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Sediment Transport through Recessed Culverts: Laboratory Experiments

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16. Abstract (Limit: 250 words)

Recessed culverts are often installed in Minnesota to facilitate aquatic organism passage (AOP) by providing a natural streambed through the culvert. The least expensive option when installing a recessed culvert is to allow the culvert to fill in with sediment naturally over time; however, previous field studies suggest that in many cases, sediment fails to deposit within the culvert. The objective of this research was to understand the function of a culvert set below the streambed elevation under various sediment transport conditions. Laboratory experiments were designed to assess the performance of recessed culverts across a range of geomorphic characteristics representative of Minnesota streams. These experiments explored the functionality of a culvert that is prefilled with sediment representative of the stream as a part of the installation process against one that is empty after installation and assessed the potential for headcutting and downstream degradation. The experiments evaluated the need for artificial roughness installations within recessed culverts in high gradient streams. Three sets of experiments were conducted examining: 1) the effect of sediment grain size, slope, and flow hydrograph on sediment transport through a single recessed box culvert, 2) the effect of bed roughness structures on sediment stability in a single recessed box culvert in high-gradient streams, and 3) the effect of culvert offset and skew on sedimentation in multi-barrel culverts.

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Final Report

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Executive Summary

In recent decades, concern over stream fragmentation (the inability of fish or other aquatic organisms to move past a barrier) has led to interest in designing culverts to minimize aquatic organism passage (AOP) impedance at road crossings. Culverts can become barriers when conditions exceed fish or aquatic organism ability by: excessive drop at outlet, insufficient pool depth, excess flow velocity, excessive turbulence, or behavioral barriers. To accommodate fish passage, a common design practice in Minnesota is to embed, or set the culvert below the stream bed elevation in an attempt to maintain a consistent streambed through the culvert with roughness characteristics similar to the stream.

A series of experiments were conducted at St. Anthony Falls Laboratory (SAFL) at the University of Minnesota designed to elucidate sediment transport processes in embedded box culverts. The first set of experiments evaluated the influence of filling an embedded box culvert as part of the installation process in low, moderate, and high gradient streams. In general, filling the culvert resulted in less risk of upstream erosion or head cuts. Placement of streambed material within the culvert during the installation process also ensured that sediment remained in the culvert under both bankfull flow and a simulated storm hydrograph. For the high gradient channel, geomorphic structures such as steps, ribs, boulders and riffles were critical to the stability of the sediment within the culvert. An experiment that utilized these structures directly in the culvert showed that they helped to stabilize the channel bed upstream of the culvert.

A second set of experiments was conducted to examine the processes responsible for the deposition of sediment in offset multiple barrel box culverts. In the field, large amounts of sediment are observed to deposit in the elevated culvert (where one or more culvert barrel(s) is embedded below the stream grade). In laboratory experiments under a simulated hydrograph, this phenomenon was not replicated for straight or skewed culverts. Although some sediment deposited in the elevated culvert barrel, it is hypothesized that vegetation plays an important role in the large sediment deposits see in multi-barrel culverts in the field. For example, once flood waters recede and the majority of flow is directed to the recessed barrel, vegetation can grow on sediment deposits, leading to increased roughness which encourages additional deposition (a positive feedback loop). More fieldwork is required to investigate this process further.

Based on these experiments, the following design recommendations are suggested for embedded culverts where maintaining a natural stream bed is an AOP design goal:

- Set the culvert width equal to or slightly greater than bankfull width (as recommended by MESBOAC or USFS Stream Simulation).
- Site specific analysis of flow, shear stress, and mobility of the range of sediments is recommended to predict sediment movement into the culvert.
- Fill the culvert with a grain size mix representative of the stream to protect against upstream scour or head cuts (provided the culvert is of a similar width to the stream.)
- For high gradient streams, install structures made up of large interlocking pieces within the culvert to maintain sediment stability in culverts and to prevent headcuts upstream. These structures are also critical to providing flow complexity (resting areas, etc.) needed by fish and aquatic organisms for upstream passage.

- Structures upstream of the culvert and on the upstream end inside the culvert are the most susceptible to failure and should be sized accordingly. No structures are recommended less than one-half to one times bankfull width from the upstream end of the culvert (within the culvert).
- The degree of armoring in the stream should be evaluated if sediment transport into the culvert is expected.
- For multi-barrel culverts, embed one barrel below the stream bed. If the culvert is skewed or if the culvert is placed on a bend (not recommended), the embedded barrel should be on the outside of the bend to capture the channel thalweg and maintain a low-flow channel.

These experiments were designed to be screening level experiments to investigate sediment transport in realistic representations of generalized streams. For all of these experiments, the box culvert width was set equal to bankfull width and the recessed culvert was set at one foot (scaled) below the streambed. To fully optimize the design of recessed box culverts for fish passage and sediment transport, a range of culvert widths and embedded depths needs to be tested. Results from these experiments reinforce the need to collect site-specific data on sediment transport, hydrology, grain size distribution, armoring, and roughness elements to be able to predict the movement of sediment into and through the culvert.

Chapter 1
Introduction

In recent decades, concern over stream fragmentation (the inability of fish or other aquatic organisms to move past a barrier) has led to interest in designing culverts to minimize aquatic organism passage (AOP) impedance at road crossings. Culverts can become barriers when conditions exceed fish or aquatic organism ability by: excessive drop at outlet, insufficient pool depth, excess flow velocity, excessive turbulence, or behavioral barriers (Hotchkiss and Frei 2007). Culvert barriers can leave fragmented populations subject to die off by chance events (e.g. Farhig and Merriam 1985) and longer term loss of genetic diversity (e.g. Jackson 2003) thus decreasing overall populations within a stream network. The design of culverts to accommodate AOP requires an understanding of organism habitat requirements, swimming ability and migration needs, as well as an understanding of how a culvert design will perform in a specific geomorphic and hydrologic context.

The studies on fish passage in the Midwest that have been conducted indicate that fish passage is a likely issue in many culverts. A survey referenced by Hansen et al. (2009) of surveyed road crossings in the Pine-Popple watershed in the forested northeast portion of Wisconsin found that 67% of the crossings partially or totally blocked fish passage. Rayamajhi et al. (2012) conducted a screening level assessment of 55 culverts in Northeast Ohio and found that none of the selected fish species (all fish species found in MN: golden shiner, white sucker, northern pike, greenside darter, pumpkinseed, longear sunfish, smallmouth bass, largemouth bass, golden shiner, and blacknose dace) were able to pass upstream through any of the culverts during the 2-yr flood. This analysis utilized FishXing as a screening level tool similar to the Utah fish passage prioritization tool used by Beavers et al. (2008). Only two fish species (greenside darter and gold shiner) were able to pass on average 3% of the culverts during the maximum average monthly flow and two fish species (greenside darter and blacknose dace) were able to pass 25% of the culverts during the minimum average monthly flow. The most common barriers for fish passage were excessive water velocity, length of culvert, and depth of water in the culvert. To evaluate the effect of lower flow near the culvert boundaries, further analysis on a single culvert was conducted using a post-processing tool for the unsteady flow calculations in HEC-RAS (Vasconcelos et al. 2011). After accounting for low flow areas near culvert boundaries, two of the fish species passed this culvert all of the time, two were never able to pass, and the remaining three species passed some of the time. The barriers under this analysis were excessive velocity and insufficient water depth. Of the 55 culverts, only 18 were deemed able pass any fish during the four flows tested (max. monthly, min. monthly, typical low flow, 2-yr flow). Combined, these studies provide some evidence of the scale of fish passage issues in the Midwest. One major limitation of extending these studies is the limited information that exists for fish swimming abilities for many Midwest fish species. Because of the difficulties in designing culverts to pass individual fish species, many AOP designs seek to pass a range of species by allowing for natural streambed material within the culvert. This report summarizes a series of experiments conducted at St. Anthony Falls Laboratory (SAFL) at the University of Minnesota designed to elucidate sediment transport processes in recessed box culverts, a common fish passage culvert design in Minnesota.

1.1 Culvert Design Practices for Aquatic Organism Passage in Minnesota

A number of state and national design guidelines on fish passage and AOP have been developed in recent years. A synthesis report published by the Federal Highway Administration in 2007 divides fish passage design methods into three categories: geomorphic simulation, hydraulic simulation, and hydraulic design (Hotchkiss and Frei 2007). Geomorphic simulation includes the United States Forest Service (USFS) Stream Simulation (USFS 2008) and other methods to recreate representative geomorphic characteristics within a culvert; hydraulic simulation includes embedded structures and roughness elements used to create favorable hydraulic conditions; and hydraulic design includes weirs, baffles, and other hydraulic structures used to accommodate specific swimming abilities of target species. Other AOP guidelines for culvert design include the Technical Supplement 14N published by the National Resource Conservation Service (NRCS) in the National Engineering Handbook (NEH) Part 654 (NRCS 2007) and guidelines published by the Federal Highway Administration in 2012 (HDS-5; Schall et al. 2012). NEH 654 TS 14N focuses primarily on hydraulic design approaches, but includes guidance for the incorporation of geomorphic simulation and no slope designs (NRCS 2007). HDS-5 (3rd Edition) includes a chapter introducing the HEC-26 and USFS stream simulation approaches. HEC-26 methods focus on streambed stability and may result in oversized material being placed in the culvert to maintain stability at high flows (Kilgore et al. 2010).

Both hydraulic simulation and geomorphic simulation attempt to move away from targeting the swimming abilities of target species. These simulation methods are based on the assumption that that if the culvert adequately mimics the hydraulic or geomorphic characteristics of the stream, fish passage (and other aquatic organism passage) will occur without a barrier for species that can move through the larger stream system. Geomorphic simulation methods include a detailed analysis of the stream and streambed material, the placement of natural streambed material, with geomorphic elements (e.g. steps, pools, riffles, etc.) constructed within the culvert to match a reference channel geomorphology (USFS 2008). Hydraulic simulation includes embedded culverts, natural or synthetic bed mixes and roughness elements to create similar hydraulic conditions. Unlike hydraulic design, these methods do not attempt to design for a specific fish species. Many states, including Minnesota, have adapted some form of embedded culvert to address fish and aquatic organism passage with the intentions that embedding a culvert will both provide adequate flow depth and allow natural streambed material to be deposited within the culvert. In Minnesota, specifically, a method referred to as MESBOAC was developed in the northern forested region of Minnesota (MN DNR 2011). MESBOAC stands for: Match culvert width to bankfull stream width; Extend culvert length though the side slope of the road; Set the culvert slope the same of the stream slope; Bury the culvert; Offset multiple culverts; Align the culvert with the stream channel; and Consider headcuts and cutoffs. In practice, there is no standardized AOP or fish passage culvert design method in Minnesota, although many fish passage culverts include elements of other fish passage designs such as embedding or recessing culverts anticipating that the culvert will fill in with natural streambed sediment over time (Hansen et al. 2011).

Two recent studies funded by Mn/DOT and the Local Road Research Board (LRRB) evaluated the cost and performance of alternative culvert installations in Minnesota (Hansen et al, 2009 and 2011). Hansen et al. (2009) conducted a literature review to determine how knowledge obtained from fish passage studies in other parts of the country translated to the Midwest. Many fish passage culvert studies focused on salmonids on the west coast because they are important game fish and have large migration distances interrupted by dams and road crossings (Hansen et al. 2009). However, since the 1980s, biologists have begun to realize the importance of the ability of all aquatic species to pass through culverts at all life stages in a wide range of flows (Cenderelli et al. 2011). Similar studies are being conducted in the Midwest to accommodate native fish species as well as other aquatic organisms. To translate these studies and apply the information to the Midwest, we must take into account that many Midwest fish are non-anadromous and live in streams with lower gradients and turbulence. Additionally, many Midwestern fish species must navigate among lakes and rivers for feeding and overwintering and all need a relatively large navigable stream section for daily foraging (Hansen et al. 2009). Hansen et al. (2009) summarized the following differences and similarities between the Midwest and the West coast where many of the fish passage studies have been conducted:

Differences in fish passage considerations:

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

Similar fish passage issues:

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

To develop a statewide picture of fish passage concerns related to road crossings in public waters, statewide general and county permits were reviewed and a survey of local and regional hydrologists and engineers was conducted to compile information about the knowledge and use of alternative culvert practices. Based on the findings of this survey, culverts were typically designed for hydraulic conveyance with alternative (fish passage) designs accounting for less than 30% of the total. Alternative designs for culverts in Minnesota included: 1. weirs, 2. roughened channels, 3. baffles, and 4. MESBOAC (a form of recessed culvert design). Key findings of the survey include a general lack of: a regional or statewide ranking or prioritization system for fish passage; evaluation of existing alternative designs; understanding outside of the Minnesota Department of Natural Resources (MN DNR) of alternative culvert practices; and knowledge about the effects of culverts on fish passage and sediment transport. A cost analysis of the four listed alternative culverts, based on materials alone (and not accounting for longevity, etc.) found that weirs increased installation costs by 15.1 %; roughened channel increased costs by 10%, baffles increased costs by 12.5 %, and MESBOAC designs ranged from -5% to 33% greater costs over the traditional culvert design. Recent work by the USFS, however, indicates that although stream stimulation designs are more expensive up front, they can provide substantial economic benefits through enhanced resilience to large flood events (Gillespie et al. 2014).

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

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

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

Hansen et al. (2011) evaluates culvert performance primarily by the presence or absence of sediment in recessed culvert barrels. Of 13 recessed culverts examined, six had a lack of sediment in the culvert barrel. Four potential reasons for lack of sedimentation were listed as: a large flow event prior to the survey, culvert too new for sediment to accumulate, culvert slope steeper than channel bed, and lack of transportable sediment or bed load. In addition, improperly sized culvert width and side barrel sediment accumulation were determined to be potential causes of lack of culvert performance. At all 13 sites, the recessed culvert width was less than the recommended bankfull channel width. The authors identified possible solutions to the problem, including a better understanding of stream and site data, improved procedure for placing sediment or anchoring sediment to the culvert, and different designs that work better with the wider channels and floodplains found more commonly in Minnesota. Similar evaluations have been conducted in Ohio and North Carolina and the general consensus is that culverts with adequate cross sectional area and low slopes (<1%) exhibited more stable stream and culvert conditions (Roberts 2009; Tumeo and Pavlick 2011). In Ohio, embedded culverts with slopes greater than 1% had no sediment present inside recessed culverts that were expected to maintain a continuous streambed. These studies identify a need to understand the physical processes that drive sediment transport into and through embedded culverts over a range of geomorphic characteristics (slope and grain size). These studies suggest that embedded or recessed culverts do not always perform as intended (i.e. fill in with natural streambed sediment) and this seems to be a function of culvert dimensions (specifically width) or slope. There is a need to understand sediment transport through embedded culverts with various site characteristics (i.e. slope and grain size) to inform design guidelines for the placement of sediment (or not) in embedded culvert designs.

1.2 Minnesota AOP in a Geomorphic Framework

Steeper streams are generally composed of larger substrate with more frequent pools, more turbulence, and rapid sediment transport, while a stream with a very small gradient (< 0.001 ft/ft) will have a lower velocity, lower turbulence, finer sediments, and slower sediment transport (Montgomery and Buffington, 1998). General regional geomorphic characteristics as related to fish passage in Minnesota were compiled by Hansen et al. (2009). Streams in Minnesota range from high gradient cobble beds to low gradient sand/fine bedded streams (Table 1.1). Additional information on regional geomorphic and landuse characteristics can be derived from the Level III Ecoregion descriptions for Minnesota (Figure 1.1; Table 1.2). Understanding regional geomorphic characteristics is important for developing general guidance for AOP culvert design.

For example, in low gradient streams with highly mobile sediment, placing large roughness elements or filling the culvert may not be necessary to maintain a consistent stream bed, but in steeper channels where the larger bed material is only mobile during larger less frequent storms, roughness may need to be added to the culvert to create appropriate AOP conditions.

Table 1.1. Major River Basins in Minnesota and Fish Passage Considerations (Hansen et al, 2009).

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

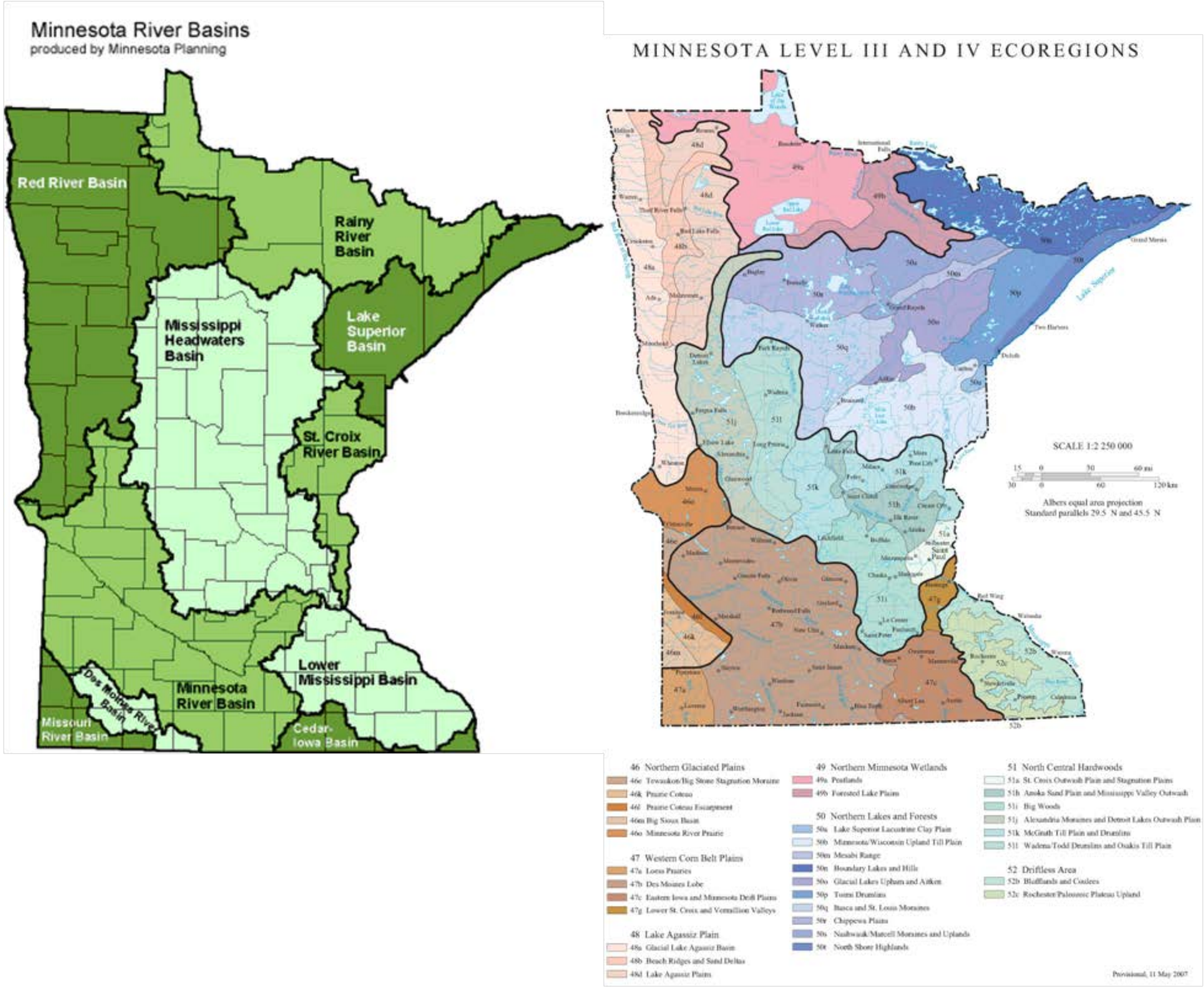

Figure 1.1. Major River Basins of Minnesota and Level III and IV Ecoregions of Minnesota (See Table 2 for fish passage considerations in each river basin and Table 1.2 for general ecoregion descriptions).

Table 1.2. Descriptions from the Level III Ecoregion for Minnesota (Wilken et al. 2011).

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

Chapter 2
Experimental Design for Sediment Transport in Recessed Culverts

The unimpeded sediment transport through a culvert is not only important for long term culvert function (e.g. no excessive buildup or scour of sediment that can destabilize the structure), but a continuous stream bed with similar roughness characteristics is considered to be the best scenario for allowing fish and aquatic organism passage through the culvert over a range of flows (see review in Hansen et al. 2011). Understanding the sediment transport (bedload) through culverts is necessary for an efficient design of a structure that accommodates aquatic organism passage (AOP). To maintain a natural streambed, AOP culvert design often involves burying or embedding the culvert below the streambed. Sometimes these recessed culverts are simply recessed and stream bed sediment is allowed to fill in the culvert bottom; however, recent research both in Minnesota and other areas of the Midwest (e.g. Ohio, see Chapter 1) have indicated that this assumption is not applicable under all bed slope and grain size combinations. Therefore, in order to understand the basic transport of sediment through a recessed culvert and how it is affected by slope and grain size, a series of experiments were conducted to model bedload transport through a stream channel and culvert system in a long recirculating flume. Experiments under both steady state and a hydrograph examined how sediment is transported into and out of a model embedded culvert with two different initial conditions: 1) filled with streambed material similar to the native streambed, or 2) left unfilled after construction. Sediment grain size was scaled and armoring was modeled as closely as possible to understand the effect of these variables on overall transport and bed morphology through the culvert. This chapter describes the experimental design and selection of variables for low, moderate, and high gradient experiments.

2.1 Review of Sediment Transport or Fish Passage Experiments in Culverts

A literature review on physical modeling of culvert systems returns few studies focusing on modeling of stream simulation or recessed designs. Nevertheless, the studies on other aspects of stream simulation design or physical models of non-recessed culverts have some pertinent details that help to inform our experimental design. Table 2.1 gives information on various physical model studies including focus and findings.

There are numerous studies on the hydraulic analysis of fish passage design, especially as it relates to baffle or weir design. Table 2.1 lists a few recent studies on baffle design, but the more relevant studies are those such as Clark and Kehler who examined turbulent flow in corrugated culverts to understand the variation in flow fields within a culvert (Clark and Kehler 2011). Understanding the flow field distribution has implications for both fish and sediment transport.

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

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

Table 2.1. Focus and findings of flow and sediment transport model studies on culvert performance.

Citation	Title	Parameters	Key Findings	Sediment
Hydraulic Analysis of Fish Passage Design				
Clark and Kehler 2011	Turbulent Flow Characteristics in Circular Corrugated Culverts at Mild Slopes	cross-sectional velocity and turbulence	significant percentage of the cross-sectional flow had streamwise velocity lower than mean bulk velocity	NA
Ead et al 2002	Generalized Study of Hydraulics of Culvert Fishways	velocity field in culvert fishways	recommended spacing of baffles; weir and slotted weir are simpler than other designs yet equally effective	NA
Kerenyi 2012	Fish Passage in Large Culverts with Low Flows- ongoing	velocity distributions above and between corrugations	goals: determine the local velocities and flow distributions in corrugated metal pipes; practical design method for estimating average local velocities in culverts	with and without fixed sediment
Morrison et al, 2009	Turbulence Characteristics of Flow in a Spiral Corrugated Culvert Fitted With Baffles and Implications for Fish Passage	Velocity and turbulent kinetic energy distribution	minor differences in turbulent distributions with different baffle types did not relate to biological fish passage tests	NA
Knight and Sterling 2000	Boundary Shear in Circular Pipes Running Partially Full	cross-sectional velocity distributions boundary shear stress	distribution of boundary shear stress within culvert is highly sensitive to cross-sectional shape; examined the implication of secondary flows for sediment transport	smooth flat bed representing sediment
Inlet and Outlet Scour				
Liriano et al, 2002	Scour at Culvert Outlets as Influenced by the Turbulent Flow Structure	mean velocity turbulence intensities scour hole geometry	fundamental understanding of scour hole formation at culvert outlet; initial formation of outlet scour hole results from mean velocity exceeding the critical velocity; further scour is associated with the turbulent structure of the flow	uniform gravel
Abt et al 1996	Enhancement of the Culvert Outlet Scour Estimation Equations	Scour Geometry Drop Height	summary of previous outlet scour experiments, simplified expressions in 1983 HEC-14 scour calculations; general expression relating outlet scour geometry to discharge, culvert dimensions, time, and bed material gradations	non-cohesive gradations
Emami and Schleiss 2010	Prediction of Localized Scour Hole on Natural Mobile Bed at Culvert Outlets	Scour hole geometry	dimensionless relationships between scour hole geometry with discharge and tail water depths	uniform

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

2.2 Single Barrel Experimental Set Up

Experiments were conducted to examine the effect of filling or not-filling embedded culverts in the tilting bed flume at St. Anthony Falls Laboratory (SAFL). This flume is 48 ft long by 3 ft wide has the ability to tilt from -1 to 6^{o}, can recirculate sediment up to approximately 0.4 in (1.0 cm) in diameter, and has a fully automated precision measurement carriage (Figure 2.1). This cart is instrumented with sonar to measure underwater bed topography during the run, an ultrasonic transducer to measure water surface elevation, and a downward looking laser range finder to collect high-resolution measurements of pre- and post-run bed topography. The instrument cart was also used to collect velocity measurements using a side looking acoustic Doppler velocimeter (ADV).

Figure 2.1. Instrumentation cart on the tilting bed flume with sonar, ultrasonic transducer, and laser range finder. This cart is also used to collect velocity measurements with an acoustic Doppler velocimeter (ADV).

For the tilting bed flume experiments (low, moderate, and high slope), a scaled culvert was constructed using standard plans for a box culvert installation per Mn/DOT (http://www.dot.state.mn.us/bridge/culverts.html). This culvert was a single barrel culvert at a 1:8 geometric scale (18 in model: 12 ft prototype). The culvert was installed without a top to allow instrumentation access during the run. This culvert was installed in the middle of the length of the tilting bed flume to minimize entrance and exit effects. A simplified channel was constructed upstream and downstream of the culvert. This channel was trapezoidal with a 18 in top width and 2H:3V side slopes, similar to the steep side slopes measured in the representative channels. The banks were roughened with asphalt shingle (roughness on the order of one mm). This channel was inset in a floodplain (9 in wide on either side) covered in artificial grass

(Figure 2.2). The elevation of the culvert was designed to be adjustable to ensure proper embeddedness.

Figure 2.2. Model culvert and channel configuration in the tilting flume.

At the start of each set of experiments (low, moderate, or high gradient), sediment was placed within the channel and screed flat at 5 in above the flume bottom (3 in below the floodplain elevation). The first run for each gradient was designed to 1) allow the bed to armor, and 2) allow the bed to adjust slightly to an equilibrium bed slope without the influence of the culvert. To do this, the culvert was placed on the flume bottom and temporary banks were installed in the culvert region (Figure 2.3). The flume was then run at bankfull flow conditions with sediment recirculation until the slope equilibrated. Following this equilibrium run, the culvert was set at one scaled foot (1.5 in) below the equilibrium grade. Two bankfull runs were conducted with an initially filled, and an initially not filled culvert (see Figure 2.4) to examine the sediment transport processes though embedded culverts. Following the bankfull runs, two hydrograph runs (with overbank flow) were conducted with initially filled and not filled culverts. For the high-gradient experiment, additional runs were conducted with structures (steps, boulder, ribs) installed within the culvert for bankfull and hydrograph runs. Table 2.2 has a full list of all tilting bed flume runs.

Figure 2.3. Pre-run equilibrium stream channel with temporary stream banks through culvert section. This image is from the fine sediment/low gradient experiments.

