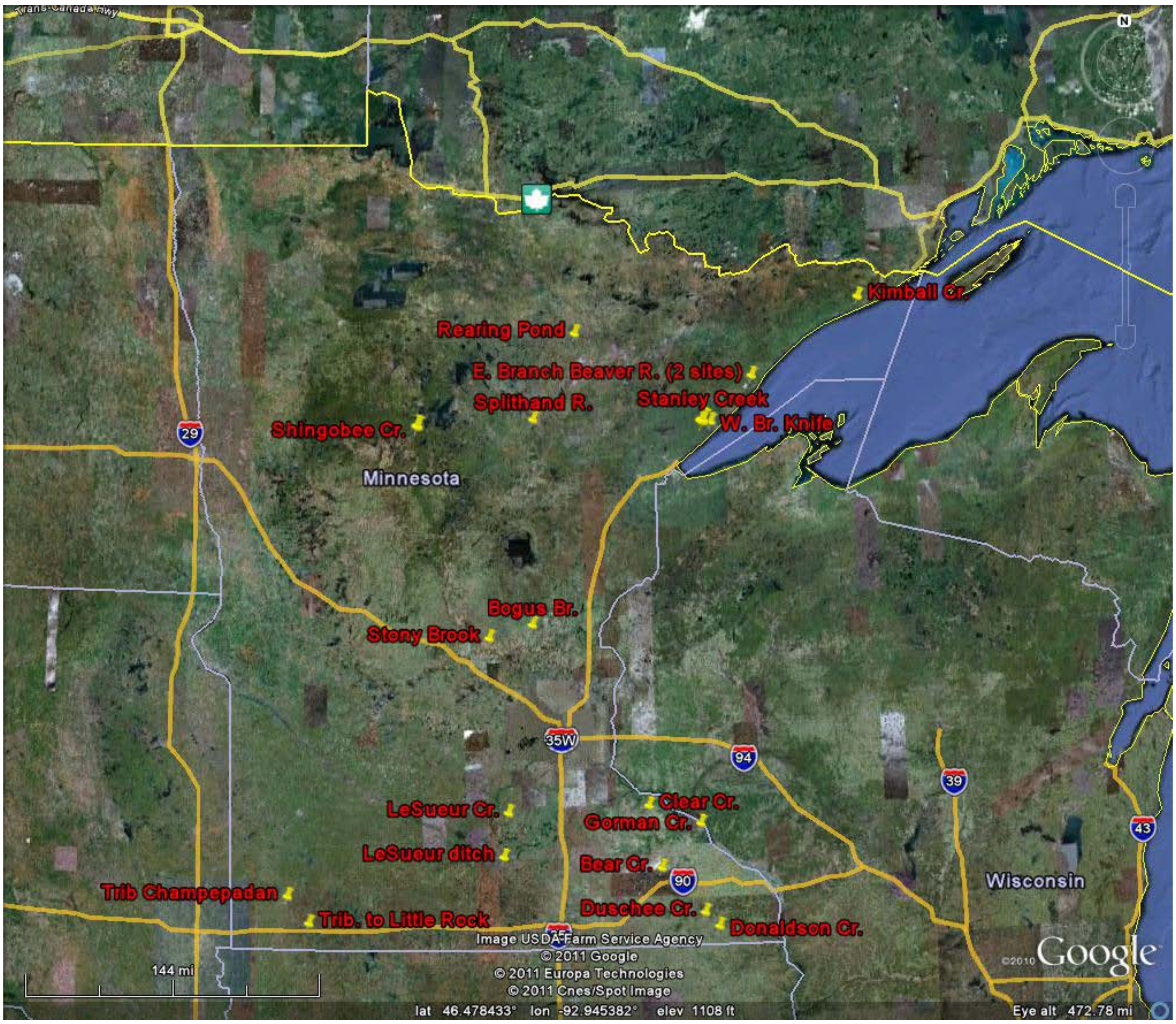


Figure 1. Map of Minnesota showing the location of the nineteen culvert sites included in this study. Courtesy of Google Maps. Locations are: Rearing Pond, Kimball Creek, East Branch Beaver River (2 sites), Shingobee Creek, Splithand River, West Branch Knife River, Stanley Creek, Stony Brook, Bogus Brook, Le Sueur Creek, Le Sueur ditch, Tributary to Champepadan Creek, Tributary to Little Rock River, Clear Creek, Gorman Creek, Bear Creek, Duschee Creek, Donaldson Creek.

Photographs of the selected sites are presented by region in the following.

Sites selected for Southeastern Minnesota

Photo 1. Gorman Creek (Wabasha County).

Photo 2. Clear Creek (Goodhue County).


Photo 3. Donaldson Creek (Fillmore County).


Photo 4. Duschee Creek (Fillmore County).

Photo 5. Bear Creek (Olmsted County).

Sites selected for northeastern Minnesota


Photo 6. Kimball Creek, (Cook County).


Photo 7. East Branch Beaver River upstream (Lake County).


Photo 8. Stanley Creek (St. Louis County).


Photo 9. East Branch Beaver River downstream.


Photo 10. Knife River (St. Louis County).

Sites selected for north central Minnesota

Photo 11. Little Sturgeon River (Rearing Pond, Itasca County).

Photo 12. Shingobee Creek (Cass County).

Photo 13. Splithand Creek (Itasca County).

Photo 14. Stoney Brook (Benton County).


Photo 15. Bogus Brook (Mille Lacs County).

Sites selected for south central Minnesota

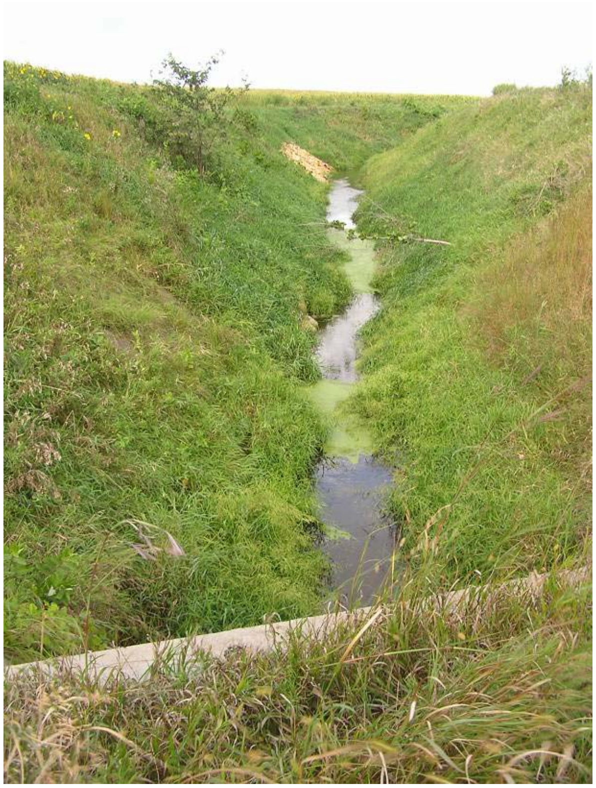


Photo 16. County ditch 25 (Blue Earth County).


Photo 17. LeSueur Creek (LeSueur County).

Photo 18. Tributary to Champepadan (Nobles County).


Photo 19. Tributary to Little Rock River (Nobles County).