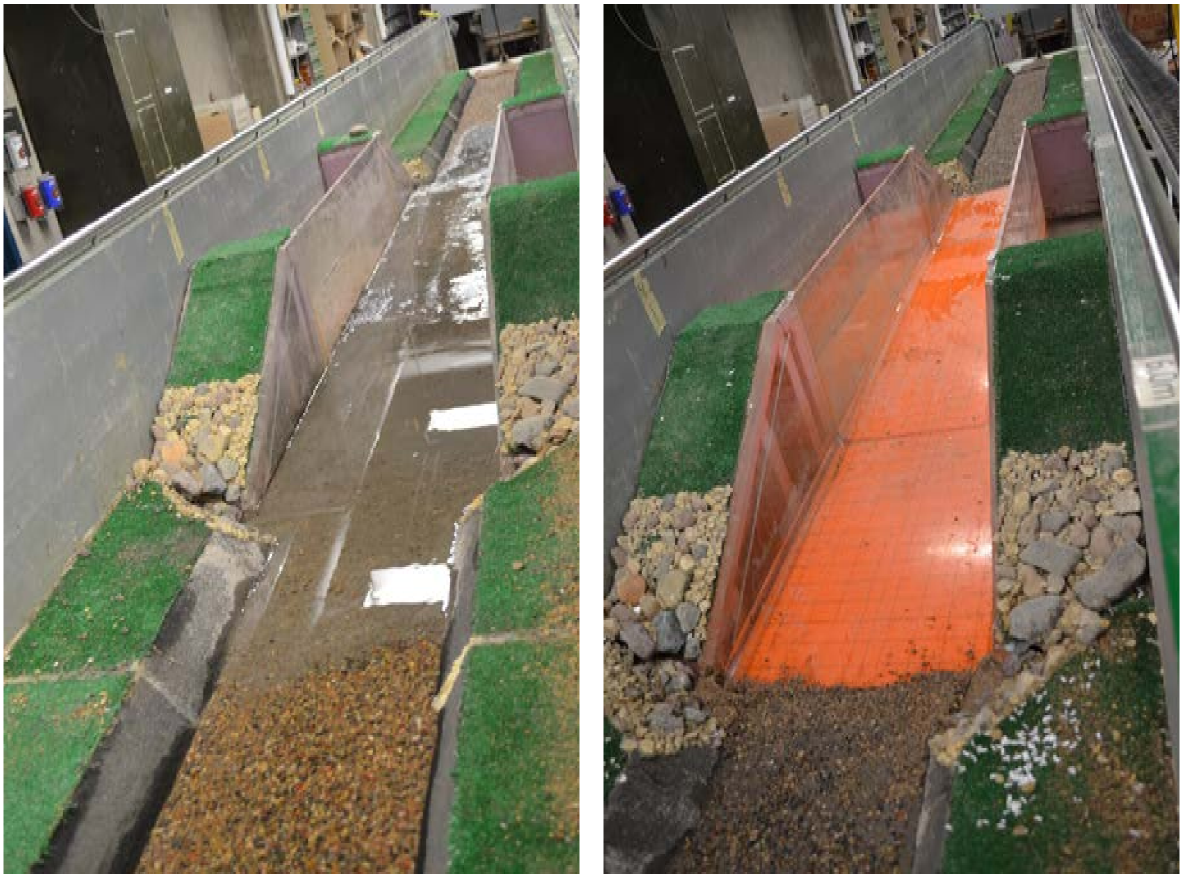

Figure 2.4. Initially filled culvert (left) and intially not-filled culvert (right) for low gradient experiments.

Table 2.2. Experimental matrix for low, moderate, and high gradient experiments.

Run #	Flow rate	Gradient	Culvert Initial Condition
1	BANKFULL	LOW	EQUILIBRIUM
2	BANKFULL	LOW	FILLED
3	BANKFULL	LOW	NOT-FILLED
4	HYDROGRAPH	LOW	FILLED
5	HYDROGRAPH	LOW	NOT-FILLED
6	BANKFULL	MODERATE	EQUILIBRIUM
7	BANKFULL	MODERATE	FILLED
8	BANKFULL	MODERATE	NOT-FILLED
9	HYDROGRAPH	MODERATE	FILLED
10	HYDROGRAPH	MODERATE	NOT-FILLED
11	BANKFULL	HIGH	EQUILIBRIUM
12	BANKFULL	HIGH	FILLED
13	BANKFULL	HIGH	NOT-FILLED
14	BANKFULL	HIGH	FILLED - STRUCTURES
15	HYDROGRAPH	HIGH	FILLED
16	HYDROGRAPH	HIGH	NOT-FILLED
17	HYDROGRAPH	HIGH	FILLED - STRUCTURES

During each experiment, continuous bed and water surface elevation data were collected down the middle of the flume using the data acquisition cart outfitted with a sonar probe and ultrasonic transducer. After each experiment, the final bed was scanned using a high-resolution laser scanner. Pre- and post- bed photos were taken. Velocity data were collected after the experiments over a filled culvert bed with a side-looking ADV.

2.3 Representative Slope and Grain Size Distributions

To capture the variation in stream morphology across the state of Minnesota, low, medium, and high-gradient Minnesota streams were selected to provide realistic slope and grain size distribution combinations. This section describes the selection of low- and moderate- gradient slope and grain size combinations. Representative low and medium- sloped sites were selected from previous culvert surveys in Minnesota (Hansen et al. 2011). As no average regional or state-wide data were available, representative sites were selected to ensure that flow depths and grain size distributions were appropriate and fell within general geomorphic stream classifications (i.e. Montgomery and Buffington 1998). The advantage of using these sites is the detailed survey data of channel cross-section and slope, bed material and culvert dimensions. A separate high-gradient site was selected to collect detailed information on slope, grain size distribution, and geomorphic characteristics.

The following criteria were used to narrow down the list of candidate sites to represent the low, medium, and high-sloped streams in Minnesota. These parameters were chosen by selecting culverts in Minnesota previously studied in Hansen et al. (2011) by the following criteria:

- The stream must have a gradient that fits into one of the following Montgomery-Buffington classes: pool-riffle (slope <0.015), plane-bed (slope 0.015-0.03) or step-pool (slope 0.03-0.08). Thus the stream must have a slope between 1% and 8%. The bed material of each stream must reflect the same Montgomery-Buffington class as its gradient to ensure the site is a typical stream. The high slope maximum was lowered to 6% to be representative of Minnesota streams on the North Shore of Lake Superior.
- The bed material of each site may contain a maximum of 10% silt and fine sand as these cannot be adequately scaled in flume experiments.
- The change of slope upstream and downstream of the culvert must be as small as possible to ensure that the culvert is not influencing the stream's classification.
- The floodplain must be no more than two to three times the bankfull width of the stream to ensure that both can be accurately modeled.
- The land cover within the watershed delineated upstream of the culvert must contain as little developed land as possible to avoid potential urban effects on the culvert hydrology.

To estimate flow rates for various return intervals for ungaged streams, StreamStats, an online tool developed by ESRI and USGS to make calculations on ungaged stream sites, was utilized (StreamStats 2013). StreamStats uses regional regression analysis as well as topographical and terrain data to delineate the drainage basin, calculate peak flow rates, and determine flow path profiles in Minnesota as described in Lorenz et al. (2010).

2.3.1 Low Gradient Pool-Riffle Stream

The representative low gradient stream selected for this study is Stoney Brook, located in Benton County, in central Minnesota, as shown in Figure 2.5. The stream slope upstream of the culvert was measured at 0.0019 while the slope downstream of the culvert was measured at 0.001. The change in slope from upstream to downstream is approximately 47.4% (Hansen et al. 2011). This slope was verified using the flow path profile tool on StreamStats which provided an approximate slope of 0.002. The slope of Stoney Brook at this culvert site is within the pool-riffle range of 0.001 to 0.02 (Montgomery and Buffington 1998).

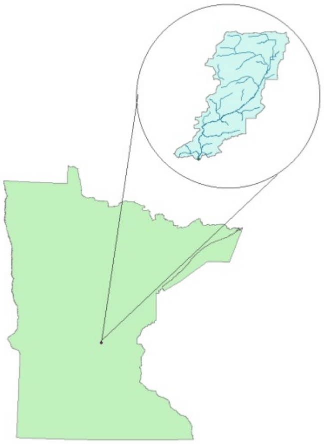

Figure 2.5. Map of Minnesota indicating location of Stoney Brook culvert site and map of associated drainage area; culvert located at 45.589 latitude and -93.973 longitude.

Hansen et al (2011) reported the bed material as 5% silt/clay, 41% sand, 52% gravel, 2% cobble, 0% boulder, 0% bedrock, with a D_{50} of 2.7 mm and a D_{84} of 24 mm. Montgomery and Buffington's pool-riffle stream has bed material characterized as being primarily composed of gravel, so Stoney Brook is consistent with this classification. The amount of silt in the stream is below the 10% limit.

The floodplain and bankfull widths are 32.4 feet and 14.2 feet, respectively (Hansen et al. 2011) resulting in a floodplain to bankfull width ratio of 2.3, which fits the criteria of less than 3. The floodplain width was verified using rough measurements from downloaded aerial lidar data. The bankfull depth was recorded as 2.3 feet (Hansen et al. 2011).

The watershed was delineated using ArcGIS and lidar data. Landuse was determined using the National Land Cover Database (Fry 2011). It was determined that the watershed is comprised of about 48% cropland, 27% pasture land, 9% forest, 9% developed land, and 5% wetland. Along the banks, as evident in Figure 2.6, the vegetation is mostly comprised of shrubs and grasses. The floodplain is mostly marsh and grassland.

Photos of Stoney Brook at the culvert, shown in Figure 2.6, reflect a low-sloped stream with relatively fine sediments, characteristic of a pool-riffle stream. The drainage area was estimated at 17.2 mi^2 by StreamStats with a regression equation validity range of 0.23 mi^2 to 1700 mi^2 (StreamStats 2013). Estimated flow rates are given in Table 2.3.

Figure 2.6. Photos of culvert on Stoney Brook.

Table 2.3. Flow rate statistics for culvert site on Stoney Brook (StreamStats, 2013).

Statistic	**Flow (ft^3/s)**	**Prediction Error (percent)**	**Equivalent years of record**
PK1_5	103	38	3.7
PK2	144	38	3.2
PK5	270	42	3.7
PK10	378	46	4.4
PK25	532	50	5.3
PK50	656	54	5.9
PK100	799	58	6.4
PK500	1170	67	7.2

2.3.2 Medium Gradient Plane-Bed Stream

Kimball Creek was selected as the representative medium gradient prototype stream. The surveyed culvert is located in Cook County in northeastern Minnesota as shown in Figure 2.7. The stream slope upstream of the culvert was measured at 0.01 while the downstream slope was measured at 0.013 (Hansen et al. 2011). The change in slope from upstream to downstream is 30%. The slope was verified by using the flow path profile tool on StreamStats and determined to be 0.017, which validates the measurements recorded in the report (StreamStats 2013). Kimball Creek's slope at the site of the culvert is within the plane-bed range of 0.01 to 0.03 (Montgomery and Buffington 1998).

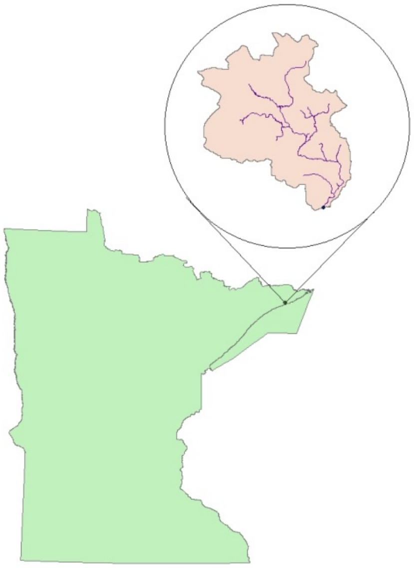

Figure 2.7. Map of Minnesota with location of Kimball Creek culvert indicated and diagram of associated drainage area magnified; culvert is located at 47.812 latitude and -90.210 longitude.

Hansen et al (2011) reported the bed material as 0% silt, 8% sand, 52% gravel, 40% cobble, and 0 % boulder, with a D_{50} of 49.8 mm and a D_{84} of 135.5 mm. This is consistent with typical plane-bed stream bed material characterized as being primarily composed of gravel and cobble (Montgomery and Buffington 1998).

The bankfull and floodplain widths as well as the average bankfull depth recorded are 17.7 feet, 200 feet, and 1.5 feet, respectfully (Hansen et al. 2011). Thus, the floodplain to bankfull width ratio is greater than 3, which does not meet our criteria. However, a rough analysis of the floodplain width using topography data on StreamStats approximates the floodplain to bankfull width ratio to be closer to 2.

Land cover in the Kimball Creek watershed is comprised of about 75% forest, 13% shrub land, 8% wetland, 2% developed land, and 2% water (StreamStats 2013; Fry 2011). The banks are comprised mostly of shrubs, grasses, cobble, and organic material, and the floodplain is mostly forested, as evident in Figure 2.8.

Photos of Kimball Creek at the culvert shown in Figure 2.8 reveal a medium sloped stream with a mixture of finer sediments and cobble, characteristic of a plane-bed stream and consistent with the above observations. The drainage area is estimated at 11.6 mi^2 with a regression equation validity range of 0.21 mi^2 to 607 mi^2 (StreamStats 2013). The estimated flow rates appear in Table 2.4.

Figure 2.8. Photos of culvert on Kimball Creek (Hansen et al. 2011).

Table 2.4. Flow rate statistics for culvert site on Kimball Creek (StreamStats 2013).

Statistic	Flow (ft^3/s)	Prediction Error (percent)	Equivalent years of record	90-Percent Prediction Interval	
				Minimum	Maximum
PK1_5	177	45	2.8	80.6	337
PK2	228	47	2.4	99.3	444
PK5	386	50	2.8	158	786
PK10	520	53	3.5	205	1080
PK25	722	56	4.5	272	1550
PK50	905	59	5.1	328	1980
PK100	1110	62	5.7	385	2500
PK500	1700	71	6.5	521	4120

2.3.3 High-Gradient Step-Pool Stream

Moderate and high-gradient streams provide a special design challenge for fish passage. Bed roughness, in the form of steps and pools, riffles and transverse ribs are important considerations for flow fields within the stream and culvert. Based on our literature review and previous work (Hansen et al. 2009 and 2011), very little research has been conducted examining the importance of bed roughness in a culvert to fish passage applications, yet bed structures such as riffles and transverse ribs are expected to be important for both bed stability (maintaining sediment at stream bed grade in the culvert) and fish passage.

In addition to slope and grain size information, information on the spacing and height of bed forms (steps, ribs and riffles) was needed to set up high gradient experiments. In Minnesota, high gradient streams are found primarily in the Lake Superior Basin and in high gradient tributaries to the Lower Mississippi River, while moderate gradient streams are found in the Upper Mississippi, St. Croix, and Rainy River Basins (Hansen et al. 2009; see Figure 2.9 for watershed boundaries). Beginning with a list of sites visited in a previous Mn/DOT project (Hansen et al.

2011), we visited sites that fell within the moderate (1-3%) or high (3-8%) gradient streams. These streams were identified by overlaying culvert sites with sub-watershed slopes in the Lake Superior Basin (Figure 2.9). In addition to slope, site selection criteria included stream width < 20 ft, well-displayed organized stream structures such as ribs, riffles and pools, accessibility, and lack of dense vegetation in the channel. The West Branch of the Knife River provided a reasonable site with a 2% slope measured from rib to rib with a clinometer. However, the effects of the June 2012 storm were visible and deemed likely to have dramatically altered both stream morphology and sediment grain size distribution. Therefore, site selection was focused on sites away the influence of the 2012 storm (Figure 2.10). A total of approximately 10-15 sites were visited before selecting Wood's Creek north of Grand Marais, MN (Figure 2.11). This is a designated trout stream with easy access from the Superior Hiking Trail. Two sections upstream of the culvert were selected to be surveyed, a moderate and high gradient section.

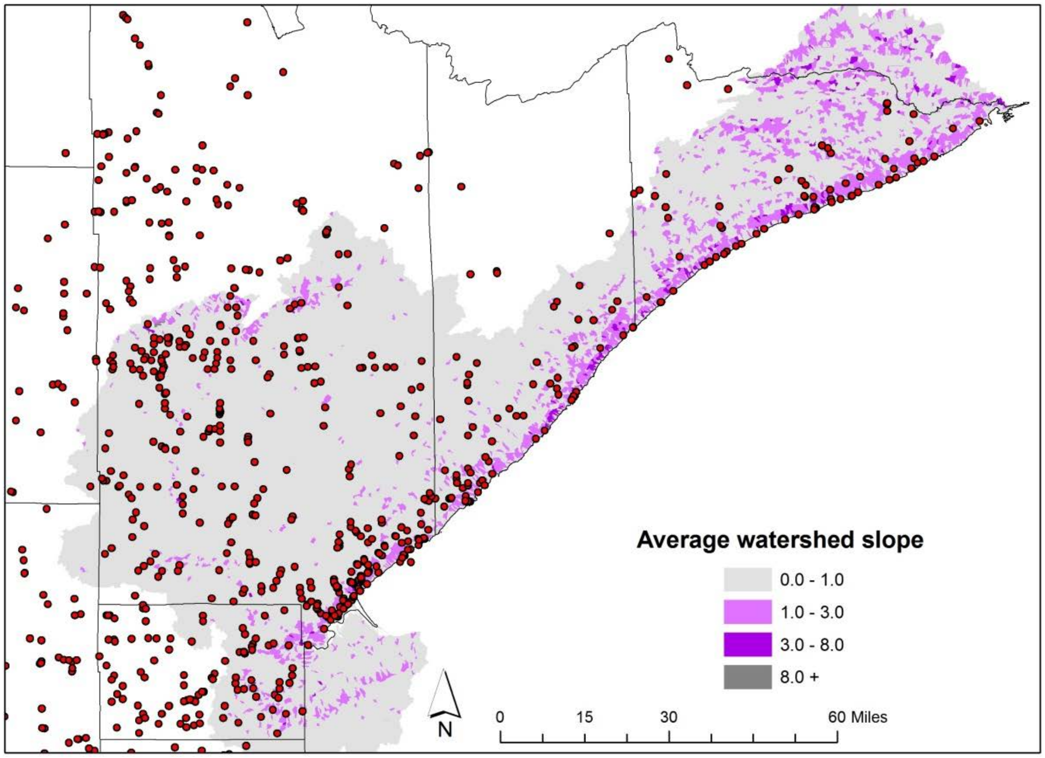

Figure 2.9. Potential culvert sites in the Lake Superior Basin by sub-watershed slope. (Data from Hollenhorst et al. 2007; http://www.nrri.umn.edu/lsgis2/watersheds/index.html and Mn/DOT).

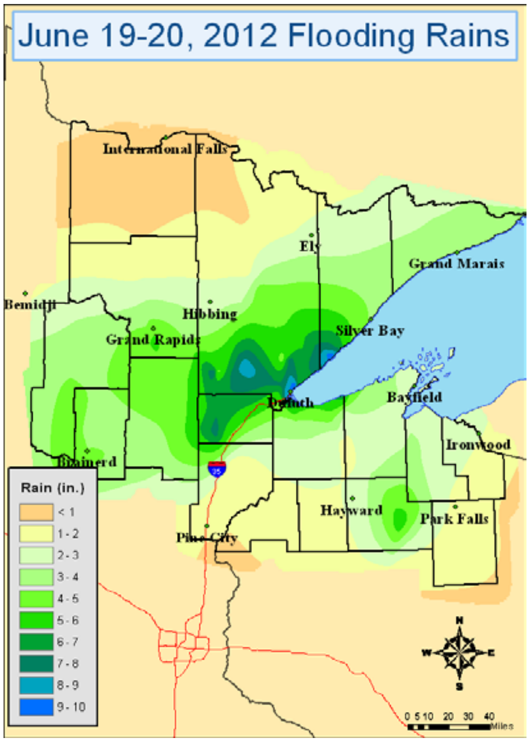

Figure 2.10. Rainfall from June 2012 storm in Duluth, MN. (http://www.crh.noaa.gov/dlh/?n=june2012_duluth_flood)

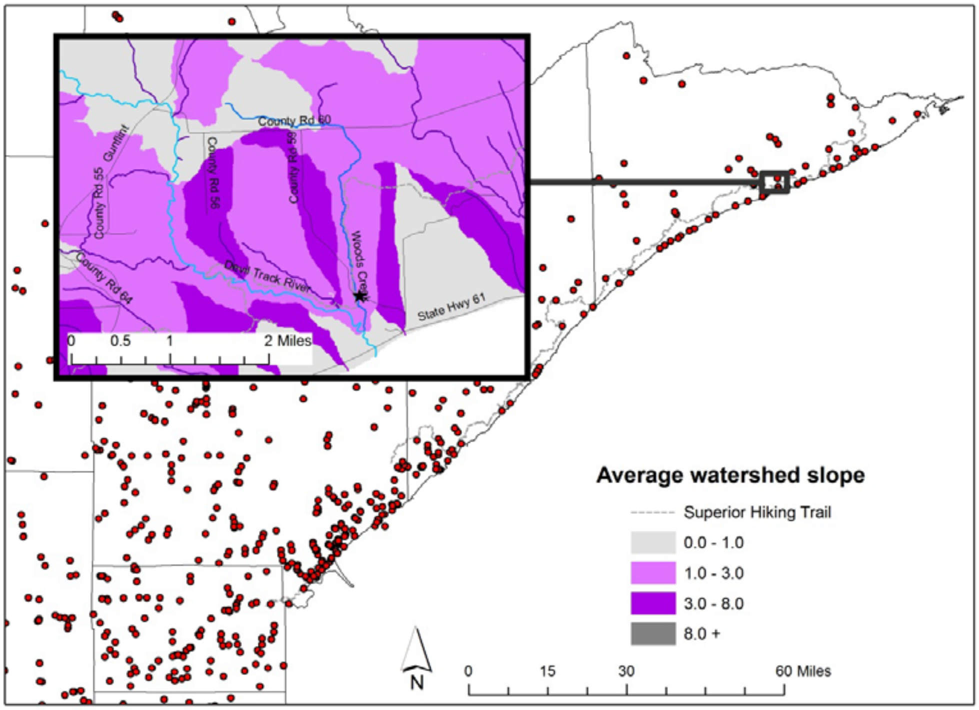

Figure 2.11. The study site to collect high and moderate slope information was Woods Creek, near Grand Marais, MN. This site is on the Superior Hiking Trail providing easy access. (Sub-watershed data from Hollenhorst et al. 2007; http://www.nrri.umn.edu/lsgis2/watersheds/index.html).

Two sites were surveyed at Wood's Creek, a moderate gradient section just upstream of the existing culvert, and a high gradient section further upstream. The moderate site was surveyed July 26, 2013 and the high gradient site was surveyed August 5, 2013. On the first visit, Bob Gubernick (USFS fish passage expert) accompanied the research team to assist with appropriate site selection and data collection. At each site, survey data included multiple cross-sections and a longitudinal survey to quantify variability in width, reach slope, and location of roughness elements such as steps or transverse ribs. Surface grain size data were collected by measuring the middle axis of 400 grains from each reach. These grains were spatially distributed across and along each reach. Subsurface samples were collected and were brought back to SAFL for future analysis.

Moderate Gradient Survey

Three cross-sections were surveyed using a laser level in the Wood's Creek moderate gradient section to quantify the variability in width (bank roughness) along this reach (Figure 2.12). From this survey, estimates of channel width, depth, and variability in width and depth are shown in Table 2.5.

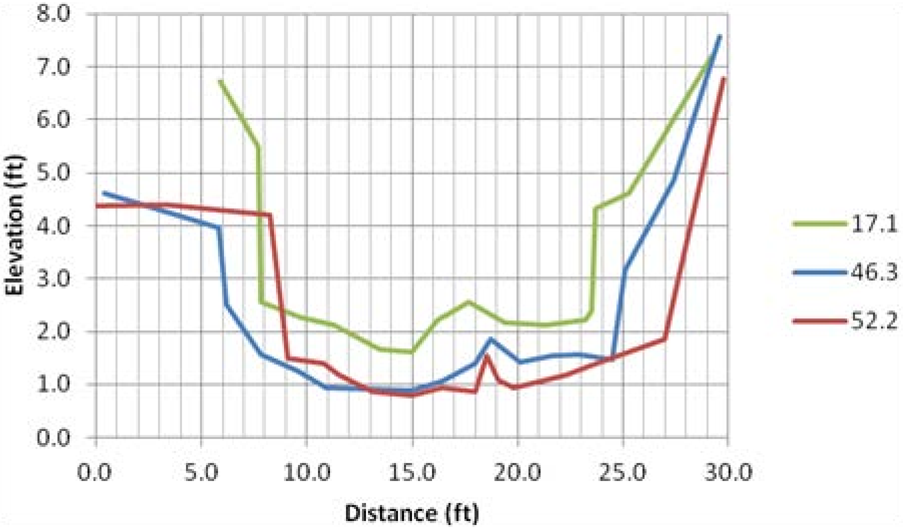

Figure 2.12. Moderate gradient cross-sectional survey.

Table 2.5. Estimates of channel width and depth for the Wood's Creek moderate gradient section.

	Station (ft)	Width (ft)	Depth (ft)
XS1	17.1	16.0	2.7
XS2	46.3	20.5	3.3
XS3	52.2	19.2	3.2
	Mean	18.6	3.1

	Stdev	2.3	0.3

The longitudinal survey in the moderate section of Wood’s Creek was also collected using a laser level. Points were collected at breaks in slope along the channel thalweg to identify the location of ribs, steps, and pools (Figure 2.13). The slope of this section (measured from rib to rib) was 2.7%.

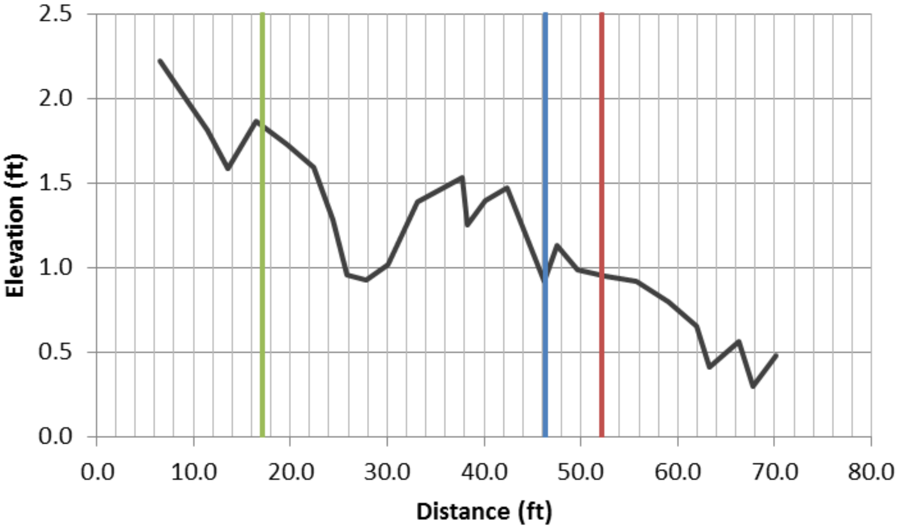

Figure 2.13. Moderate gradient longitudinal survey. Vertical lines indicate locations of cross sectional surveys.

The location and height of roughness elements were measured along the channel thalweg. In the moderate gradient section, these consisted mostly of transverse ribs (Figure 2.14).

Figure 2.14. Moderate gradient stream section of Wood's Creek, looking upstream.

Table 2.6. Location and description of roughness elements in moderate gradient section of Wood's Creek.

Location ft	Description	element size				protrusion ft	location notes ft
			in	in	in		
6.6	rib	1	9.4	15.6	5.5		
		2	8.3	9.4	5.9		
		3	7.9	5.5	5.7		
					average	**0.4**	
12.1	boulders	1	15.7	11.0	11.8	0.8	2.5 from RB
		2	41.3	47.2	18.9	1.5	5.3 from LB
		3	18.9	20.1	15.7	0.9	2.5 from LB
					average	**1.0**	
23.0	boulders	1	55.1	47.2	19.7	1.5	5.9 from RB
		2	35.4	30.7	18.1	1.1	7.9 from LB
		3	33.1	39.4	18.1	1.0	1.1 from LB
					average	**1.2**	
29.5	single boulder	1		39.4			2.5 from RB
37.7	rib	1	10.6	6.7	5.9		
		2	5.1	7.9	5.1		
		3	7.5	5.9	5.7		
					average	**0.4**	
42.3	rib	1	9.8	7.7	4.7		
		2	8.3	6.5	5.7		
		3	5.9	17.3	5.1		
					average	**0.3**	
47.6	rib	1	15.0	16.5	9.8		
		2	7.9	14.6	4.7		
		3	7.5	9.4	5.2		
					average	**0.3**	
53.5	boulders	1	19.3	13.0	13.0		
		2	17.7	18.5	9.1		
					average	**0.6**	
59.7	boulders	1	22.0	26.8	17.3		
		2	11.8	16.5	7.1		
					average	**0.8**	
63.3	boulders		16.9	28.3	14.6		
			11.8	19.7	9.4		
			11.8	14.2	8.3		
					average	**0.7**	
66.6	boulders	1	11.0	17.7	11.8		
		2	38.6	19.7	16.1		
					average	**0.8**	
70.2		1	16.9	11.8	11.8		
		2	7.9	35.4	40.2		
		3	17.7	19.3	9.8		
		4	37.8	23.6	14.2		
		5	16.9	11.8	18.5		

High Gradient Survey

Two cross-sections were surveyed using a laser level in the Wood's Creek high gradient section to quantify the variability in width (bank roughness) along this reach (Figure 2.15). From this survey, estimates of channel width, depth, and variability in width and depth are shown in Table 2.7.

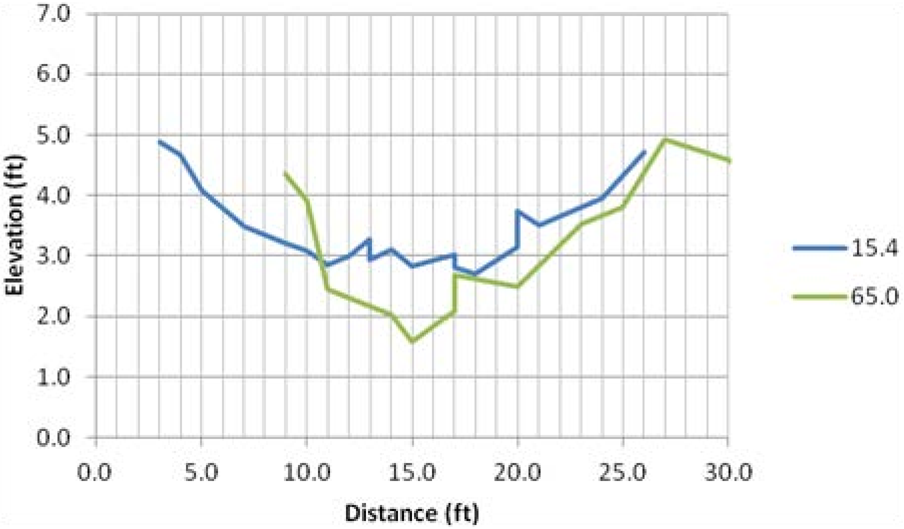

Figure 2.15. High gradient cross-sectional survey.

Table 2.7. Estimates of channel width and depth for the Wood's Creek high gradient section.

	Station (ft)	Width (ft)	Depth (ft)
XS1	15.4	18	2.1
XS2	65	22	3.1
	Mean	20	2.6
	Difference	4.0	1.0

The longitudinal survey in the high gradient section of Wood's Creek was also collected using a laser level. Points were collected at breaks in slope along the channel thalweg to identify the location of ribs, steps, and pools (Figure 2.16). The slope of this section (measured from rib to rib) was 5.4%.

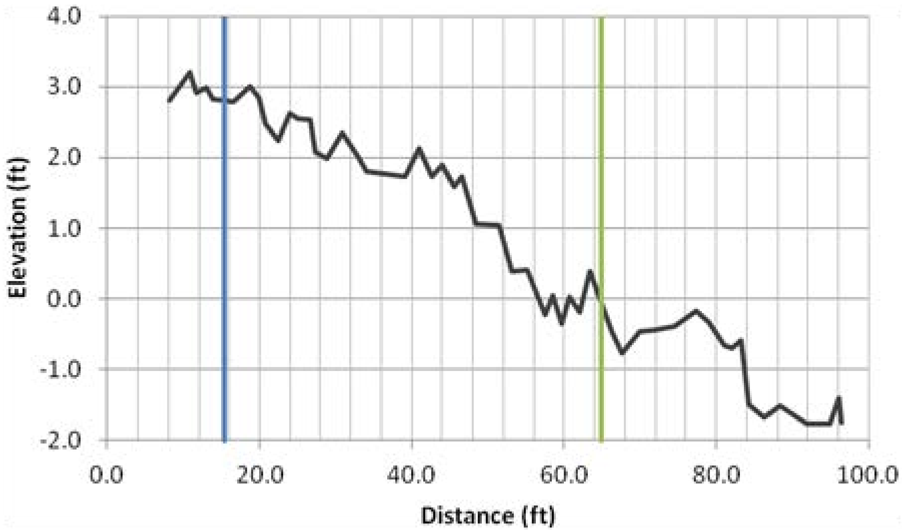

Figure 2.16. High gradient longitudinal survey. Vertical lines indicate locations of cross sectional surveys.

The location and height of roughness elements were measured along the channel thalweg. In the high gradient section, these consisted of transverse ribs, steps, cascades, and riffles (Figure 2.17).

Figure 2.17. High gradient stream section, looking upstream.

Table 2.8. Location and description of roughness elements in high gradient section.

Location ft	Description	element size				protrusion ft	location notes ft
			in	in	in		
19.7	rib	1	10	14	10.5		
		2	6	8.5	11.5		
		3	5.5	20	20.5		
					average	0.7	
26.9	rib	1	16	24	11.5		
		2	27.5	37	7.5		
		3	11	18	7		
					average	0.5	
34.8	roughness element	1	10.5	22	13	1.3	7 from RB
		2	bedrock				2.7 from LB
41.0	riffle	1	9	11	5		
		2	6	3.5	8		
		3	10	10.5	10		
		4	8.5	14	6.5		
		5	16	5	6.5		
		6	7.5	105	8		
					average	0.8	
47.6	cascade	1	19	25	11.5		
		2	18	15	9.5		
		3	23	35	17.5		
		4	34	32	14		
		5	11.5	20	22		
		6	18	36	7.5		
					average	2.0	
60.0	roughness element	1	BEDROCK				3 from LB
		2	19	27.5	15	1.4	5 from RB
		3	2	20	8	0.8	6.5 from RB
					average	1.1	
69.9	roughness element	1	19.5	21	11	1.3	2.5 from LB
		2	14.5	20	8	1.0	6 from LB
		3	13	21	8	0.8	5 from RB
					average	1.0	
77.4	cascade	1	10	13	6.5		
		2	13	19	8		
		3	22	20	13.5		
		4	18	26	11		
					average	0.7	
83.3	step		33	15.5	13		
			18.8	17	9.5		
			16.5	22	19		
					average	2.2	
92.8	roughness element	1	12	15	13	1.5	1.8 from LB
		2	18	10.5	13.5	1.2	3.6 from LB
		3	27	21	12	1.7	3 from RB
					average	1.5	
96.1	rib	1	10	12.5	8.5		
		2	9.5	12	10		
		3	10.5	16	7		
					average	0.6	

Grain Size Analysis

Surface grain size measurements (grain roughness) were collected using a spatially distributed pebble count in each reach. Each reach was split into approximately 20 equally spaced transects where 10-20 equally spaced grains (12 inch spacing) were collected for a total of 300 samples. An additional 100 samples were collected in equally spaced longitudinal transects. Grains were measured on their intermediate axis and data were pooled to obtain a grain size distribution for each reach (Figure 2.18). All samples less than 2 mm were entered as sand (0.1 – 2 mm). As expected, the high gradient reach had a much coarser distribution of grain sizes (Table 2.9).

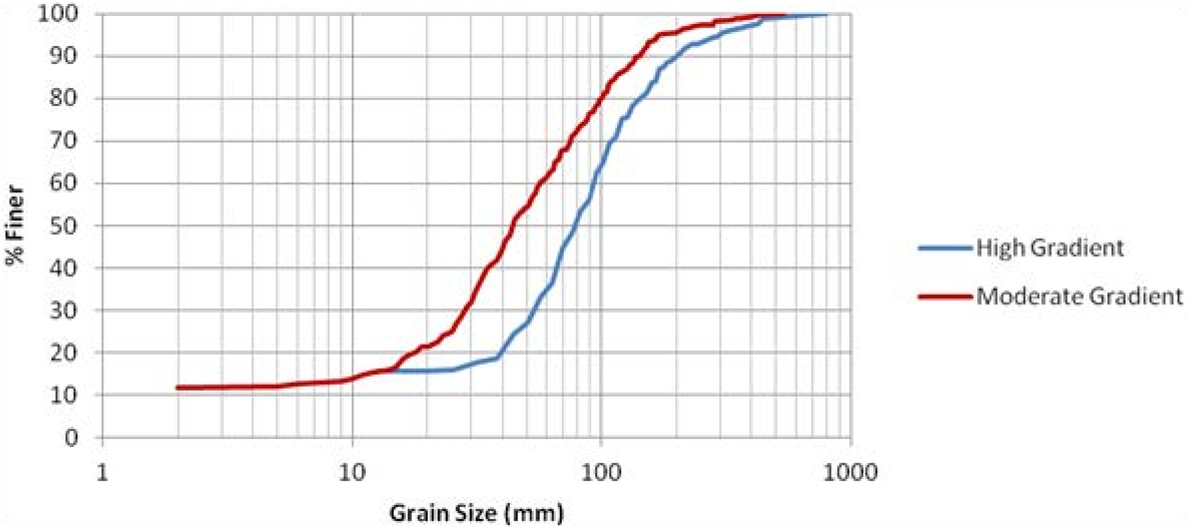

Figure 2.18. Grain size distributions for high and moderate gradient sections of Wood’s Creek based on 400 grains from each sub-reach. The smallest fraction (below the line) was measured as sand (0.1-2.0 mm).

Table 2.9. Grain sizes for surface pebble counts for high and moderate gradient sections of Wood’s Creek.

	Grain Size (mm)	
	High Gradient	**Moderate Gradient**
D90	191	139
D84	165	109
D50	76	44
D16	24	14
D5	1	1

Table 2.10. Flow Rate Statistics for Culvert Site on Kimball Creek (StreamStats 2013)

Statistic	**Flow (ft^3/s)**	**Prediction Error (percent)**	**Equivalent years of record**	**90-Percent Prediction Interval**	
				Minimum	**Maximum**
PK1_5	78.4	45	2.8	36.2	147
PK2	106	47	2.4	47	204
PK5	203	50	2.8	84.2	405
PK10	292	53	3.5	117	596
PK25	439	56	4.5	169	922
PK50	581	59	5.1	215	1250
PK100	752	62	5.7	266	1660
PK500	1300	71	6.5	405	3060

2.4 Model Setup

The goal the tilting bed flume experiments was to examine sediment transport through single barrel recessed box culverts under various geomorphic conditions found in Minnesota. The culvert was scaled directly at 8:1 prototype to model scaling. The 18 in model culvert represented a barrel size of 12 ft. The model culvert was 10 ft long representing an 80 ft long culvert. As no data could be located for average regional characteristics, representative slopes and grain size distributions were chosen from representative field sites. Target depth, slope, discharge, and grain size distributions were scaled to maintain both geometric and kinematic similarity between the representative reaches and the experimental flume systems using Froude and Shields scaling relationships (for more information see Parker et al. 2003). The horizontal and vertical scale factors were the same (no distortion).

Froude scaling relationships:

$$Fr = \frac{U}{\sqrt{Hg}}$$

Where Fr is the Froude number, U is the mean flow velocity, H is the flow depth, and g is the gravitational acceleration constant. To achieve similarity between both systems, the model Froude number is set equal to that of the prototype. It follows that:

$$Fr_m = Fr_p$$

$$\frac{U_m}{\sqrt{H_m g}} = \frac{U_p}{\sqrt{H_p g}}$$

Correctly scaling the size and distribution of sediment in the model is important to capturing the transport behavior. This scaling relationship is governed by the Shields stress, τ^*, dimensionless parameter which characterizes the dimensionless bed stress relative to resistance of the grains to motion. The goal is to have similarity in the Shields stress between the prototype and model. Shields stress is written as follows:

$$\tau^* = \frac{\tau_0}{(\gamma_s - \gamma_w) D} = \frac{\gamma_w HS}{(\gamma_s - \gamma_w) D} = \frac{HS}{1.65D}$$

where γ_s and γ_w are specific weights of sediment and water, respectively, τ_0 is the bed shear stress, S is slope, and D is particle size. Similarity in Shields stress between the model and the prototype is shown as follows:

$$\tau_m^* = \tau_p^*$$

$$\frac{H_m S_m}{1.65D_m} = \frac{H_p S_p}{1.65D_p}$$

$$\frac{D_p}{D_m} = \frac{H_p}{H_m} \frac{S_p}{S_m}$$

The grain size distribution parameters from the representative sites are D_{max}, D_{84}, and D_{50} where the subscript represents the percentile in the cumulative grain size distribution. Because these samples were taken from the sediment surface, the Fuller Thompson method was used to estimate the fine end of each distribution (Fuller and Thompson 1906; see TetraTech 2011). This is important to represent the bulk mix before armoring processes. The fine components of the grain size distributions were determined using the following equations and scaled directly.

$$D_{30} = 0.6^{1/n} D_{50}$$

$$D_{10} = 0.2^{1/n} D_{50}$$

$$D_5 = 0.1^{1/n} D_{50}$$

In the experiments, a representative bed armor layer was achieved by running the scaled grain size distribution through the flume for a long period of time (to equilibrium as determined by no visual change in grain size, and no measureable change in the time-averaged slope) prior to the collection of data, similar to Mao (2012). This allows the flume to reach an equilibrium slope and allows the armoring process to occur.

Chapter 3
Single Barrel Slope and Grain Size Experiments

3.1 Low Gradient Experiments

The tilting bed flume was set at 0.2 % for the low gradient experiments. A sediment mix based on the scaled representative low gradient stream grain size distribution (with an adjustment to account for surface armoring) was created by combining sediment mixes from local quarries (Figure 3.1). Because the scaled sediment fell within the cohesive range, an adjustment was made by changing density with appropriately sized ceramic microspheres such that the fall velocity between adjusted grain size and scaled grain size remained the same using the following equation:

$$W_s = \frac{gRD^2}{18\nu}$$

where W_s is fall velocity, g is acceleration due to gravity, D is representative grain size, and v is kinematic viscosity. A target bankfull discharge appropriate for the low gradient system was selected using Manning's equation. The discharge was set by trial and error to the bankfull elevation, and then the measured velocity was verified to fall within the range of velocities from the 1.5 yr return interval flows estimated for the low gradient representative stream. A hydrograph was developed by selecting a target maximum flood stage and stepping from below bankfull to bankfull to two overbank flows. Each step on the hydrograph was 30 minutes (Figure 3.2). For each run, sediment recirculation was continuous. The effect of culvert filling was tested for both steady state bankfull flows and for a simulated hydrograph. During each experiment, continuous bed and water surface elevation data were collected down the middle of the flume using the data acquisition cart outfitted with a sonar probe and ultrasonic transducer. After each experiment, the final bed was scanned using a high-resolution laser scanner. Pre- and post- bed photos were taken. Velocity data were collected after the experiment over a filled culvert bed with a side looking ADV.

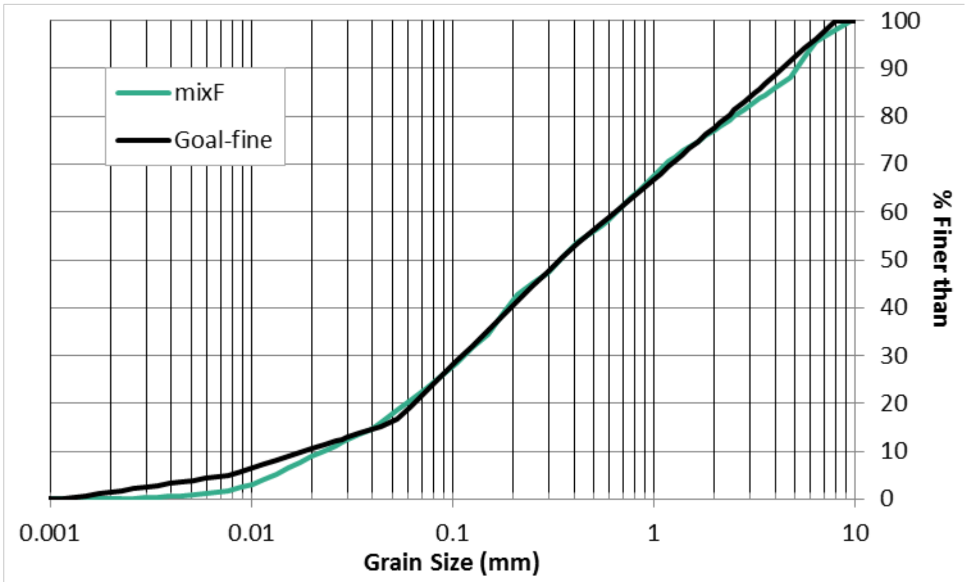

Figure 3.1. Target and mixed grain size distribution for the low gradient experiments.

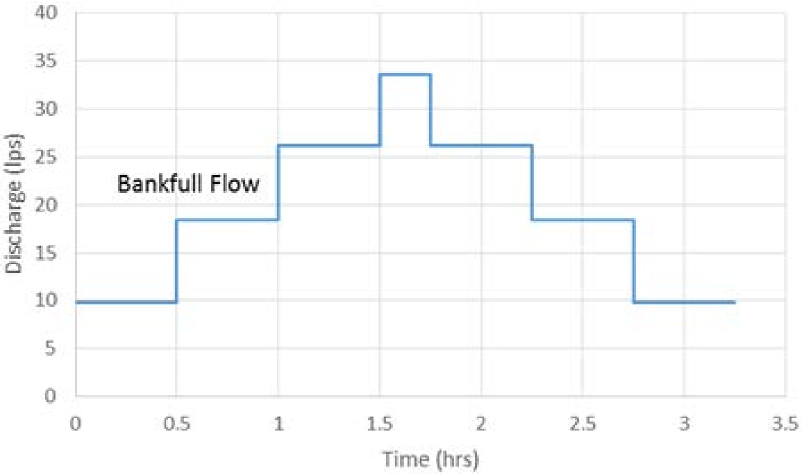

Figure 3.2. Hydrograph and bankfull flow rates for low gradient experiments.

Final topography for the equilibrium channel (no culvert), intial condition and final bed elevation for each run in the low gradient tilting bed flume experiments are shown in Figure 3.3. Note that in area where the signal hit the plexigas culvert bottom, some bad returns were collected. Figure 3.4 compares the surface bed material in the center of the culvert for each run.

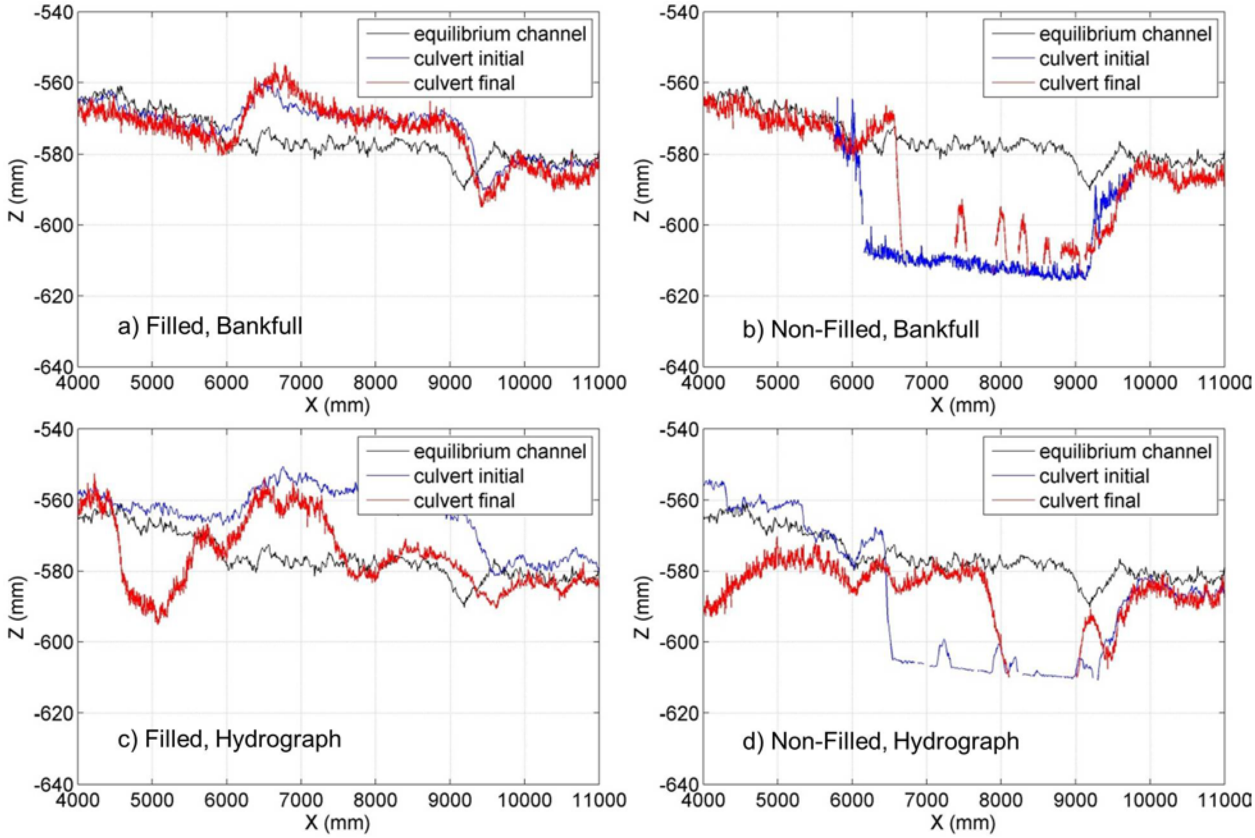

Figure 3.3. Comparison of equilibrium (no culvert; black), initial (blue), and final (red) bed elevation along the channel midline for the low gradient experiment. The culvert extends from X=6160 mm to X=9210 mm.

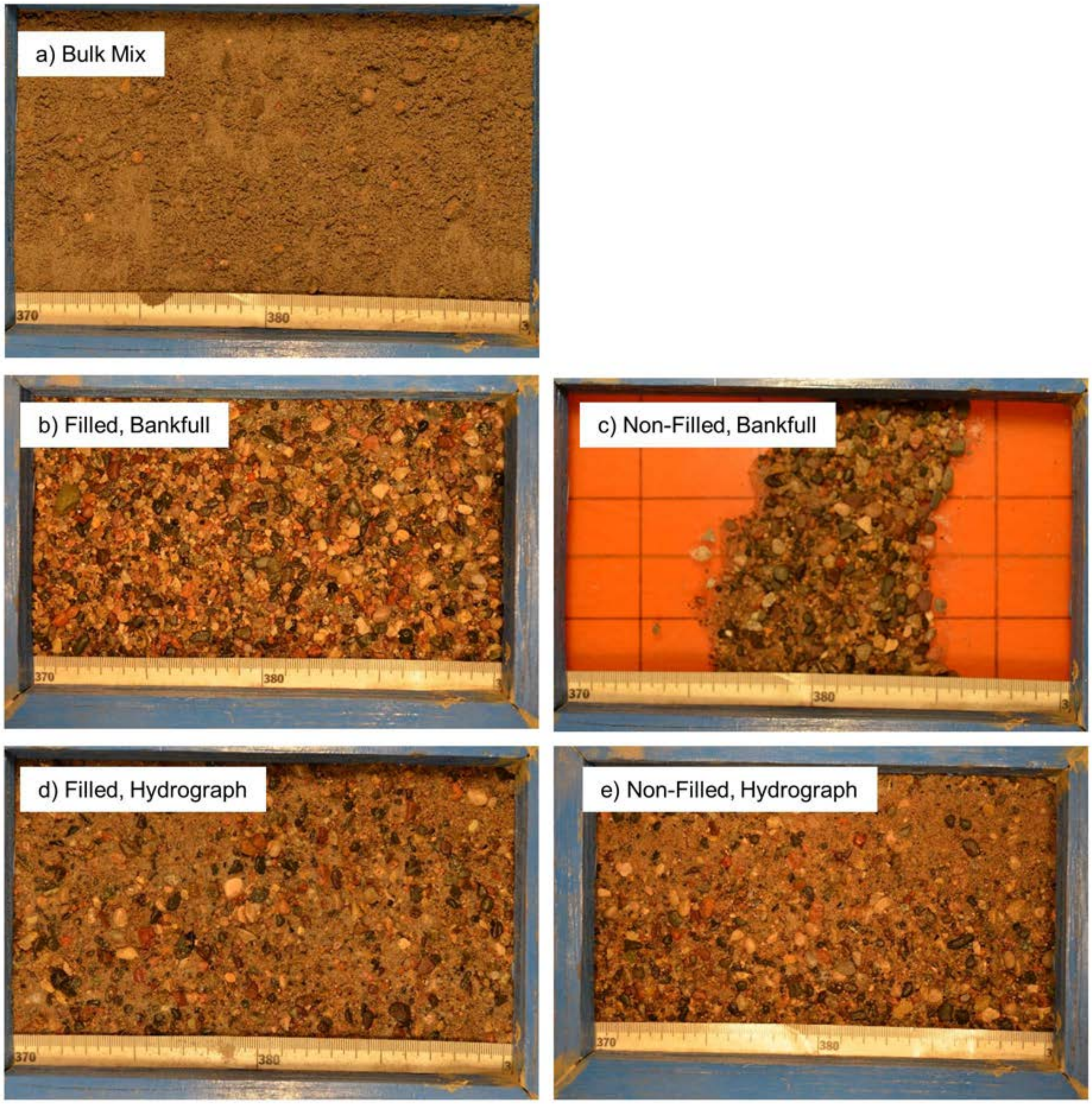

Figure 3.4. Surface bed material collected a) before flow (bulk mix), and b-e) at the end of each run for the low gradient experiment.

Depth-averaged velocity measurements for each flow rate were collected in the middle of the culvert and upstream of the influence of the culvert with a side-looking ADV (Table 3.1). All velocity measurements in the culvert were collected under the filled culvert scenario. The first flow rate was below bankfull, the second was at bankfull and the third and fourth were above bankfull flow.

Table 3.1. Depth-averaged velocity and depth measurements collected in the middle of the culvert and upstream of the culvert for each flow rate in the hydrograph for the low slope experiments. All culvert measurements were collected for the filled case.

	CULVERT		**UPSTREAM**	
Flow Rate (lps)	**V (m/s)**	**H (cm)**	**V (m/s)**	**H (cm)**
9.8	0.42	8.6	0.62	7.6
18.4	0.59	10.2	0.74	9.9
26.1	0.70	11.6	0.77	11.4
33.6	0.81	11.4	0.81	13.6

Simultaneous bed and water surface measurements were collected during each run. To examine how the bed changed during the hydrograph runs, three points were selected within the culvert: near the upstream end, in the middle, and near the downstream end. A time series of the bed and water surface elevations collected at these points is shown in Figure 3.5. Note the sonar probe had issues with a bare plexiglass culvert bottom in resulting in obviously erroneous points.

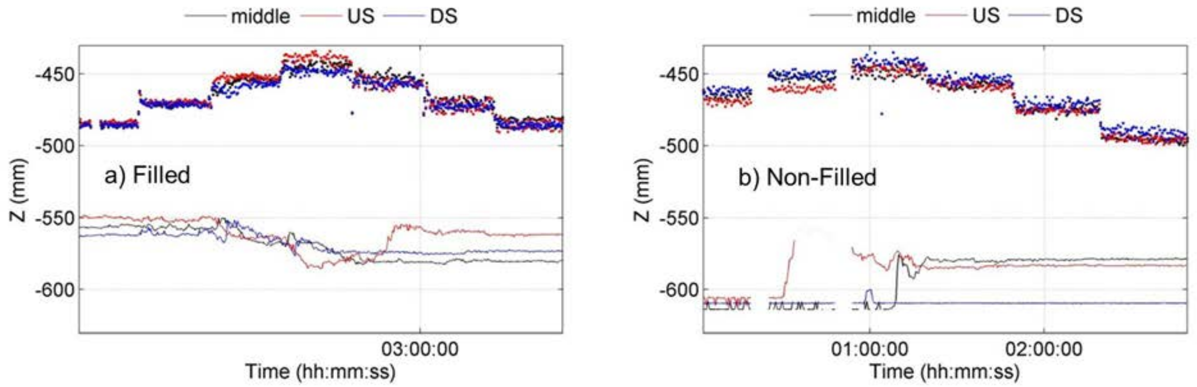

Figure 3.5. Simultaneous bed and water surface elevations collected at three points within the culvert for the initially a) filled and b) non-filled low gradient culvert hydrograph runs. Black = middle of culvert, red = upstream end of culvert (X=6670 mm), blue = downstream end of culvert (X=8590 mm).

3.2 Moderate Gradient Experiment

The tilting bed flume was set at 1.5 % for the moderate gradient experiments. A sediment mix based on the scaled representative moderate gradient stream (plane bed) grain size distribution (with an adjustment to account for surface armoring) was created by combining sediment mixes from local quarries (Figure 3.6). A target bankfull discharge appropriate for the moderate gradient system was selected using Manning's equation. The discharge was set by trial and error to the bankfull elevation, and then the measured velocity was verified to fall within the range of velocities from the 1.5 yr return interval flows estimated for the moderate gradient representative stream. A hydrograph was developed by selecting a target maximum flood stage and stepping from below bankfull to bankfull to two overbank flows. Each step on the hydrograph was 30 minutes except for the highest flow, which was only maintained for 15 minutes because it was difficult to keep up with the manual recirculation (Figure 3.7). For each run, sediment recirculation was continuous. Because material moving through the stream was larger than what the recirculation system could handle, large (>1 cm) sediment was collected off of a screen at the downstream end of the flume and recirculated by hand at the top of the flume. The effect of culvert filling was tested for both steady state bankfull flows and for a simulated hydrograph (see Figure 3.8). During each experiment, continuous bed and water surface elevation data were collected down the middle of the flume using the data acquisition cart outfitted with a sonar probe and ultrasonic transducer. After each experiment, the final bed was scanned using a high-resolution laser scanner. Pre- and post- bed photos were taken (Figure 3.9). Velocity data were collected after the experiment over a filled culvert bed with a side looking ADV.

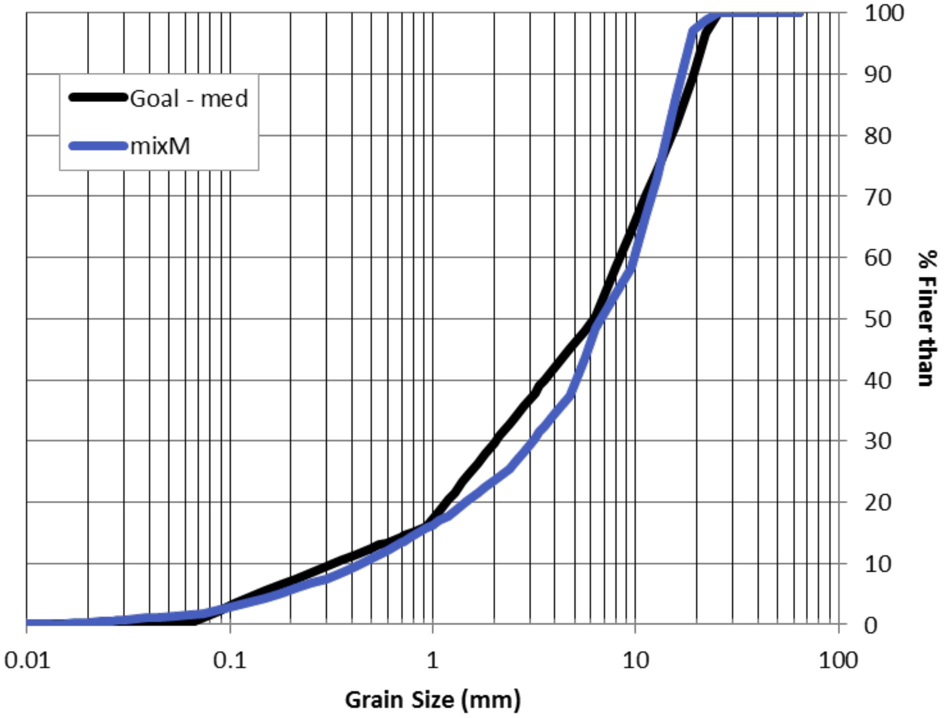

Figure 3.6. Target and mixed grain size distribution for the moderate gradient experiments.

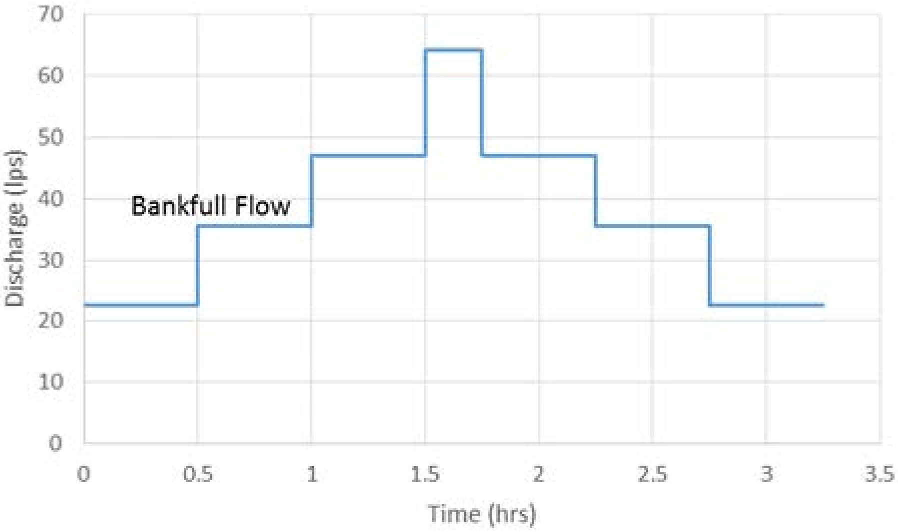

Figure 3.7. Hydrograph and bankfull flow rates for moderate gradient experiments.

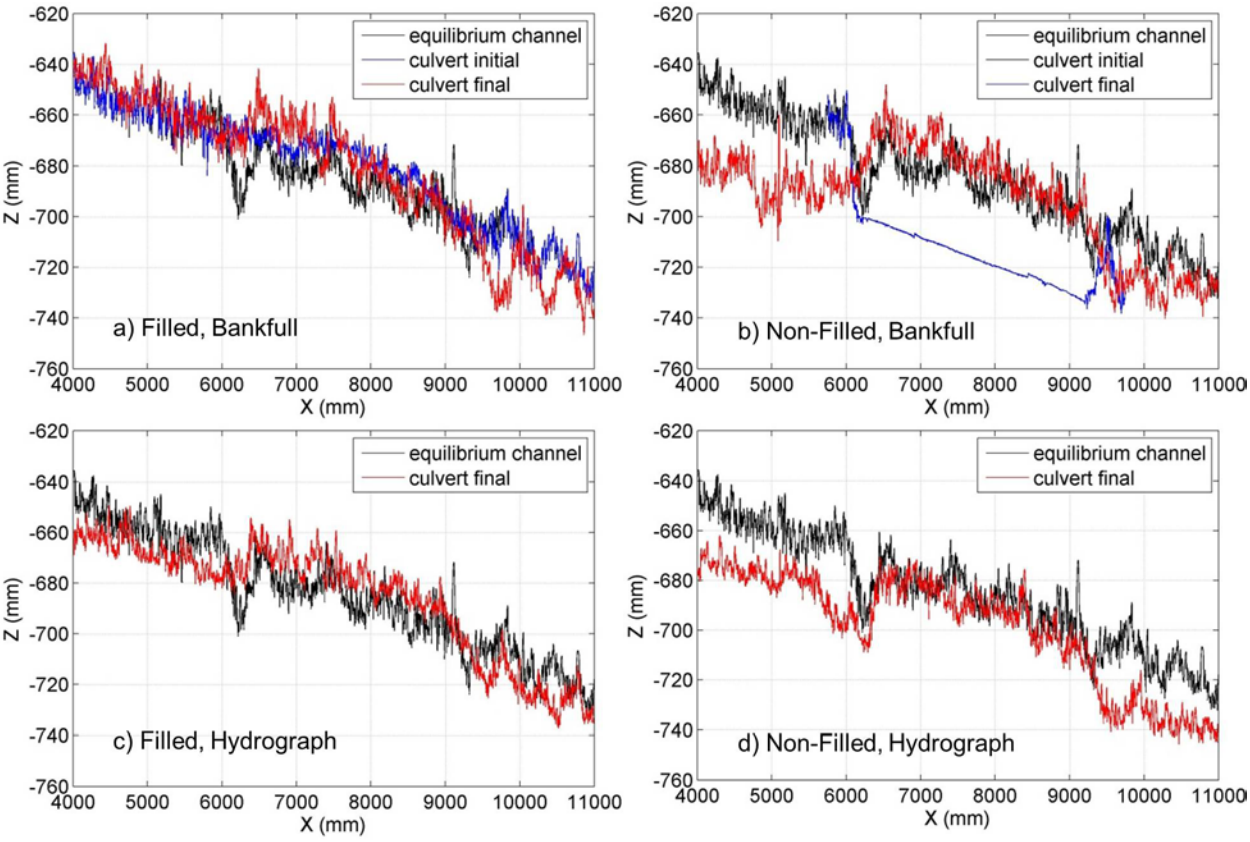

Figure 3.8. Comparison of equilibrium (no culvert), initial, and final bed elevation along the channel midline for the moderate gradient experiment. The culvert extends from X=6150 mm to X=9200 mm.

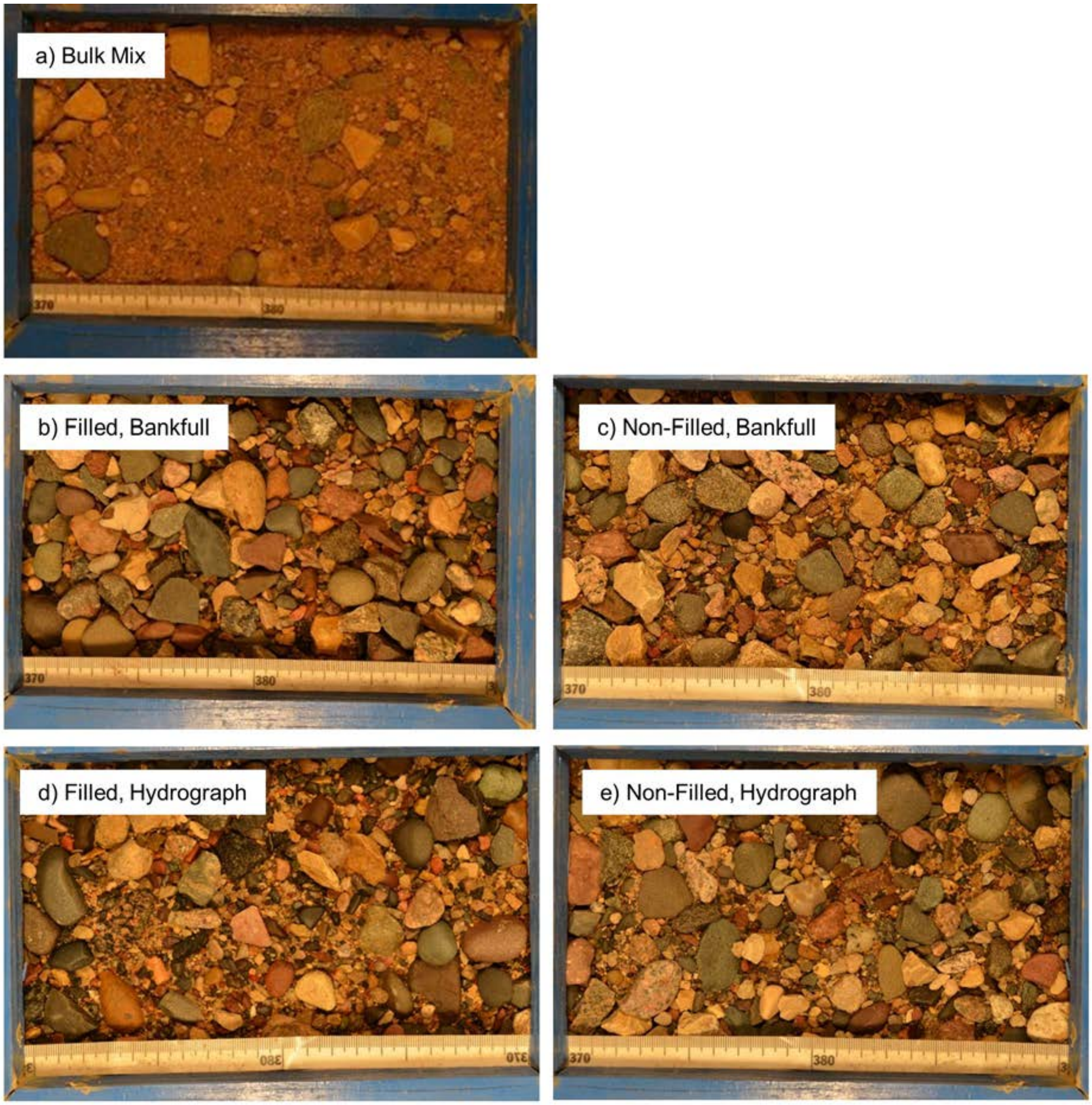

Figure 3.9. Surface bed material collected a) before flow (bulk mix), and b-e) at the end of each run for the moderate gradient experiment.

Depth-averaged velocity measurements for each flow rate were collected in the middle of the culvert and upstream of the influence of the culvert with a side-looking ADV (Table 3.2). All velocity measurements in the culvert were collected under the filled culvert scenario. The first flow rate was below bankfull, the second was at bankfull and the third and fourth were above bankfull flow.

Table 3.2. Depth-averaged velocity and depth measurements collected in the middle of the culvert and upstream of the culvert for each flow rate in the hydrograph for the moderate slope experiments. All culvert measurements were collected for the filled case.

	CULVERT		**UPSTREAM**	
Flow Rate (lps)	**V (m/s)**	**H (cm)**	**V (lps)**	**H (cm)**
22.5	0.70	9.3	0.97	9.6
35.5	0.92	10.8	0.87	12.5
47.2	1.29	11.8	1.41	13.8
64.3	1.41	13.8	1.39	17.3

Simultaneous bed and water surface measurements were collected during each run. To examine how the bed changed during the hydrograph runs, three points were selected within the culvert near the upstream end, in the middle and near the downstream end. A time series of the bed and water surface elevations collected at these points is shown in Figure 3.10 for the filled and non-fill cases, respectively.

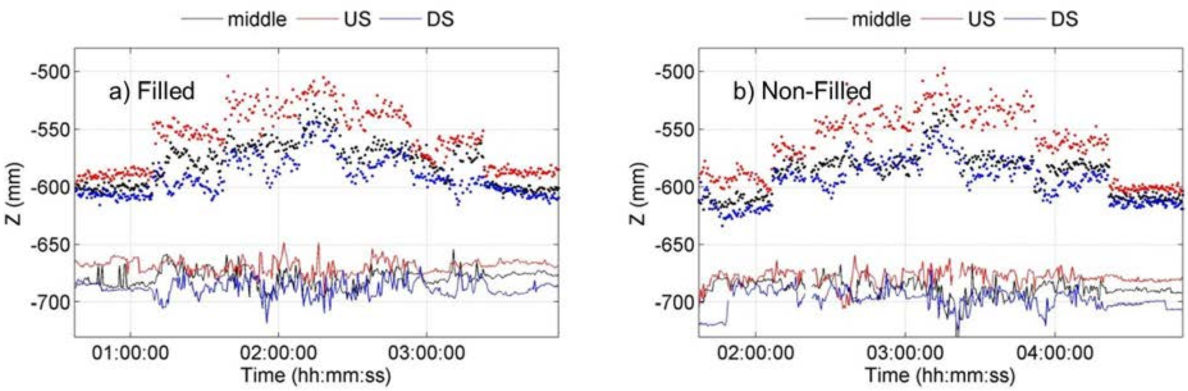

Figure 3.10. Simultaneous bed and water surface elevations collected at three points within the culvert for the initially a) filled and b) non-filled moderate gradient culvert hydrograph runs. Black = middle of culvert, red = upstream end of culvert (X=6670 mm), blue = downstream end of culvert (X=8590 mm).

3.3 High Gradient Experiment

The tilting bed flume was set at 3% for the high gradient experiments. This slope was representative of a longer reach in Wood’s Creek (combining the two surveyed sections for more data). A sediment mix based on the scaled representative high gradient stream (step pool) grain size distribution (with an adjustment to account for surface armoring) was created by combining sediment mixes from local quarries (Figure 3.11). Based on the field surveys, structures (ribs, riffles, steps, cascades and boulders) were placed along the flume. The scaled mean and standard deviation of the structure spacing was maintained as was the distribution of each type of structure, by developing a randomization script in MATLAB to place structure types along the flume. Structures greater than five bankfull channel widths away from the culvert were glued in place to facilitate experiment resetting. Structures within five channel widths from the culvert were reset for each run and allowed to adjust.

A target bankfull discharge appropriate for the high gradient system was selected using Manning's equation. The discharge was set by trial and error to the bankfull elevation. A hydrograph was developed by selecting a target maximum flood stage and stepping from below bankfull to bankfull to two overbank flows. Each step on the hydrograph was 30 minutes, except for the highest flow, which was only maintained for 15 minutes because it was difficult to keep up with the manual recirculation (Figure 3.12). For each run, sediment recirculation was continuous. Because material moving through the stream was larger than what the recirculation system could handle, large (>1 cm) sediment was collected off of a screen at the downstream end of the flume and recirculated by hand at the top of the flume. The effect of culvert filling was tested for both steady state bankfull flows and for a simulated hydrograph (see Figure 3.13). In addition, the effect of structures on bed stability within the culvert was tested by installed structures for both a bankfull and hydrograph run. During each experiment, continuous bed and water surface elevation data were collected down the middle of the flume using the data acquisition cart outfitted with a sonar probe and ultrasonic transducer. Bed data collected during the run, are spotty, however, as the turbulent flow created surface waves and the sonar could not be set too close to the bed to avoid damage. If the sonar was out of the water, no data was collected. After each experiment, the final bed was scanned using a high-resolution laser scanner. Pre- and post- bed photos were taken (Figure 3.14). Velocity data were collected after the experiment over a filled culvert bed with a side looking ADV.

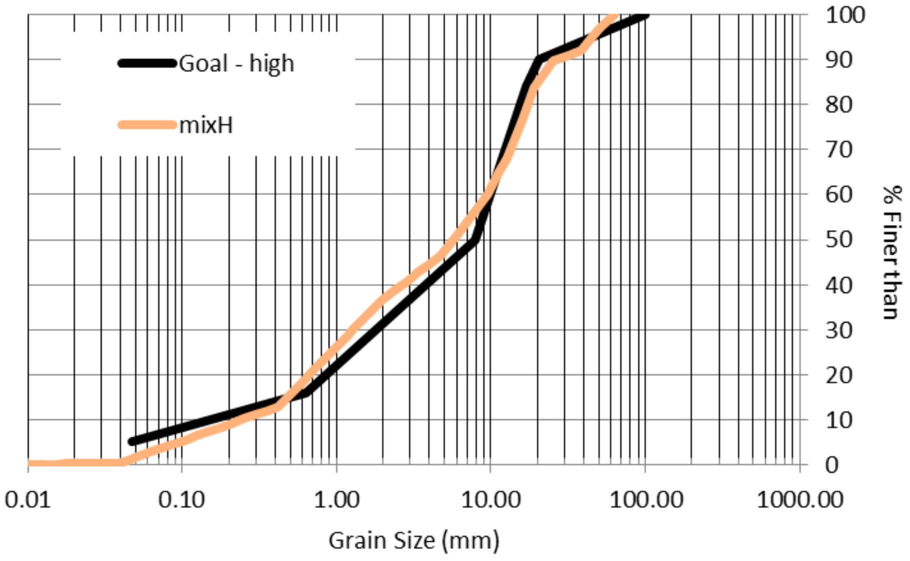

Figure 3.11. Target and mixed grain size distribution for the high gradient experiments.

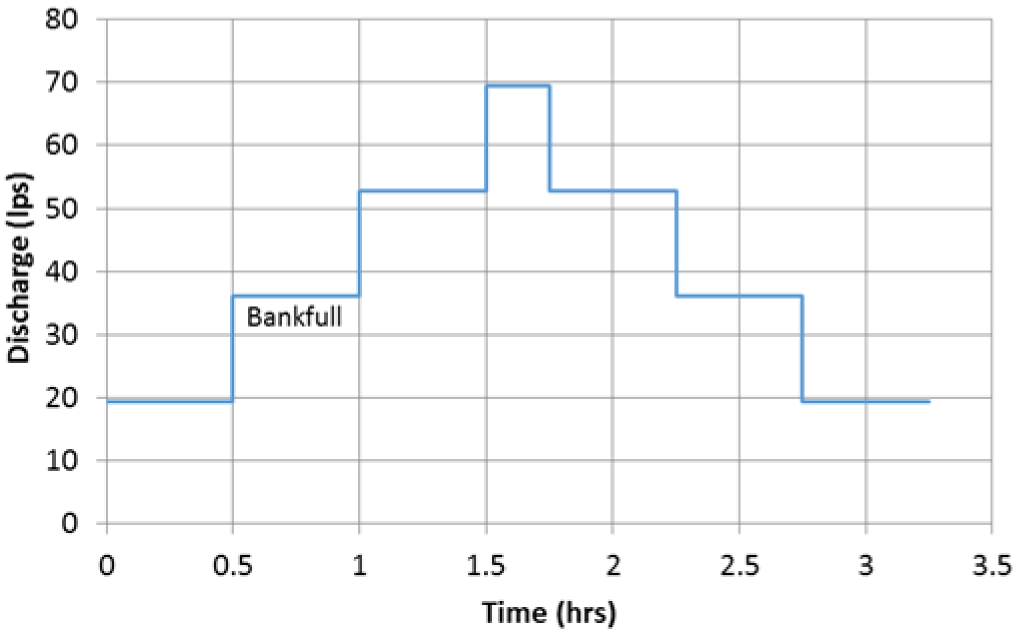

Figure 3.12. Hydrograph and bankfull flow rates for high gradient experiments.

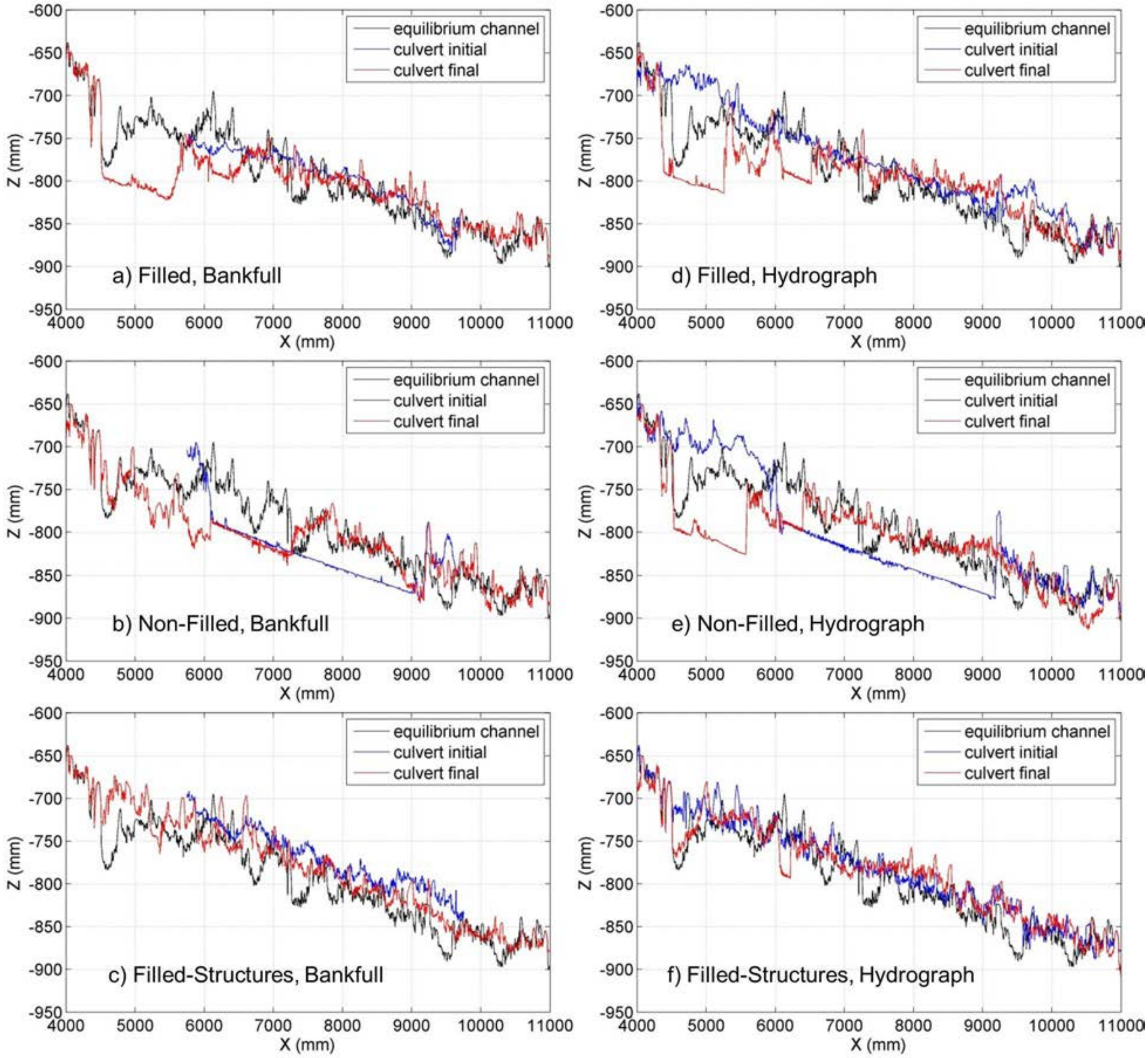

Figure 3.13. Comparison of equilibrium (no culvert), initial, and final bed elevation along the channel midline for the high gradient experiment.

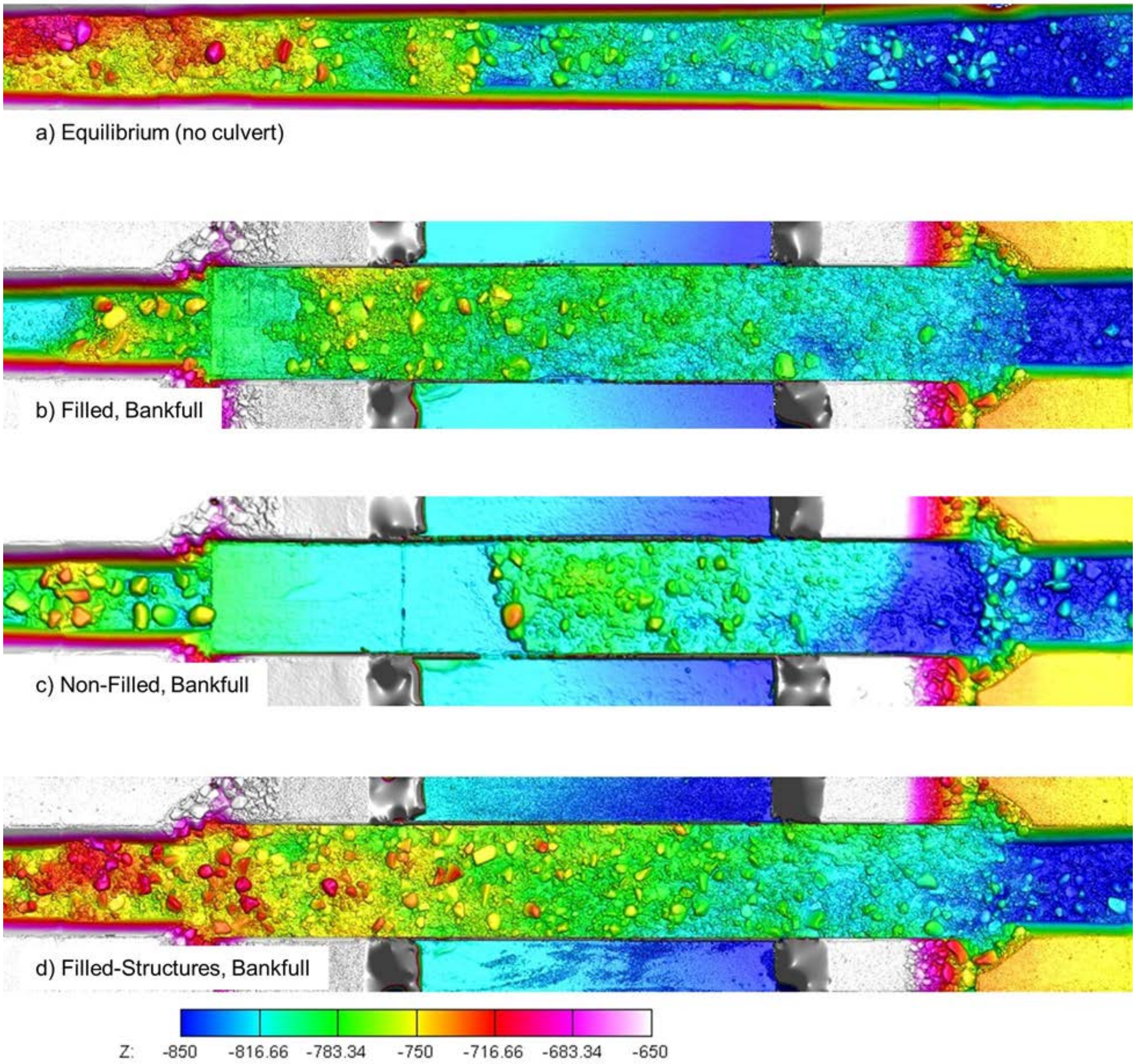

Figure 3.14. Final topography for equilibrium (no culvert), filled, non-filled and filled with structures initial conditions for the high gradient experiment with bankfull flow. Z is measured in mm from the probe to the bed.

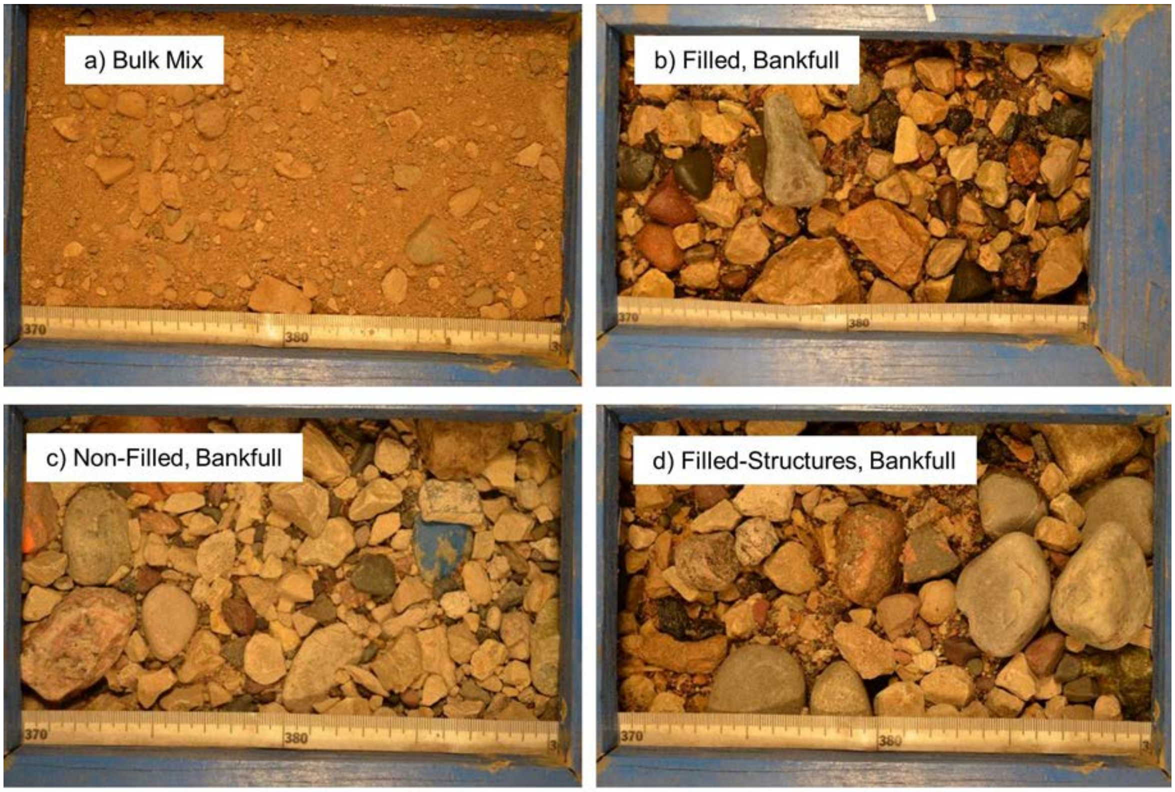

Figure 3.15. Surface bed material collected a) before flow (bulk mix), and b-d) at the end of each bankfull run for the high gradient experiment.

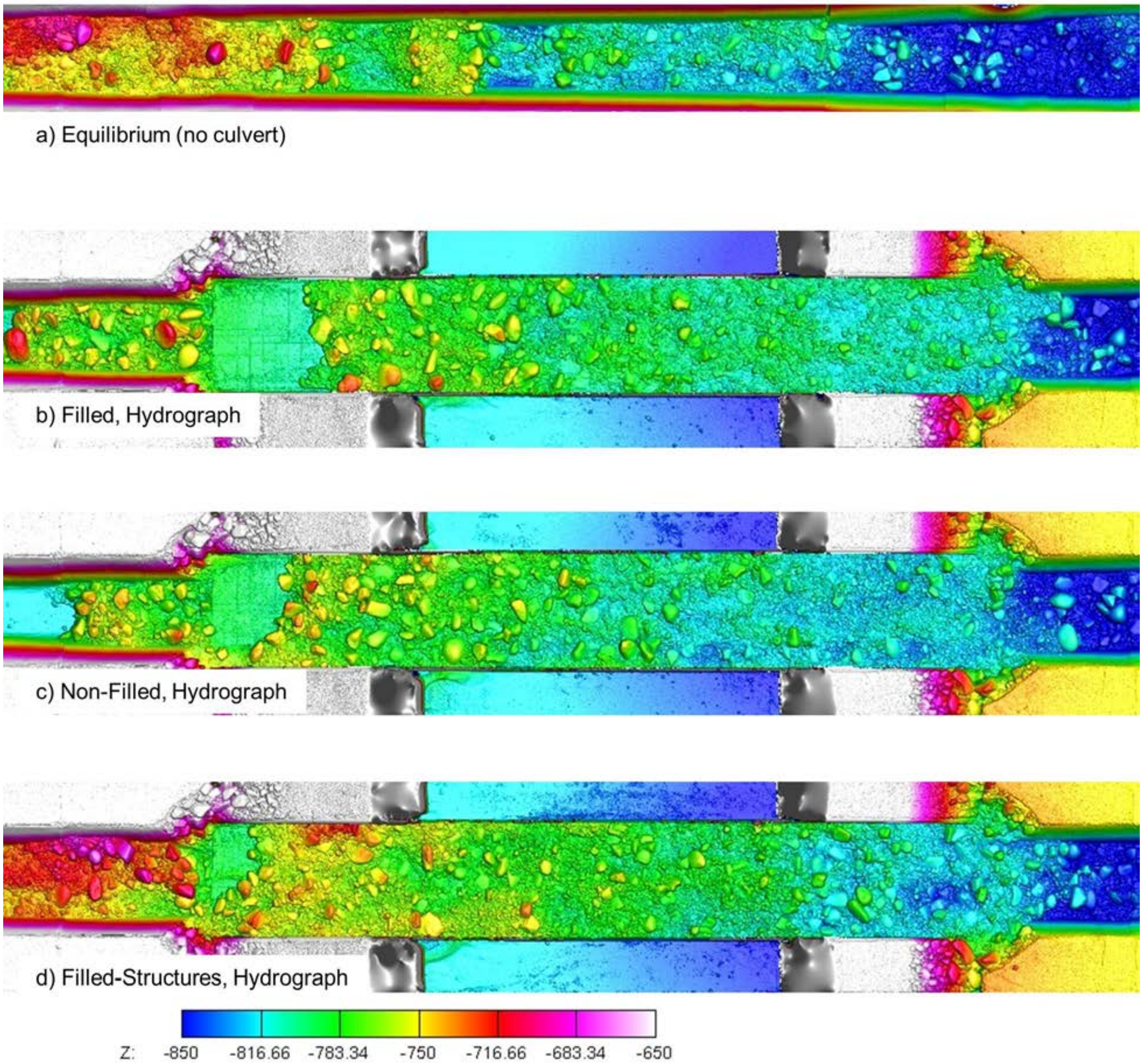

Figure 3.16. Final topography for equilibrium (no culvert), filled, non-filled and filled with structures initial conditions for the high gradient experiment with a simulated hydrograph. Z is measured in mm from the probe to the bed.

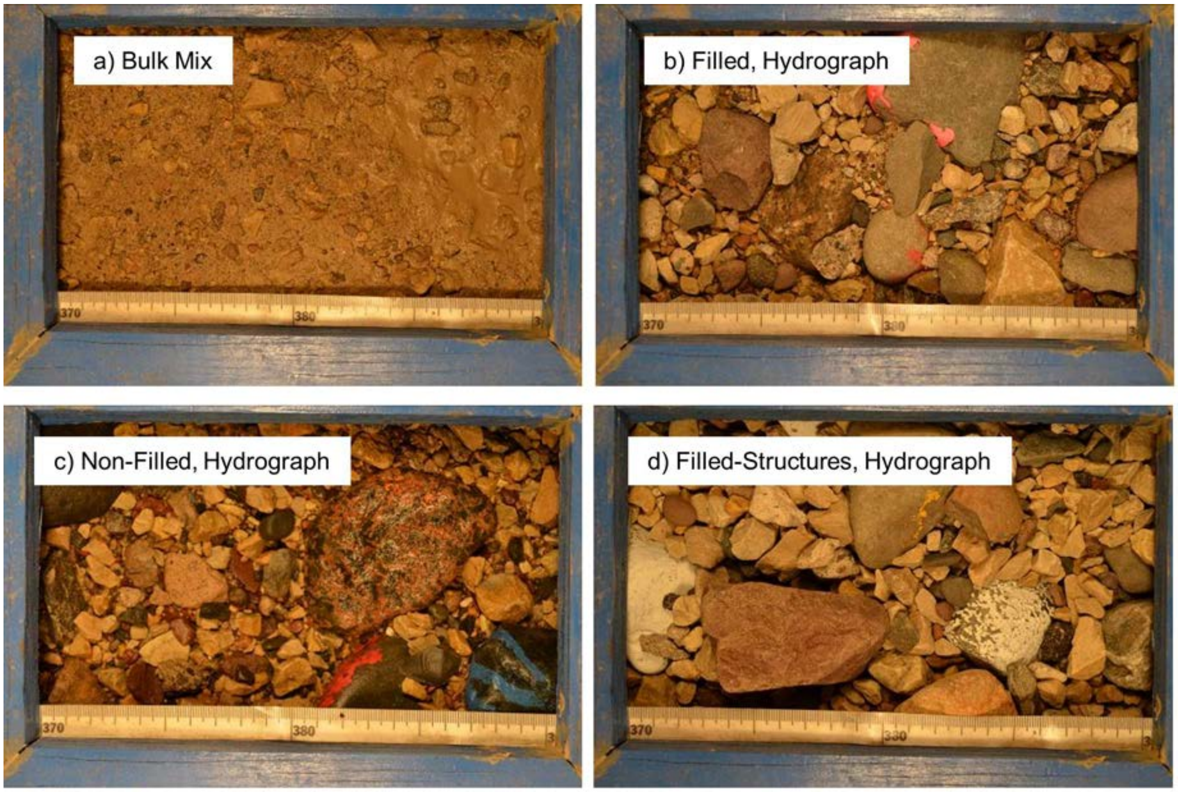

Figure 3.17. Surface bed material collected a) before flow (bulk mix), and b-d) at the end of each hydrograph run for the high gradient experiment.

To monitor the stability of structures in the hydrograph experiment with structures installed in the culvert, each set of two structures were marked with a different color of paint. Figure 3.18 illustrates the initial structure set up (based on the spacing and elevation of field data) and final bed image after the hydrograph run. Structures near the end of culvert (blue and red) were least affected by the flood, while structures near the culvert entrance (orange and white) were greatly degraded.

Figure 3.18. Pre- and post- photographs of structures placed in the culvert. Flow is from bottom to top. Each set of two structures was color coded to track the movement of structures.

Depth-averaged velocity measurements for each flow rate were collected in the middle of the culvert and upstream of the influence of the culvert with a side-looking ADV (Table 3.3). All velocity measurements in the culvert were collected under the filled culvert with structures scenario. The first flow rate was below bankfull, the second was at bankfull and the 3rd and 4th were above bankfull flow.

Table 3.3. Depth-averaged velocity and depth measurements collected in the middle of the culvert and upstream of the culvert for each flow rate in the hydrograph for the high gradient with structures experiments. All culvert measurements were collected for the filled with structures case.

	CULVERT		**UPSTREAM**	
Flow Rate (lps)	**V (m/s)**	**H (cm)**	**V (m/s)**	**H (cm)**
19.5	0.56	8.8	1.02	8.1
36.2	0.84	9.6	1.16	14.3
52.8	1.28	12.8	1.26	15.8
69.2	1.18	14.8	1.3	16.8

Simultaneous bed and water surface measurements were collected during each run. However, because of the large bedload, the sonar probe had to be set high enough to be safe. This resulting in spotty sonar data and therefore, these data are not included below. An analysis of water surface data may help us to track the location of hydraulic jumps, waves, etc. through time to get some information on the bed movement.

3.4 Conclusions

These experiments illustrated that very different sediment dynamics existed in our representative low, moderate, and high slope channels. A fraction of the sediment was mobile in all systems under bankfull flow, allowing for armoring to occur. Filling the culvert (as opposed to installing the culvert and allowing it to fill) generally protected against upstream and downstream scour. Time-lapse photos collected during the experiments show that at high flows (above bankfull), the bed, in all cases, was highly unstable with scour holes developing and disappearing with the passage of bedforms. For these experiments, the moderate slope case moved more sediment compared to the low slope allowing the culvert to fill in for all flows, while the low slope moved sediment at a much slower timescale and did not fill in the culvert for all flows (see summary Table 3.4). This further illustrates the need to collect site specific sediment grain size data to accurately predict whether the culvert will fill in or not during a reasonable time frame. We did not see the expected result of the culvert emptying of sediment at high flows. This is likely due to two reasons, 1) the flow rates encountered were not high enough to do so, and 2) the culvert design for these experiments was based on MESBOAC where the culvert width was set equal to the channel width. If the culvert had been significantly narrower than the channel with increase flow rates, sediment would be expected to behave differently.

While filling the culvert (as opposed to installing the culvert and allowing it to fill) generally protected against upstream and downstream scour in the low and moderate systems, in the high gradient channel, structures were important to overall bed stability. We saw significant scour upstream of the culvert for both filled and non-filled cases without structures (Table 3.4). In these cases, the structures installed upstream of the culvert failed, creating a deep scour hole. For the cases (bankfull and hydrograph) where structures were installed within the culvert, this scour hole was not observed. For high-gradient streams, the installation of structures within the culvert should be considered for cases where roughness is an important parameter for fish and aquatic organism passage, or upstream bed stability is a concern. To fill an unfilled culvert in the high gradient experiment, high flows (above bankfull) were required. Depending on the timing and duration of these large floods, it could take many years to fill a culvert with appropriate streambed material.

In summary, for cases where roughness is an important parameter for fish and aquatic organism passage, filling the culvert with a sediment mix similar to the sub-armor mix in the stream is the best scenario for low and moderate systems to maintain sediment within the culvert barrel; however, under certain circumstances, setting the culvert below grade and not filling is sufficient as the culvert will fill in with sediment. Making this decision ahead of time requires an understanding of the bed material and flow rates that the culvert will experience. For a high-gradient (step-pool) system, bed structure (form roughness) becomes key for maintaining similar conditions in the culvert as in the stream as a whole and minimizing the chance of upstream migrating head cuts. It should be noted that with the exception of the high gradient structure run, there was little cross-sectional variation within the sediment within the culvert barrel. This could be a concern for low flow passage as there was no low flow channel present.

Table 3.4. Summary of final conditions for all experimental runs.

Flow rate	**Gradient**	**Culvert Initial Condition**	**Culvert Final Condition**
BANKFULL	LOW	EQUILIBRIUM	
BANKFULL	LOW	FILLED	Filled
BANKFULL	LOW	NOT-FILLED	Not-filled
HYDROGRAPH	LOW	FILLED	Filled, scour hole at US end of culvert
HYDROGRAPH	LOW	NOT-FILLED	Partially filled, sediment front slowly moving into culvert at high flows
BANKFULL	MODERATE	EQUILIBRIUM	
BANKFULL	MODERATE	FILLED	Filled, upstream degradation
BANKFULL	MODERATE	NOT-FILLED	Filled
HYDROGRAPH	MODERATE	FILLED	Filled
HYDROGRAPH	MODERATE	NOT-FILLED	Filled, upstream and downstream degradation
BANKFULL	HIGH	EQUILIBRIUM	
BANKFULL	HIGH	FILLED	Significant scour at upstream end of culvert (to last glued structure); ¾ filled from downstream end
BANKFULL	HIGH	NOT-FILLED	Scour upstream end of culvert ; ½ filled from downstream end
BANKFULL	HIGH	STRUCTURES	Little change from initial
HYDROGRAPH	HIGH	FILLED	Significant scour at upstream end of culvert (to last glued structure); ¾ filled from downstream end
HYDROGRAPH	HIGH	NOT-FILLED	Significant scour at upstream end of culvert (to last glued structure); ¾ filled from downstream end
HYDROGRAPH	HIGH	STRUCTURES	Little change from initial

Chapter 4
Multi-Barrel Offset Culvert Experiment

A multi-barrel culvert testing facility was built at SAFL in order to test multiple flow scenarios through various culvert geometries and subsequently develop design guidance for the installation of multiple barrel culverts. By evaluating the effect of the relative culvert offset and culvert skew on sediment transport through each barrel, conclusions can be made on what geometry best accommodates flow and sediment movement through offset multi-barrel culverts. The unimpeded sediment transport through a culvert is not only important for long term culvert function (e.g. no excessive buildup or scour of sediment that can destabilize the structure), but a continuous stream bed with similar roughness characteristics is considered to be the best scenario for allowing fish and aquatic organism passage through the culvert over a range of flows (see Introduction and Hansen et al. 2011). Understanding the sediment transport (bedload) through culverts is necessary for an efficient design of a structure that accommodates aquatic organism passage (AOP). The goal of these tests was to investigate the sedimentation patterns within multi-barrel culverts as a function of vertical offset and skew.

4.1 Experimental setup

A facility was constructed at SAFL for the testing of various configurations of multiple barrel culverts. The interior flume dimensions are 5 ft wide by 18 in deep by 32 ft long, not including the dimensions of the headbox, tailbox and side rails. The facility was built as an open cavity such that an insert designed for a specific stream geometry can be placed inside (Figure 4.1). This flume has an inlet pipe from SAFL's main supply channel and discharges to a waste channel over an adjustable weir (Figure 4.1). Sediment was fed using a sediment feeder and was collected in the tailbox. Flow rates were verified using a weir installed on exit channel. A data acquisition cart was used to collect spatially referenced post run bed elevation.

Figure 4.1. Image of multi-barrel testing facility and tailgate control design.

To study the effect of the rising and falling limb of a hydrograph on bedload transport, a triangular hydrograph was constructed (similar to the tilting bed flume experiments). This was not a replica of an exact hydrograph because of the complicated nature of achieving fine steps with the available flume controls; instead it was simplified to a series of seven 30 minute steps (Figure 4.2).

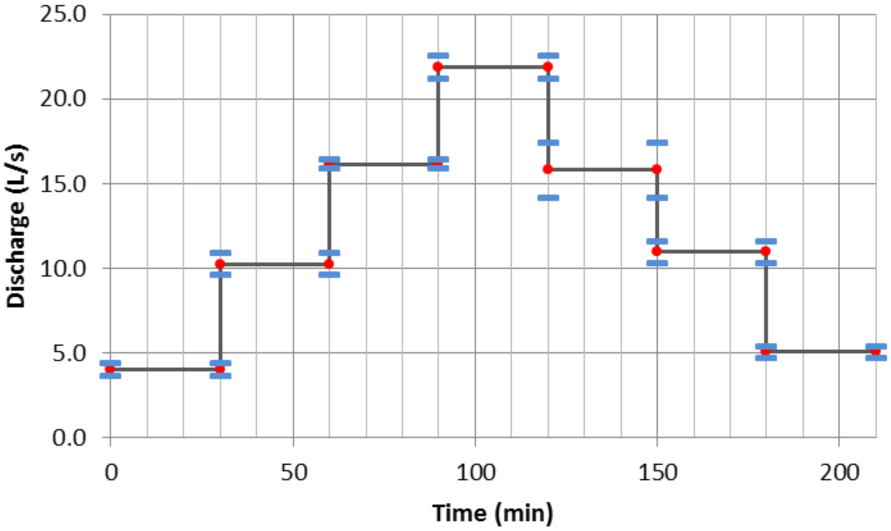

Figure 4.2. Simulated hydrograph for multi-barrel culvert runs. Line shows average measured discharge, dashes show standard deviation for measured data flow rates across all six runs.

The sediment mix used for this experiment was a fairly well-sorted sand mix. Because of the constraints of availability of fine sand we will not attempt to scale from an existing grain size distribution, but instead use a readily available mix (Figure 4.3).

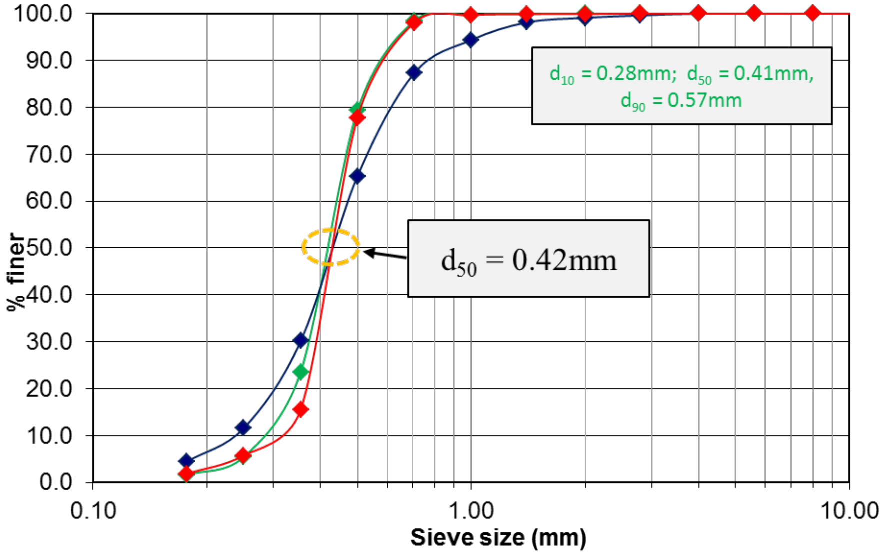

Figure 4.3. Sediment grain size distribution for sediment used in the multi-barrel flume experiments. The three colors represent three different samples. The median grain size, d_{50} was consistent at 0.42 mm for all three samples.

A floodplain was built into the flume, extending from the same trapezoidal channel banks used for the single barrel experiments, with a 3V:2H side slope (similar to the steep side slopes in the representative streams). The top width of the channel was 18 inches and a floodplain (42 inches wide total) covered with astroturf was built on either side of the channel (Figure 4.4). Two configurations were tested: one with a culvert aligned straight to the channel, and one with a culvert skewed at 16^o from the straight channel. To accommodate the skewed setup, the channel was offset so that the floodplain was nine inches on one side of the channel and 33 inches on the other side of the channel (Figure 4.4b). The culvert was installed based on the Mn/DOT CADD standards for a 1:12 scale.

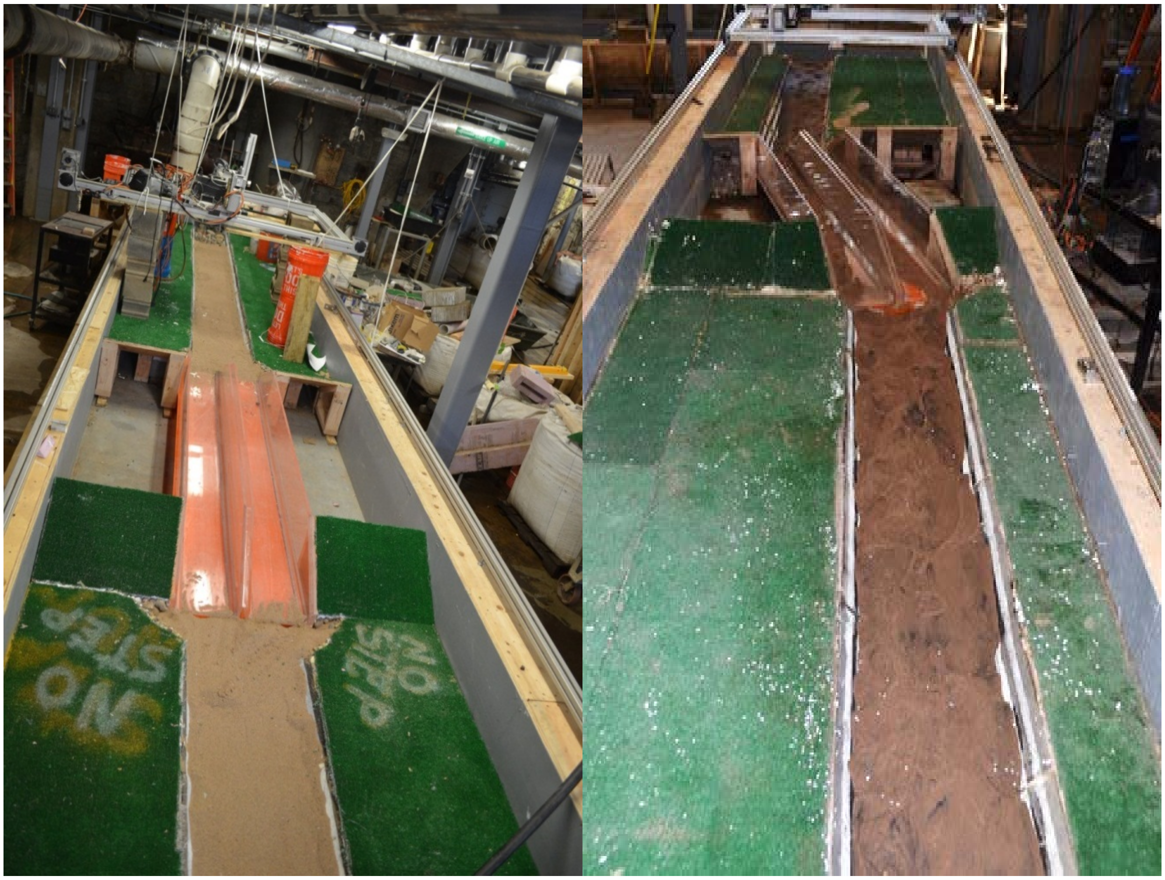

Figure 4.4. a) Looking upstream at the double barrel culvert system aligned with the channel.
b) Looking downstream at the skewed culvert setup.

The same sediment was used for all multi-barrel culvert experiments. This sediment was relatively consistent sand with a median grain size, d_{50}, of 0.42 mm (Figure 4.3). During all experiments, sediment was fed into the channel at a consistent rate of approximately 3 g/min. At the start of each experiment, the culvert was cleaned and sediment in the channel was screed to an elevation two inches below the bank. Each run consisted of a 3.5 hour hydrograph (Figure 4.2). Step one was below bankfull, step two was at bankfull, step 3 was at one inch above flood stage, and step 4 was at 1.5 inches above flood stage (above floodplain). Sediment feed was held constant during each hydrograph (similar to Ho et al. 2013).

There were six total runs for this set of experiments. For each run, the same flow and sediment transport conditions were used (Table 4.1), consisting of a hydrograph and constant sediment feed (similar to Ho et al. 2013). Final topography was measured using the computer-controlled cart, point gages, and photographs. Time lapse photographs were collected during the experiments to document the sediment within the culvert barrels. Each run lasted 3.5 hours. Three experiments were run with no skew and three had the maximum skew we could achieve in this facility (16^{o}) which was greater than the 7.5^{o} cutoff for skewed culverts in the Mn/DOT culvert design standards (http://www.dot.state.mn.us/bridge/culverts.html). For both the aligned and skewed culvert set-ups, three offset scenarios were tested. For the aligned culvert, vertical offsets of 0, 0.5 and 1.0 inches were tested. For the skewed culvert, only 0 and 1.0 inch offsets were tested, but the offset barrel was tested on both sides of the culvert. For all tests, the lowest barrel was set at 1.0 inches (1.0 scaled ft) below the screed channel bed.

Table 4.1. Experimental matrix for flume runs in multi-barrel culvert facility.

Run #	Culvert Skew	Vertical Offset Scaled ft	Flow	Sediment Feed
1	0	0	hydrograph	constant
2	0	0.5	hydrograph	constant
3	0	1	hydrograph	constant
4	16^o	1	hydrograph	constant
5	16^o	0	hydrograph	constant
6	16^o	1 in opposite barrel	hydrograph	constant

4.2 Results

For each run, the primary data collected was the final topography in the culvert after the hydrograph. In addition, time lapse photographs were collected from two locations during each run, and point gauge measurements were collected in the middle of the channel or culvert barrel once per time step as close to the end of the time step as possible. Figure 4.5 shows the scanned bed topography for runs 1-3 for the aligned culvert cases and Figure 4.6 shows the final scanned bed topography for the 16^o skew cases. Time lapse photos are included in Appendix A.

Based on the final bed scans, some trends are apparent. In cases where both barrels are equal in elevation, similar amounts of sediment were deposited regardless of skew. The pattern of deposition, however, changed with skew angle. When an offset of 1.0 in was applied to the aligned channel, more sediment was deposited in the lower barrel, although sediment deposited in the offset barrel had a higher elevation. For the skewed culvert with a 1.0 in offset barrel, the deposition within the raised barrel depended on the location of that barrel. If the raised barrel was on the outside of the bend, very little sediment was deposited, however, more sediment was deposited in the lower barrel. When the raised barrel is on the inside of the bend, some sediment is deposited in the raised barrel, and less is deposited in the lower barrel than in the opposite case. For the case with 0.5 in offset and an aligned culvert, sediment deposition patterns were similar in both barrels.

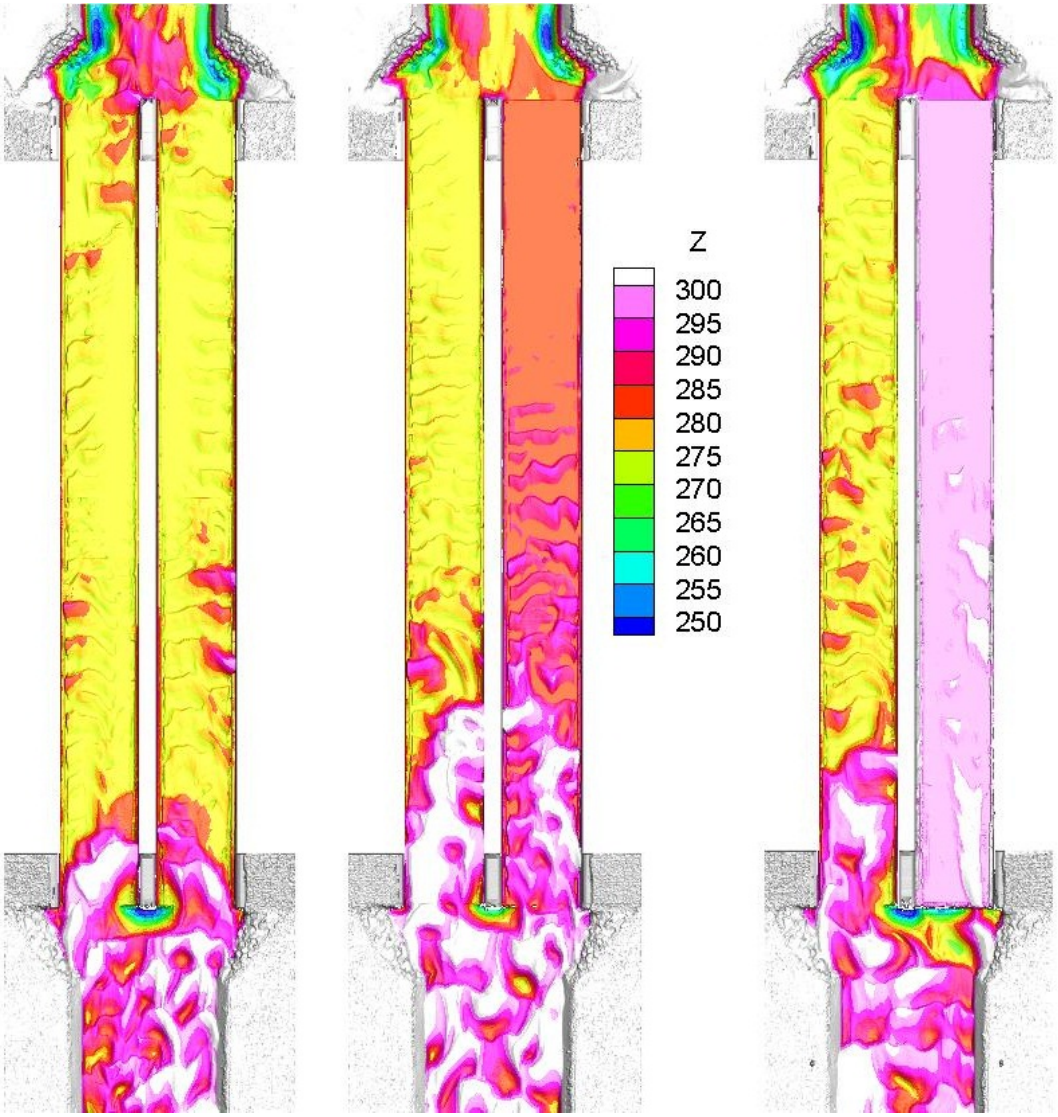

Figure 4.5. Measured bed topography for a) no offset, b) 1.27 cm (0.5 in) offset in right barrel, and c) 2.54 cm (1 in) offset in right barrel. Elevation (Z) is in mm from a zero datum below the flume bed. Flow in the figure is from bottom to top.

Figure 4.6. Measured bed topography for a) 1.0 in offset in right barrel, b) no offset and c) 1.0 in offset in left barrel. Elevation (Z) is in mm from a zero datum below the flume bed. Flow in the figure is from bottom to top.

These observations are supported by an analysis of the point gage data collected during the run. Figure 4.7 shows the measured depth upstream and within each barrel at each 30 minute time step. Flow depths are greater in the lower barrel and shallower in the offset barrel for all offset cases. In the no offset cases, flow depths are similar in both barrels. Figure 4.7 indicates a potential backwater effect when the largest offset is selected because the flow depth upstream is generally greater than that in the culvert for all 1.0 in offset cases. This is supported by the measured water surface slopes across the culvert (Table 4.2). For case 3 and cases 4 and 6 (the 1.0 in offset runs) water surface slope is greater than the no offset cases (1 and 5) especially for the hydrograph peak at 80-120 minutes.

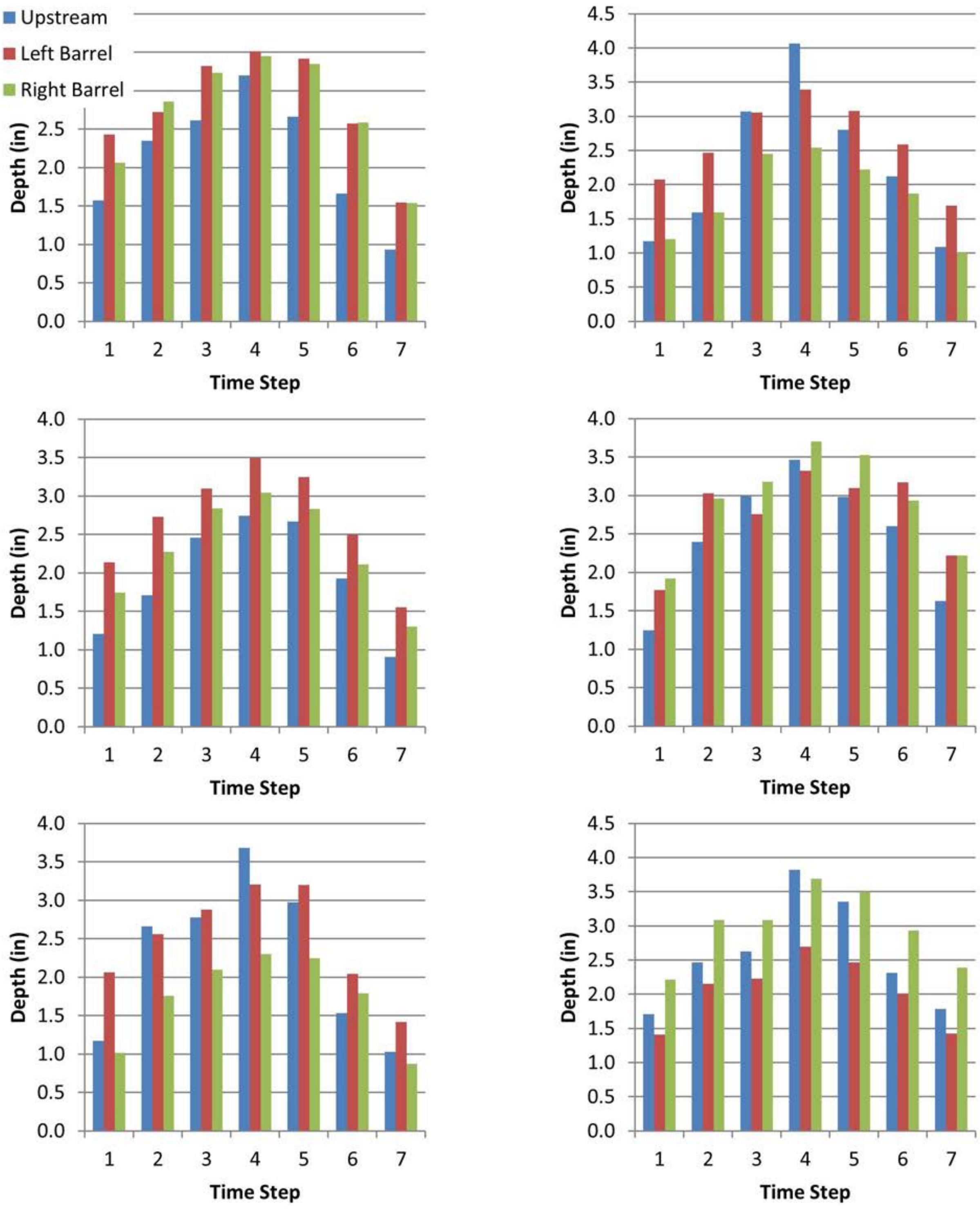

Figure 4.7. Depth throughout the hydrograph for each run. Left side (no skew) from top to bottom: no offset, right barrel offset 0.5 in, right barrel offset 1.0 in. Right side (skewed) from top to bottom: right barrel offset 1.0 in, no offset, left barrel offset 1.0 in.

Table 4.2. Water surface slopes calculated from upstream and downstream of the culvert during each hydrograph run.

Time Step	Slope					
min	1	2	3	4	5	6
0-30	0.002	0.001	0.001	0.002	0.001	0.002
30-60	0.002	0.002	0.002	0.002	0.010	0.002
60-90	0.002	0.002	0.004	0.005	0.002	0.003
90-120	0.003	0.003	0.005	0.005	0.004	0.006
120-150	0.002	0.002	0.003	0.002	0.001	0.002
150-180	0.000	0.002	0.002	0.001	0.001	0.007
180-210	0.001	0.001	0.001	0.001	0.000	0.001

4.3 Summary and Conclusions

The goal of these experiments was to examine the sediment deposition patterns in multi-barrel box culverts as a function of offset and skew. These experiments were conducted with single box culvert geometry where the open culvert width was equal to the channel width. The sedimentation of multi-barrel culverts is a documented problem in part because of the connection between dissimilar channel geometry between the culvert and stream banks (Ho et al. 2013). The geometry of this connection can affect the sedimentation patterns at the entrance to multi-barrel culverts. With specific geometry designed to direct flow toward the central culvert, some of these sedimentation issues may be avoided (Ho et al. 2013). Our project attempted to design the culvert entrance in as general a form as possible to investigate the effect of offset and skew, two parameters that were not studied in previous work (Ho et al. 2013). We specifically looked at bedload (not suspended load) and did not find any specific evidence that offsetting a culvert barrel itself leads to enhanced sedimentation within that barrel. If anything, more sedimentation occurred in the lower barrel, but generally not up to the level of the offset barrel indicating that these culverts can maintain active fish or aquatic organism passage in the lower barrel at low flows.

When sediment did deposit, it deposited in the upstream part of the culvert, similar to field observations. Based on field observations of multi-barrel box culverts, deposition was often observed in the presence of vegetation (Figure 4.8). A likely mechanism for the sedimentation observed in offset barrels in the field is the positive feedback between sediment deposition and vegetation growth. As some sediment is deposited near the entrance to the culvert, as flows recede, vegetation can start to grow leading to increased roughness and enhanced sedimentation during the next flooding event.

While not specifically part of this study, the effect of skew on scour upstream and downstream should be investigated further. We observed large scour holes on both the upstream and downstream ends of the skewed culvert.

Figure 4.8. Sediment deposition and vegetation growth upstream of multibarrel box culverts: Beaver Creek and I-90 (left), and Kanaranzi Creek and Edwards Ave (right) in southwest MN.

Chapter 5
Summary and Recommendations for AOP Culvert Design

5.1 Discussion of Scaling Interpretation

Interpretations of scaled models to sediment transport need to adequately represent the physics of the representative system including the flow and sediment transport physics. Scaled models should meet Shields similarity for both Shields stress (τ^*) and particle Reynolds number (R_p) when R_p is less than approximately 100 (see discussions in Garcia 2000 and Gill and Pugh 2009).

$$R_p = \frac{\sqrt{RgD}D}{v}$$

where R is the submerged specific gravity of sediment. Plotting R_p versus τ^* results in the Shields regime diagram (Figure 5.1). This diagram can be used to assess whether laboratory conditions are representative of field conditions (Garcia 2000). When data from the tilting bed moderate and high gradient experiments are plotted on the Shields diagram, both the representative stream and the scaled model experiment have an R_p greater than 100 and thus fall within the range where τ_c^* is approximately constant and independent of R_p. Therefore, the scaling methods are deemed to be appropriate representations of the field streams. For the low gradient model experiments, R_p for the field stream was greater than 100 while for the model experiments was less than 100 and thus in the region on the Shields regime diagram where matching both τ^* and R_p is critical (Gill and Pugh 2009). For this reason, the interpretation of the experimental results for the low gradient experiments need to be adjusted as the ratio between bed shear stress and critical shear stress does not represent the physics of the representative stream. A stream that would match the Shields parameter and particle Reynolds number for this system would have a lower slope (0.0001) and grain size (0.4 mm) than the representative site. This adjusted representative stream, is however, not necessarily appropriate as the grain size distribution was scaled based on the representative stream which should have a greater range of grain sizes than a typical sand bed stream. As little sediment transport was observed in the fine grained experiments, it is likely that the armoring of the coarser material in this mix played an important role in controlling the transport of sediment into the culvert.

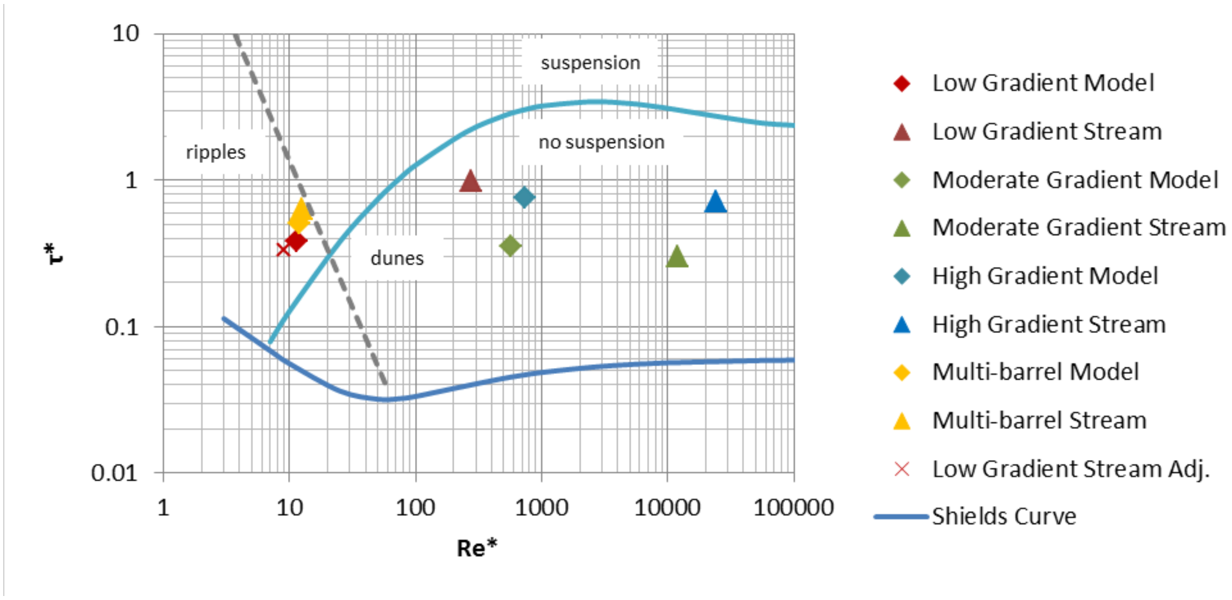

Figure 5.1. Shields diagram with representative and model stream characteristics.

5.2 Summary and Recommendations

Based on these experiments, the following summary and recommendations can be made for recessed culvert design and installation. The goal of recessed culvert design for AOP is to allow for uninhibited passage of fish and other aquatic organisms by maintaining a natural streambed. Additional design concerns include excessive headcutting or scour in the vicinity of the culvert.

- The MESBOAC recommendation of setting the culvert width equal to the channel bankfull width generally is not expected to inhibit sedimentation in culvert.
- Very different sediment dynamics exist in different geomorphic setting (slope and grain size combinations). Site specific analysis of flow, shear stress estimates and mobility of the range of sediments is recommended to predict sediment movement into the culvert.
- Filling the culvert generally protects against upstream scour or head cuts (provided the culvert is of a similar width as the stream).
- For high gradient streams, structures should be installed within the culvert to maintain sediment stability in culverts and to prevent headcuts upstream.
- In a high gradient stream, structures made up of larger interlocking pieces are critical for stream stability. Culverts may not fill with material representative of the stream until a flood flow that is large enough to displace this material from upstream. When this happens, significant scour can occur.
- Armoring can play a major role in stunting the movement of material into a culvert. The degree of armoring in the stream should be evaluated if sediment transport into the culvert is expected.
- For multi-barrel culverts, embed one barrel below the stream bed. If the culvert is skewed or if the culvert is placed on a bend (not recommended), the embedded barrel

should be on the outside of the bend to capture the channel thalweg and maintain a low flow channel.

- The potential for vegetation growth should be evaluated or monitored for multi-barrel culverts where sedimentation is a concern.
- If low flow passage is a concern, additional structures may need to be placed in low or moderate gradient culverts to maintain a low flow channel. The bed had little cross-sectional variation in these experiments and may not provide enough depth for AOP at low flows.

5.3 Future Work

While these experiments provide insight into the sediment transport processes through box culverts during flood events that are difficult or impossible to monitor during the flood itself, they do not represent all possible scenarios. Site specific characteristics (channel dimensions, slope, grain size distribution, and hydrology) are all expected to influence the ability of culverts to fill with sediment and maintain streambed characteristics similar to the stream. We examined culverts that were set equal to the bankfull width of our experimental channel. To fully optimize the design of embedded culverts, a range of widths and embedded depths should be examined. For example, if a culvert is significantly narrower than the channel itself or conveys a large percentage of overbank flow, the velocities in the culverts may exceed those in the channel leading to significant scour in, and below the culvert. Some topics identified for further study are listed below:

- The effect of culvert width to channel width ratios on sediment scour and deposition.
- The effect of embedded depth on sediment scour and deposition.
- The effect of larger overbank flows on sediment scour and deposition.
- The effect of extended low flows on sediment stability within the culvert and cross sectional variability (will a low flow channel form within a culvert?)
- The role of vegetation growth in sediment deposition in multiple barrel and wide culverts should be examined.
- The effect of entrance conditions on sediment scour and deposition in single and multi-barrel box culverts.
- More detailed analysis of channel characteristics upstream, downstream, and within the culvert relevant to AOP (will self-formed beds have similar roughness characteristics to the channel? Are there similar pool spacing and flow refugia? What is the time scale for the formation of important roughness characteristics?)

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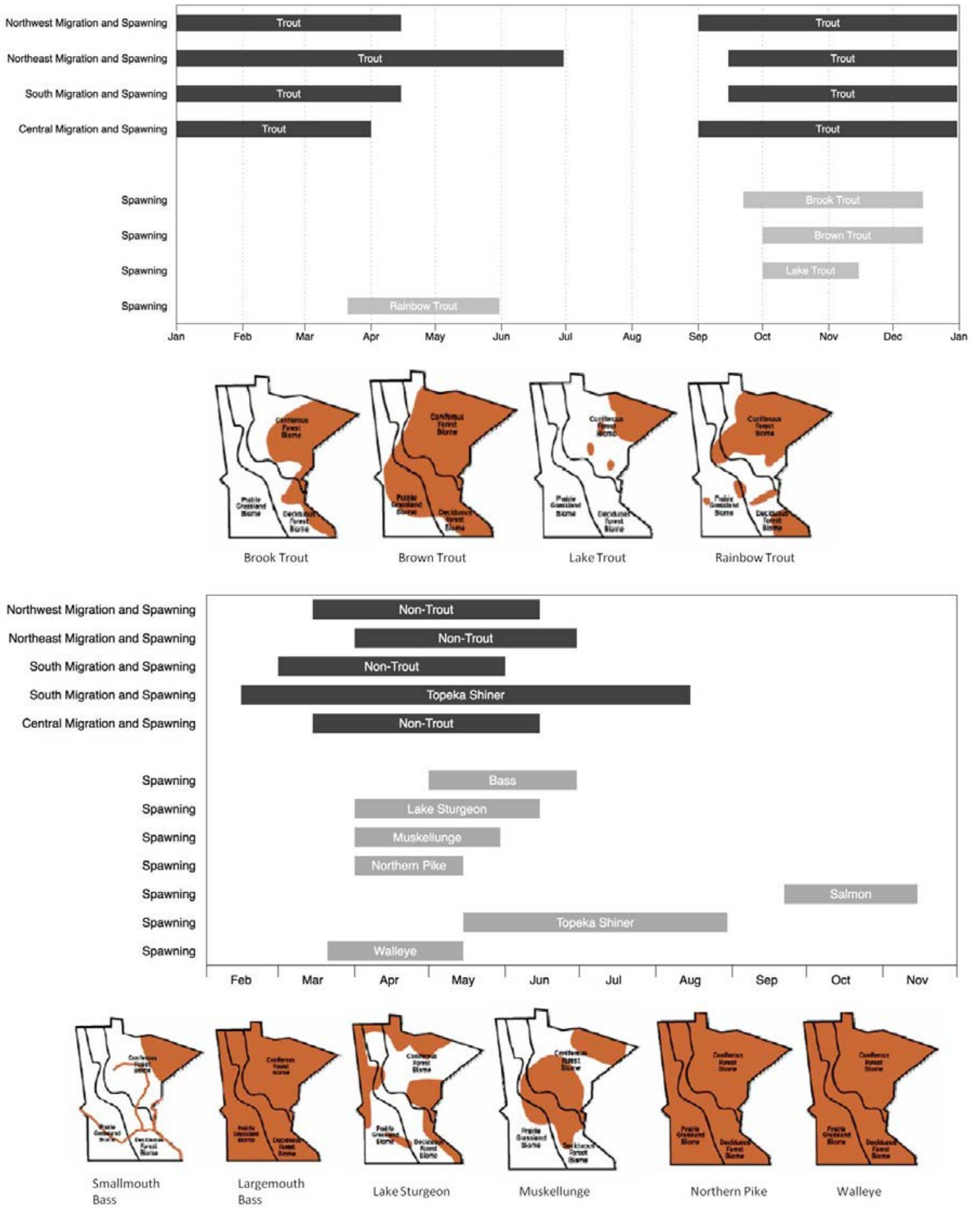
Appendix A

Brief Summary of MN Fish Passage Requirements

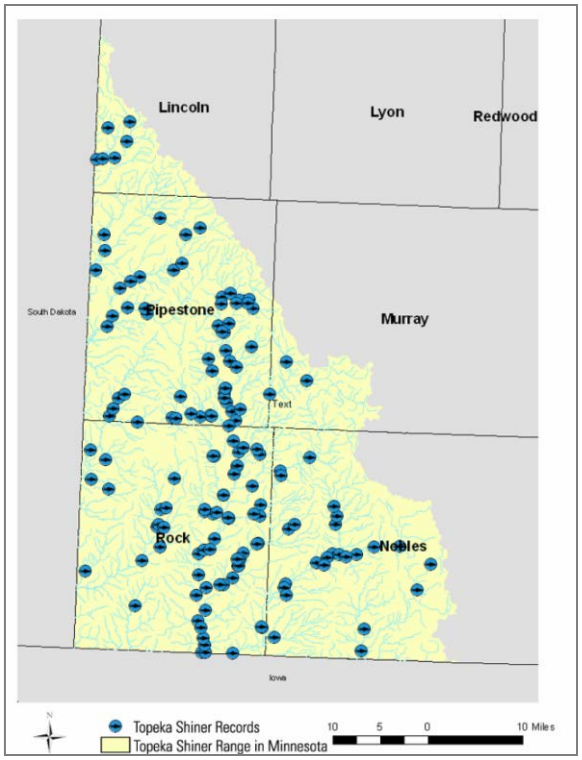
Common Minnesota fish species, such as northern pike, are weaker swimmers than fish such as salmon and trout that have been heavily studied for their swimming ability for fish passage. Many non-trout species require passage through culverts for spawning during typical high-flow periods in the early spring. While Minnesota fish species are not as well-known as salmon for their annual migration, these fish can travel large distances in the spring to spawn (e.g. smallmouth bass-60 mi, walleye-150 mi, northern pike-200 mi, lake sturgeon-250 mi).

The vast majority of culverts in Minnesota and around the Midwest were not designed to accommodate fish passage and little information exists to evaluate the effect of culverts on aquatic organism communities in these areas. Awareness of potential fish passage issues is low amongst the general public and engineers working on road projects in Minnesota. The studies on fish passage in the Midwest that have been conducted, however, indicate that fish passage is a likely issue. A survey of road crossings referenced by Hansen et al. in the Pine-Popple watershed in the forested northeast portion of Wisconsin and found that 67% of the crossings partially or totally blocked fish passage [1]. A screening level assessment conducted by Rayamajhi et al. of 55 culverts in Northeast Ohio found that none of the selected fish species (all fish species found in MN: golden shiner, white sucker, northern pike, greenside darter, pumpkinseed, longear sunfish, smallmouth bass, largemouth bass, golden shiner, and blacknose dace) was able to pass upstream through any of the culverts during the 2-yr flood [2]. While this analysis did not account for low flow areas near culvert boundaries, an additional analysis indicated that the screening results were only slightly better when accounting for the low flow areas that fish often utilize. Typical barriers were excessive velocity and insufficient water depth. Out of the 55 culverts, only 18 were able to pass any fish during the four flows tested (max. monthly, min. monthly, typical low flow, 2-year flow). Combined, these studies provide some evidence as to the scale of fish passage issues in the Midwest. The major limitation of extending these studies is the limited information that exists for fish swimming abilities for many Midwest fish species.



General range of fishes in MN and timing of migration and spawning fish passage requirements by region and species (spawning dates estimated from MN DNR 2011 and UW-Extension. Note that specific spawning dates are dependent on local characteristics such as temperature that can vary).

In Minnesota, the only federally endangered fish is the Topeka shiner. There are, however, a number of federally and state-listed mussel species in the state that rely on uninhibited fish passage for dispersal to new habitat areas. The Topeka shiner is found in a relatively limited range in the Missouri River watershed. Culverts and other road crossings act as semi-permeable barriers to upstream movement of Topeka shiner and other warm water fish species. A study conducted in Eastern South Dakota examined the ability of Topeka shiner and other warm water species to cross a variety of road crossings including box culverts and corrugated culverts [3]. General results indicated that culverts impeded fish movement for warm water species, but channel spanning embedded concrete box culverts minimized fish passage impedance. An experimental study conducted in Kansas found that road crossings acted as semipermeable barriers to Topeka shiner and other great plains fish for velocities up to 3.6 ft/s (through a 6 ft. simulated stream [4]). Increased water velocity affected the proportional upstream movement of Topeka shiners (but not green sunfish, red shiner or southern redbelly dace). Box culverts had less effect than low-water crossings; however, this stream is short compared to many culverts. In addition to the Topeka shiner, there are a number of fish species of special concern in Minnesota listed by Hansen et al. that may need to be considered in specific fish passage culverts [1].



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

Additional information on fish passage:

Fish Passage Resource Library

stream.fs.fed.us/fishxing/fplibrary.html

Joint EWRI-AFS Fish Passage Reference Database

http://scholarworks.umass.edu/fishpassage/

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[1] B. Hansen, J. Nieber, and C. Lenhart, Cost Analysis of Alternative Culvert Installation Practices in Minnesota (Minnesota Department of Transportation, 2009).

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

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

[4] W.W. Bouska and C.P. Paukert. "Road crossing designs and their impact on fish assemblages of Great Plains streams." Transactions of the American Fisheries Society 139.1 (2010): 214-222.

Appendix B

Time-lapse Photographs of Single Barrel Culvert Hydrograph Experiments

Run 4: Low Gradient, Hydrograph, Filled

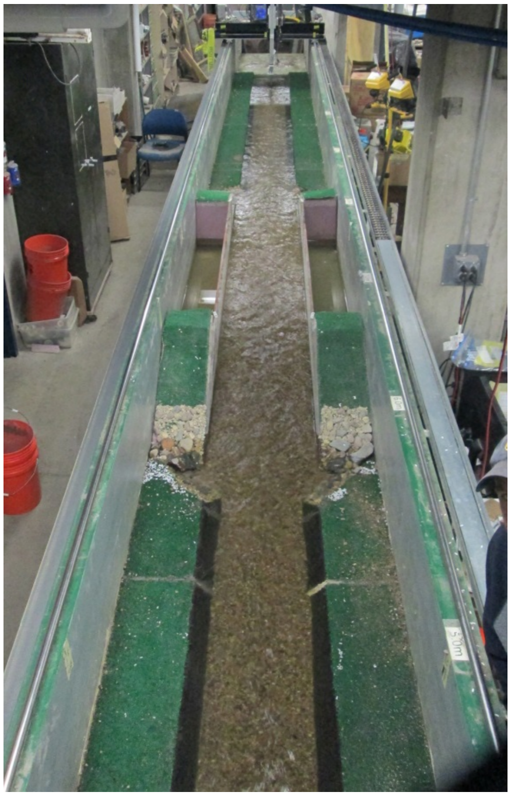

Photo 1: Rising Limb, Base Flow

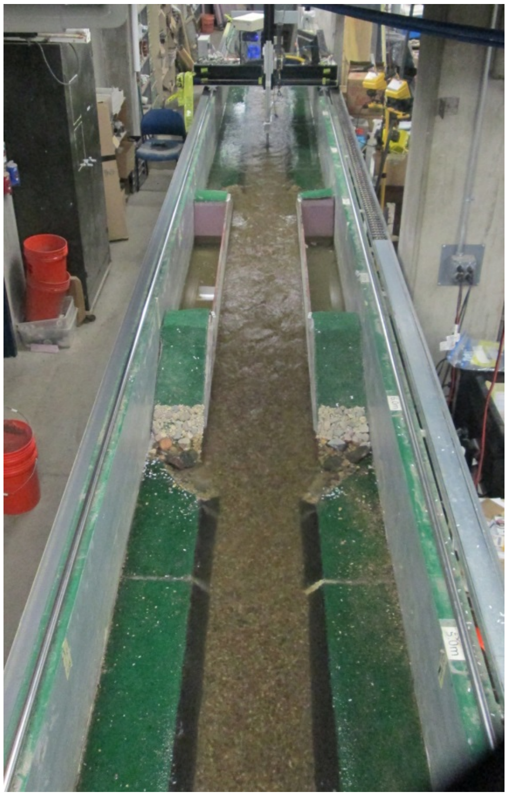

Photo 2: Rising Limb, Bankfull Flow

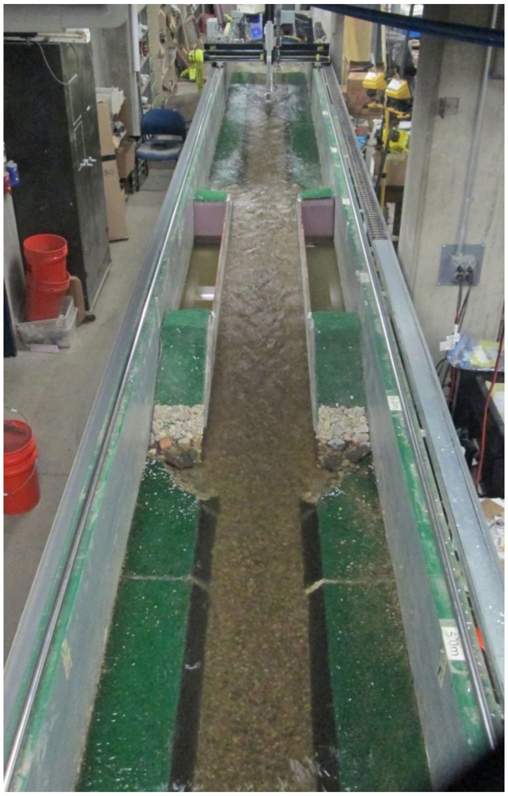

Photo 3: Rising Limb, Overbank Flow 1

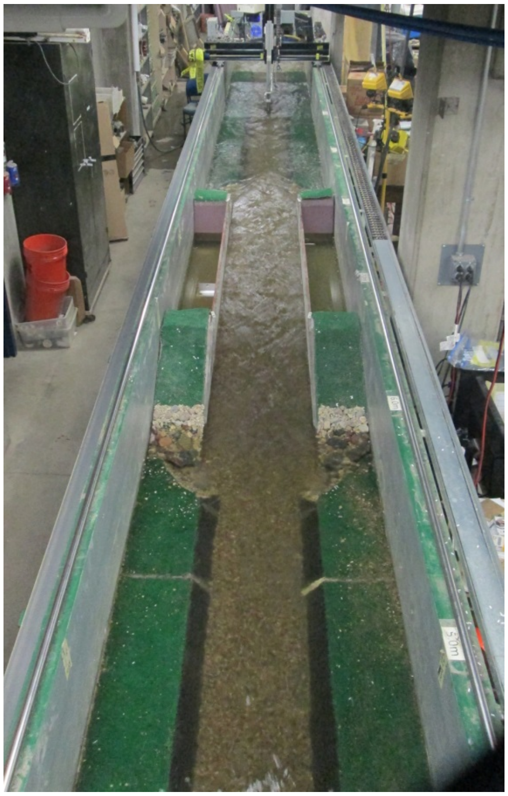

Photo 4: Overbank Flow 2

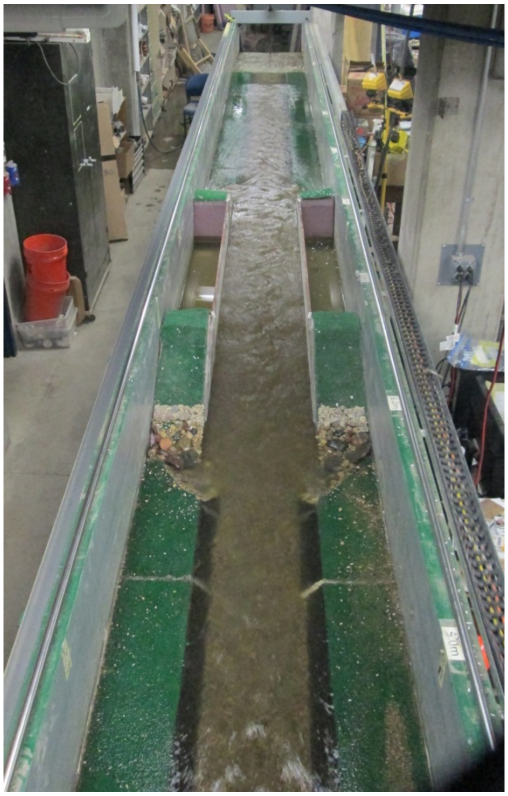

Photo 5: Falling Limb, Overbank Flow 1

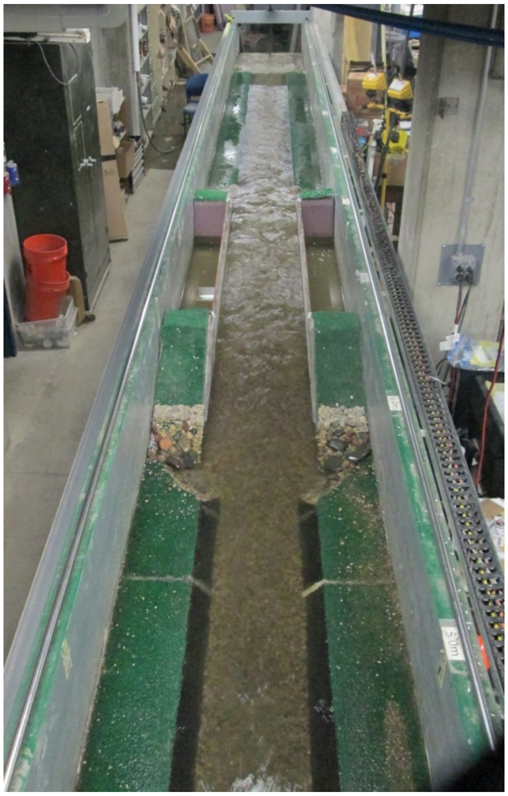

Photo 6: Falling Limb, Bankfull Flow

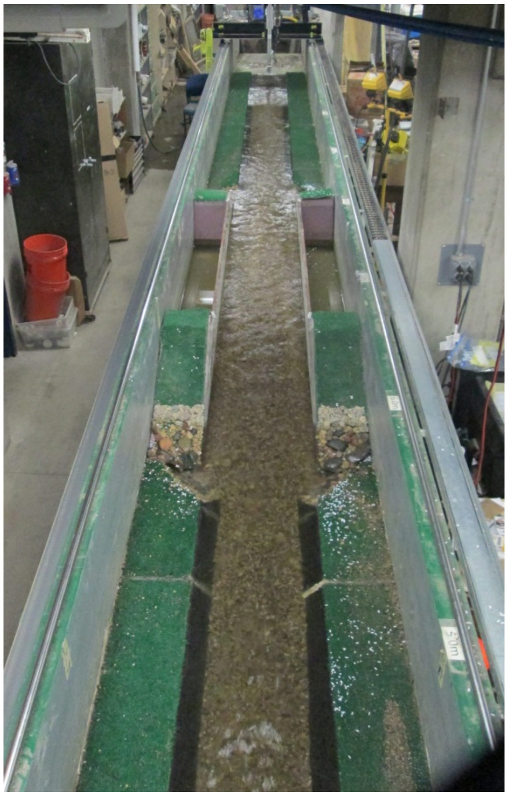

Photo 7: Falling Limb, Base Flow

Photo 8: Drained

Run 5: Low Gradient, Hydrograph, Non-Filled

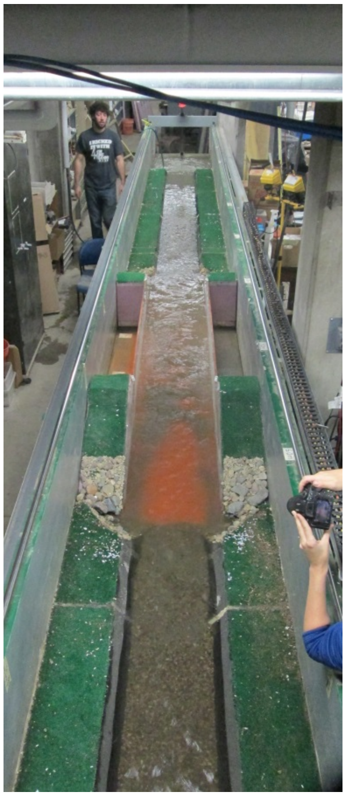
Photo 1: Rising Limb, Base Flow


Photo 2: Rising Limb, Bankfull Flow


Photo 3: Rising Limb, Overbank Flow 1

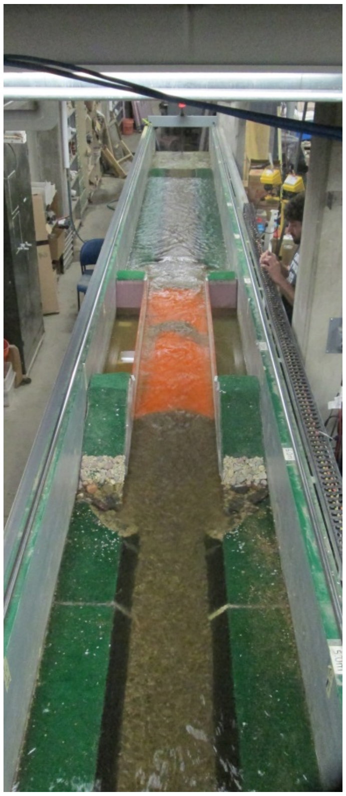
Photo 4: Overbank Flow 2

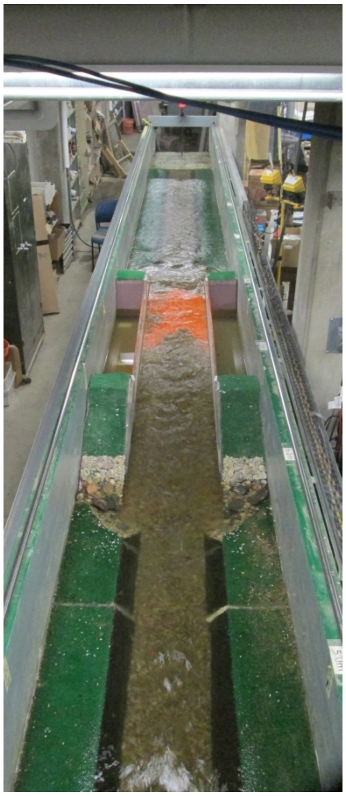
Photo 5: Falling Limb, Overbank Flow 1


Photo 6: Falling Limb, Bankfull Flow

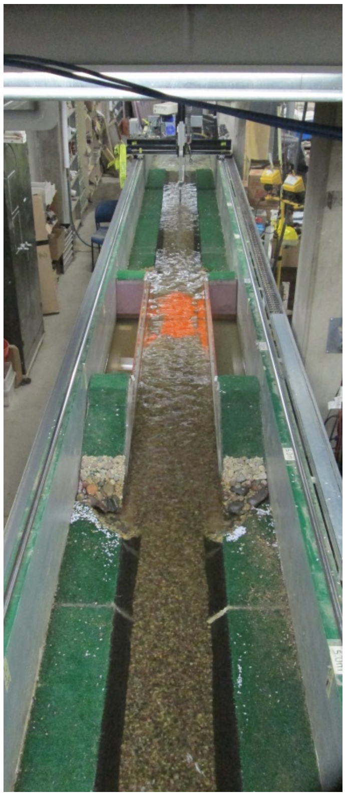
Photo 7: Falling Limb, Base Flow

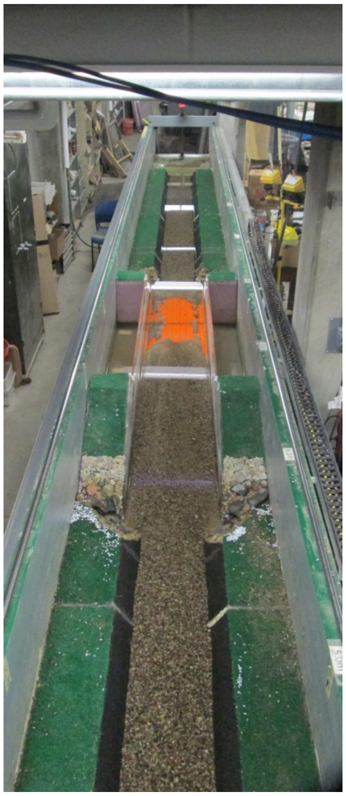
Photo 8: Draining

Run 9: Medium Gradient, Hydrograph, Filled

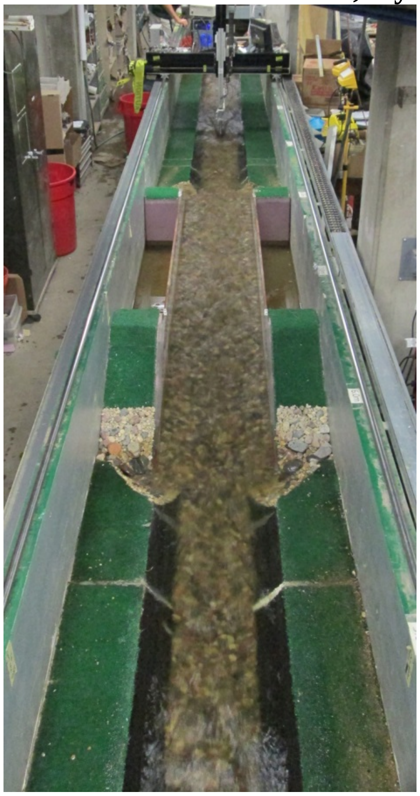
Photo 1: Rising Limb, Base Flow

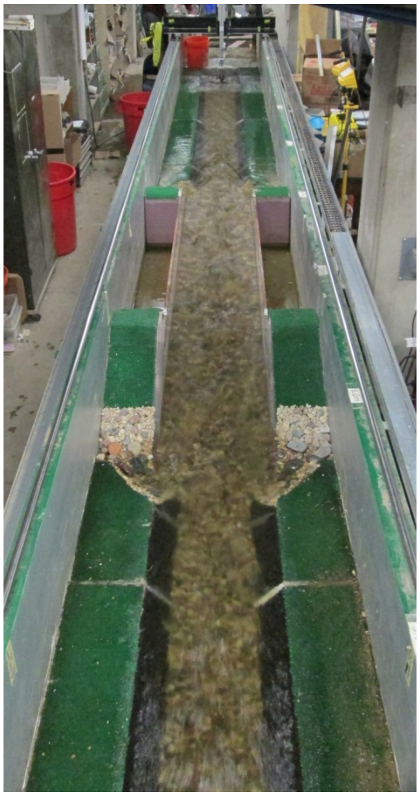
Photo 2: Rising Limb, Bankfull Flow

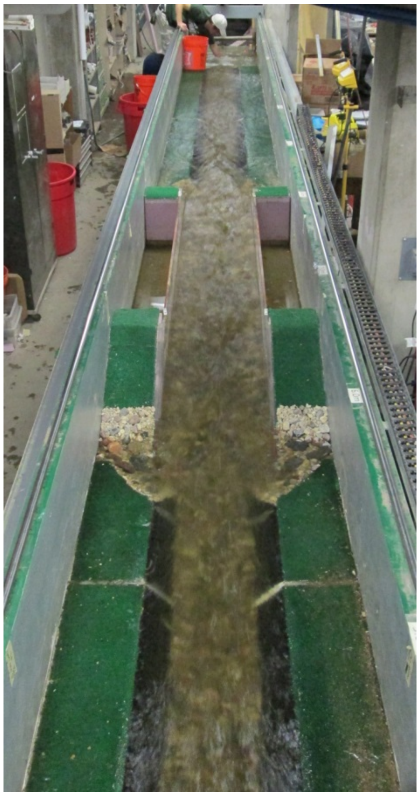
Photo 3: Rising Limb, Overbank Flow 1

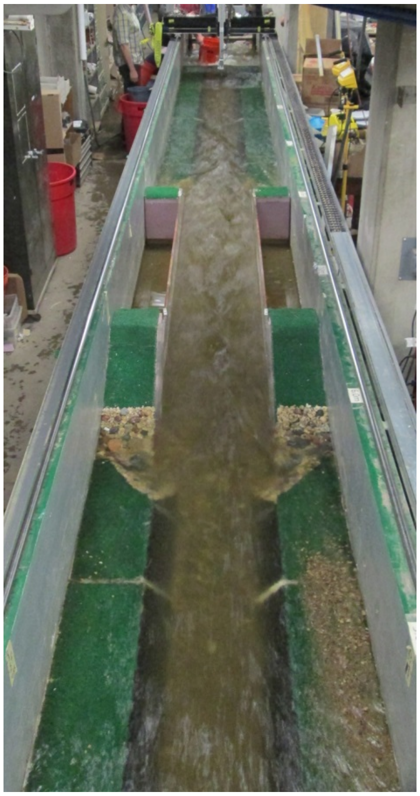
Photo 4: Overbank Flow 2

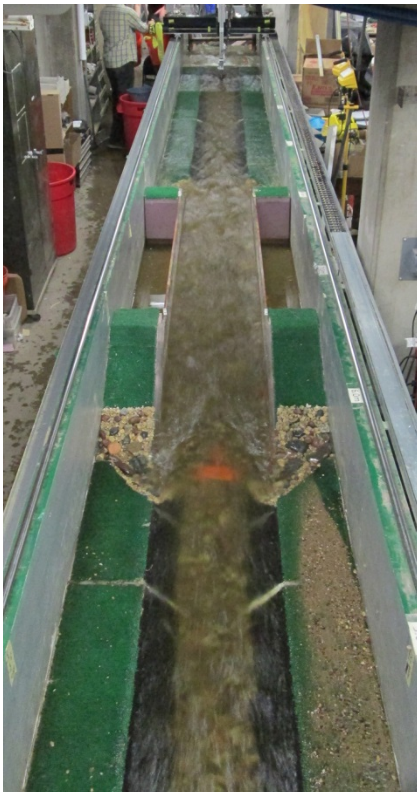
Photo 5: Falling Limb, Overbank Flow 1

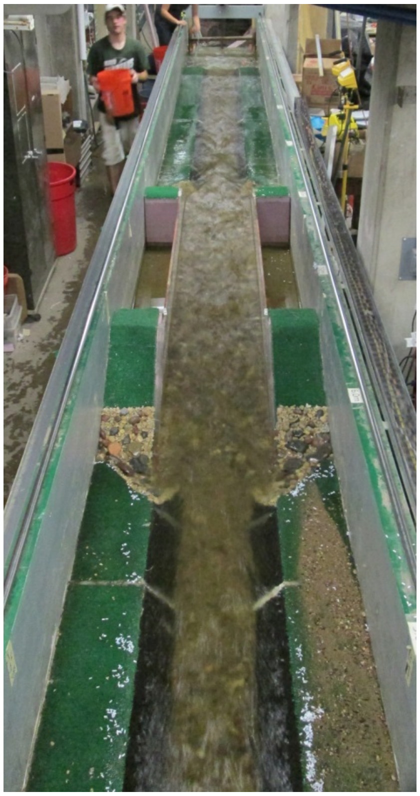
Photo 6: Falling Limb, Bankfull Flow

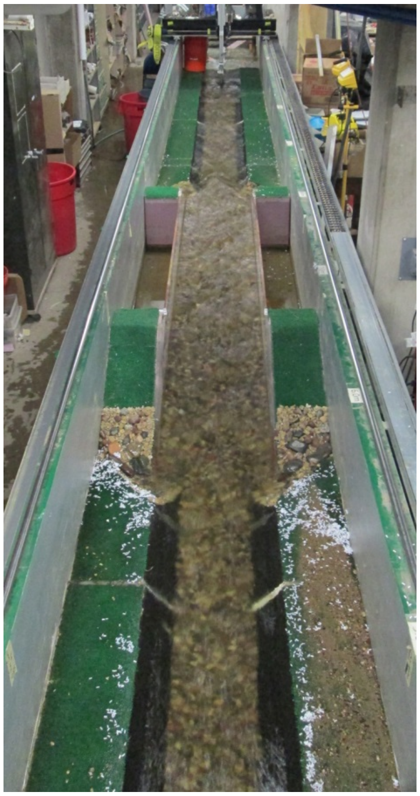
Photo 7: Falling Limb, Base Flow


Photo 8: Drained

Run 10: Medium Gradient, Hydrograph, Non-Filled

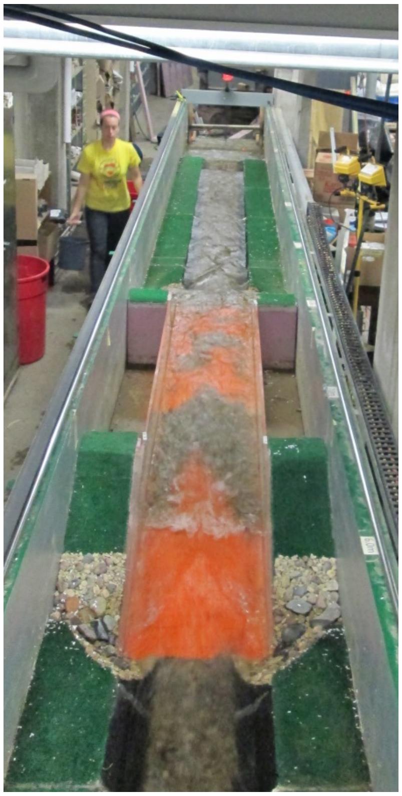
Photo 1: Rising Limb, Base Flow

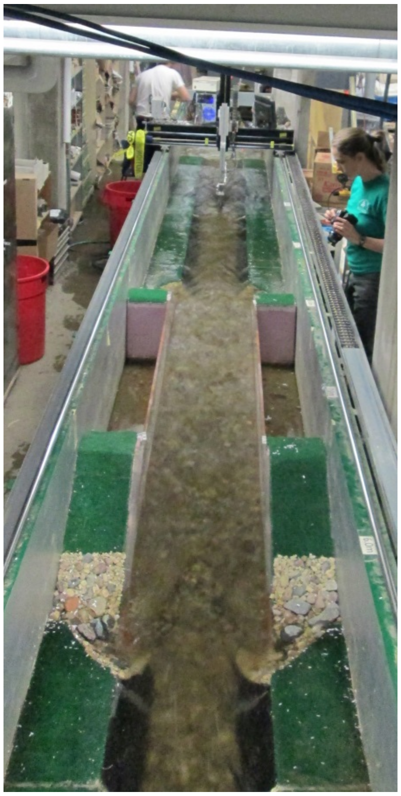
Photo 2: Rising Limb, Bankfull Flow

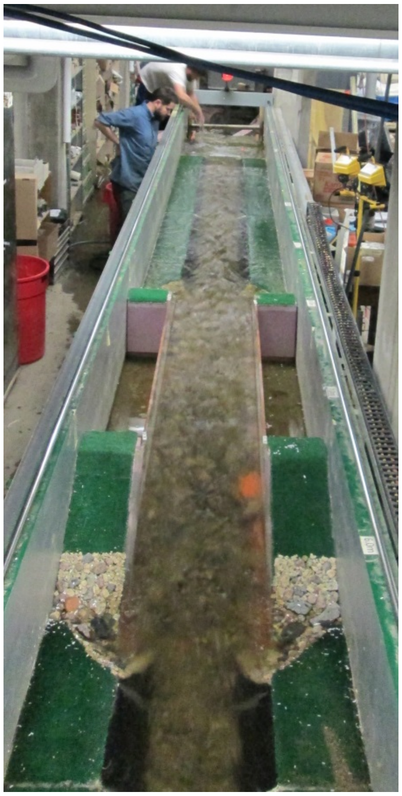
Photo 3: Rising Limb, Overbank Flow 1


Photo 4: Overbank Flow 2

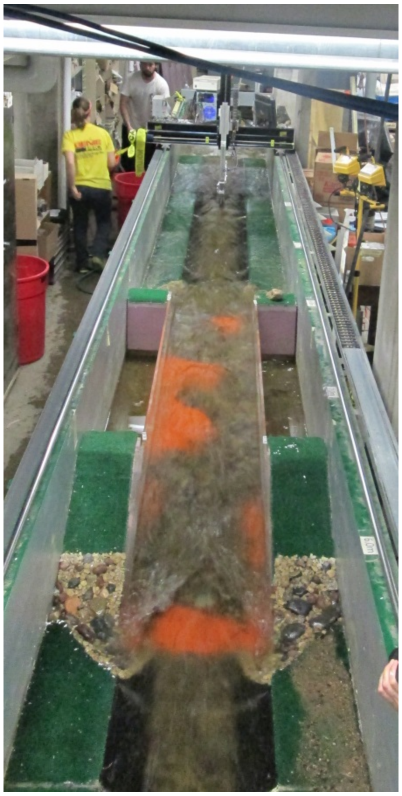

Photo 5: Falling Limb, Overbank Flow 1

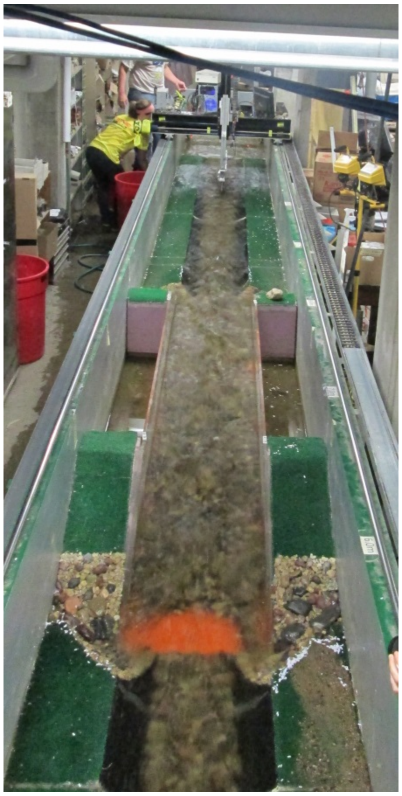

Photo 6: Falling Limb, Bankfull Flow

Photo 7: Falling Limb, Base Flow

Photo 8: Drained

Run 15: High Gradient, Hydrograph, Filled

Photo 1: Rising Limb, Base flow

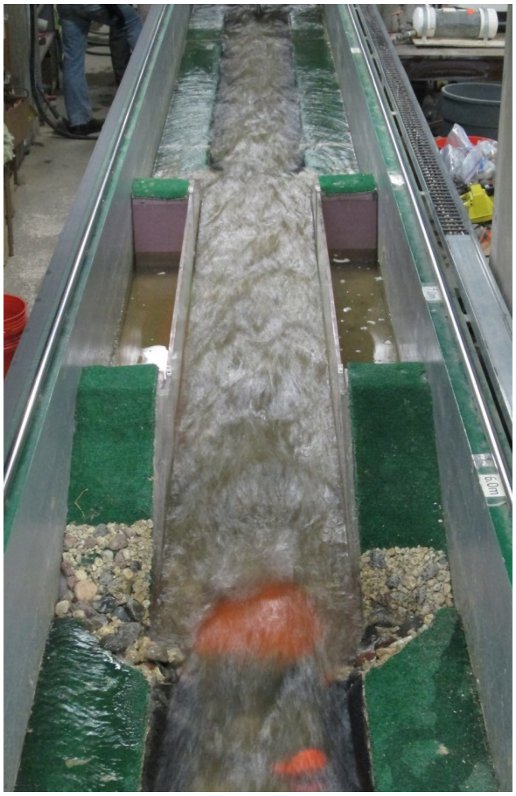

Photo 2: Rising Limb, Bankfull Flow

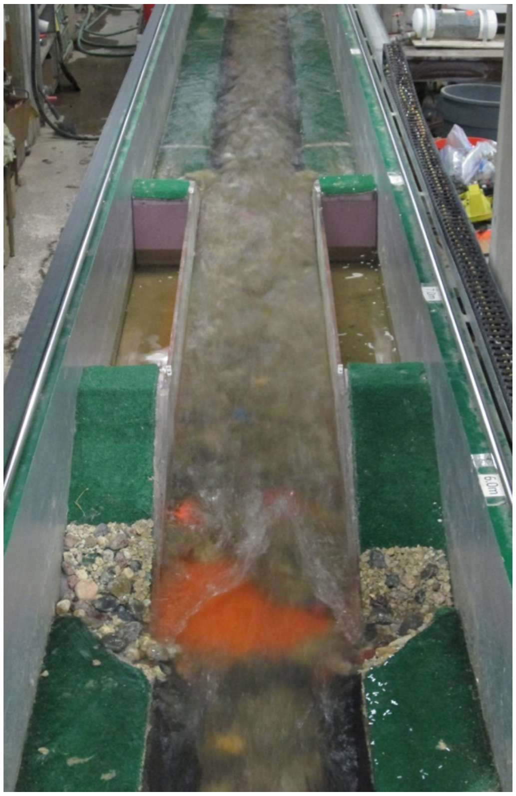

Photo 3: Rising Limb, Overbank Flow 1

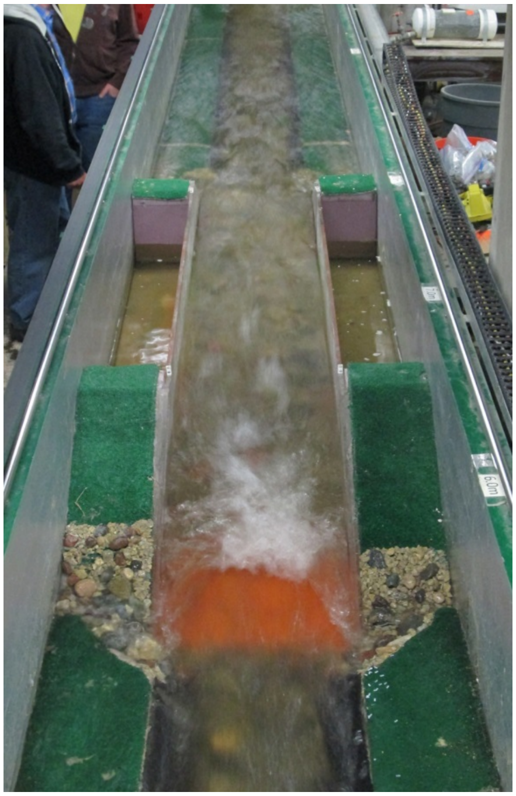

Photo 4: Overbank Flow 2

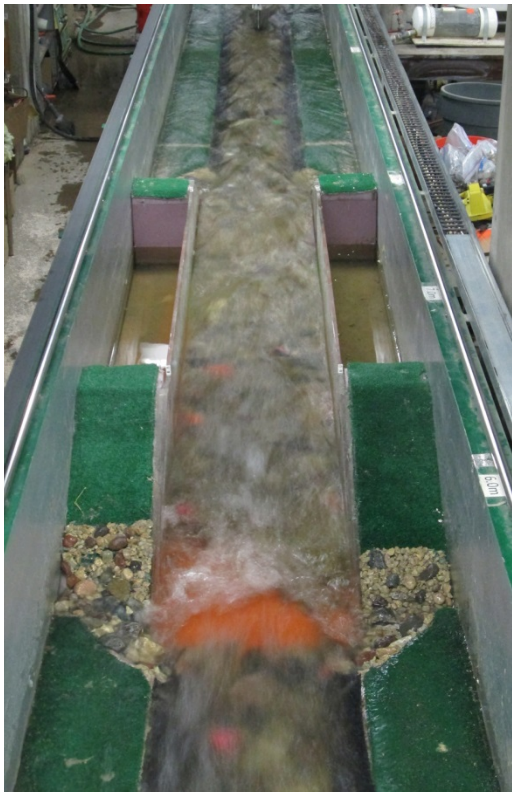

Photo 5: Falling Limb, Overbank Flow 1

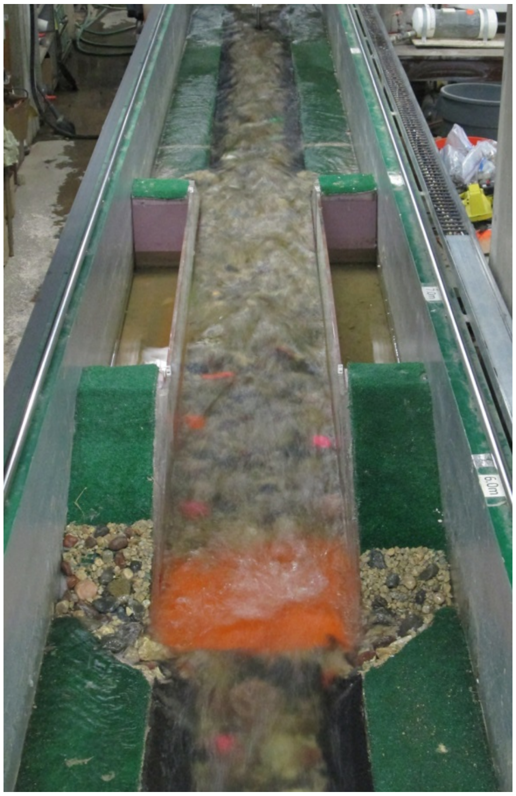

Photo 6: Falling Limb, Bankfull Flow

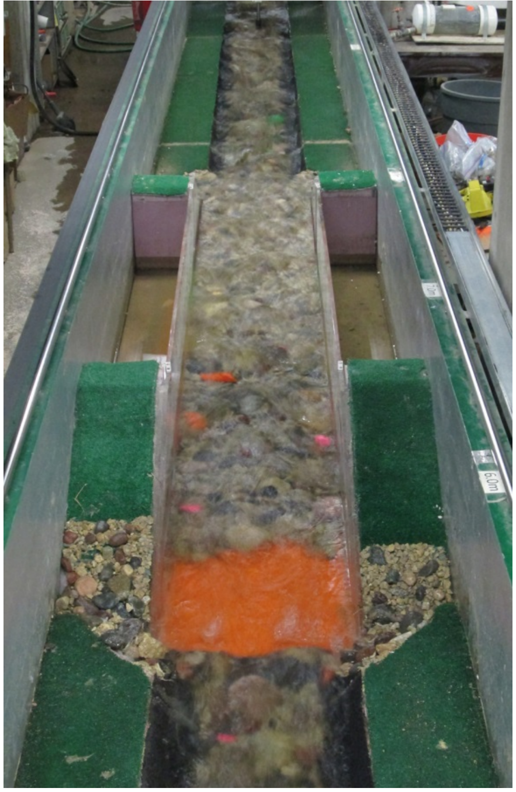

Photo 7: Falling Limb, Base flow

Photo 8: Drained

Run 16: High Gradient, Hydrograph, Non-Filled

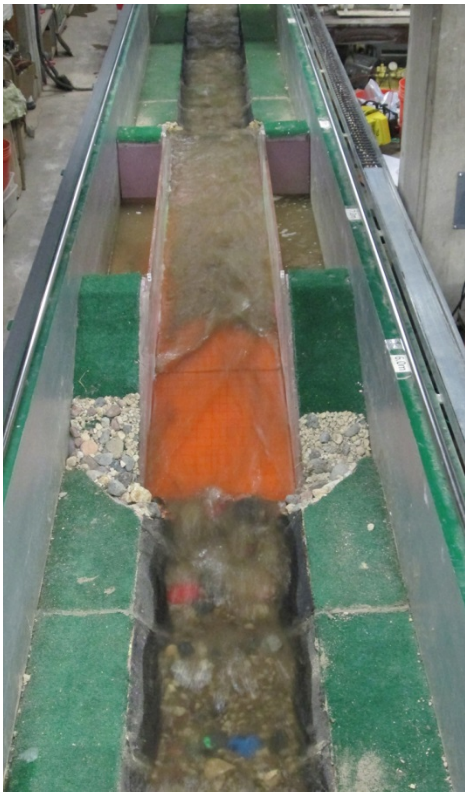
Photo 1: Rising Limb, Base flow

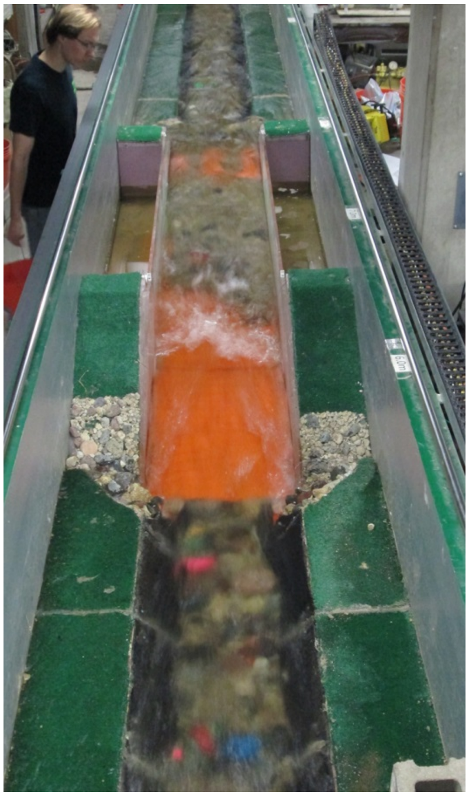
Photo 2: Rising Limb, Bankfull Flow

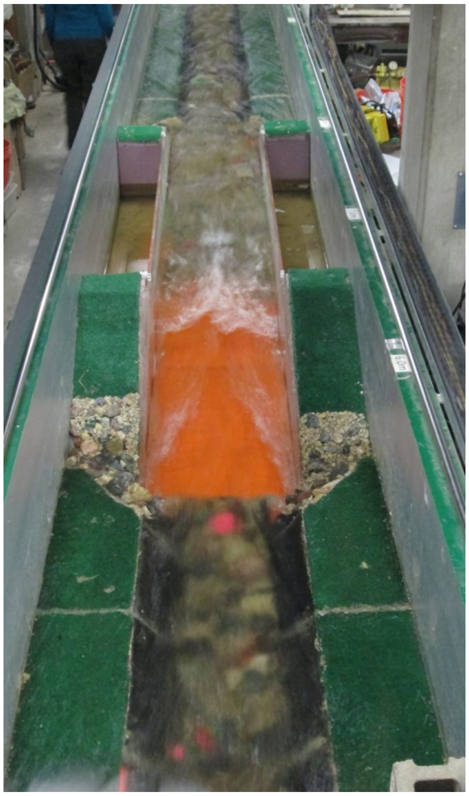
Photo 3: Rising Limb, Overbank Flow 1

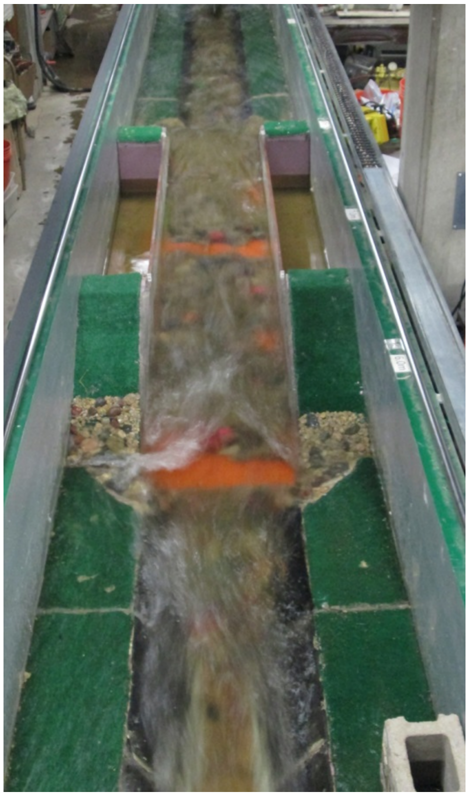
Photo 4: Overbank Flow 2

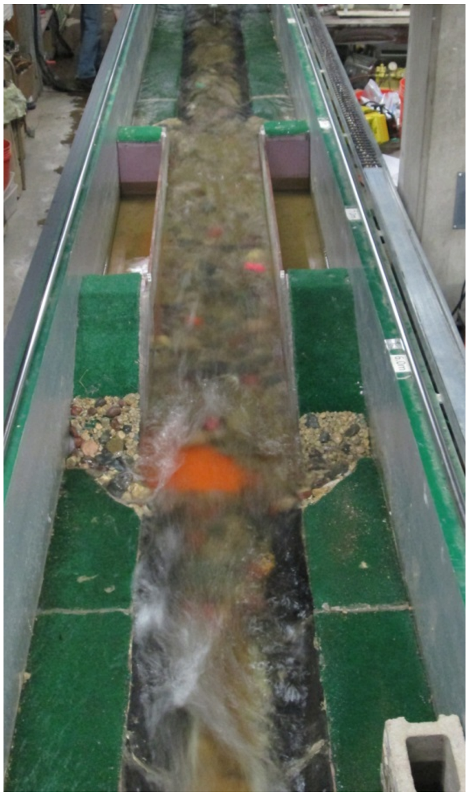
Photo 5: Falling Limb, Overbank Flow 1

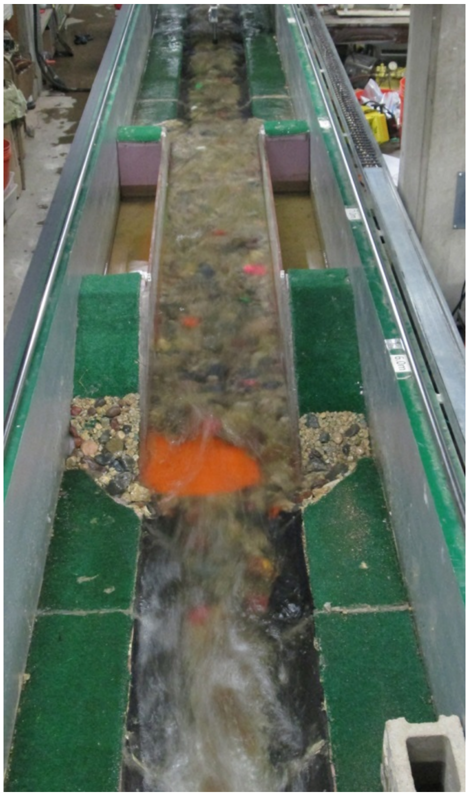
Photo 6: Falling Limb, Bankfull Flow

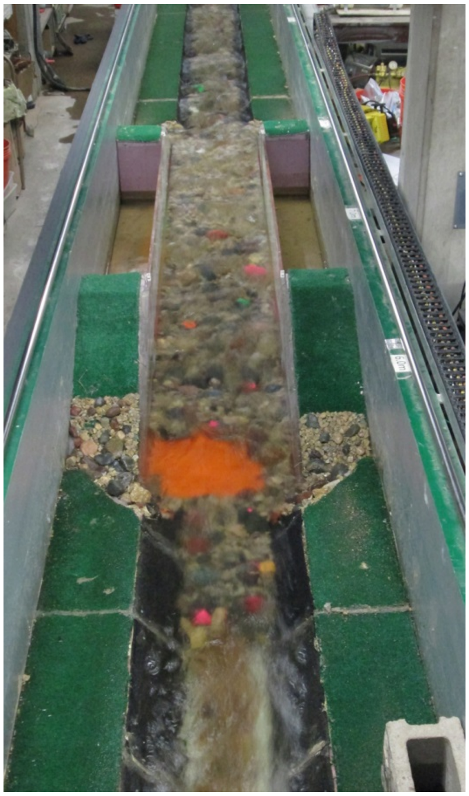
Photo 7: Falling Limb, Base Flow

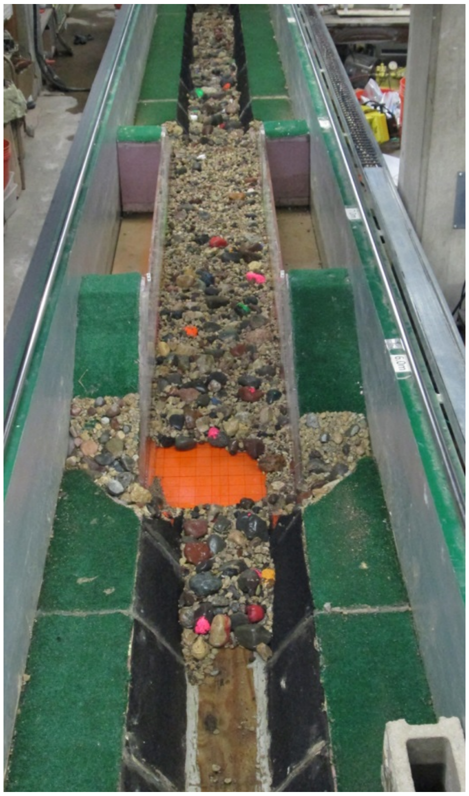
Photo 8: Drained

Run 17: High Gradient, Hydrograph, Filled With Structures

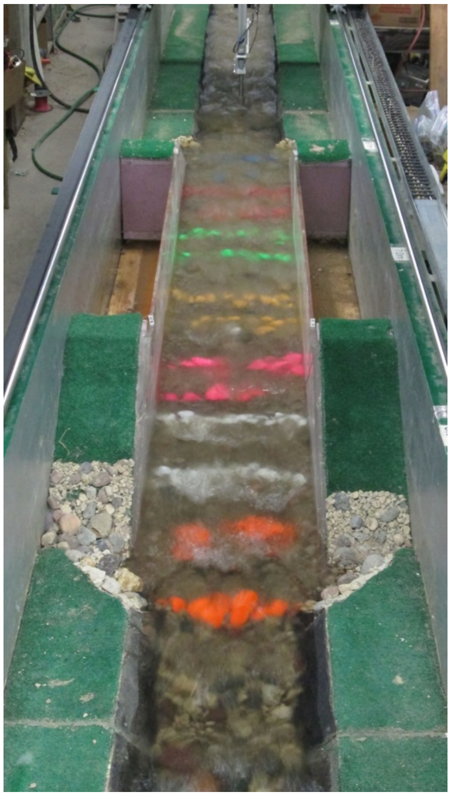
Photo 1: Rising Limb, Base Flow

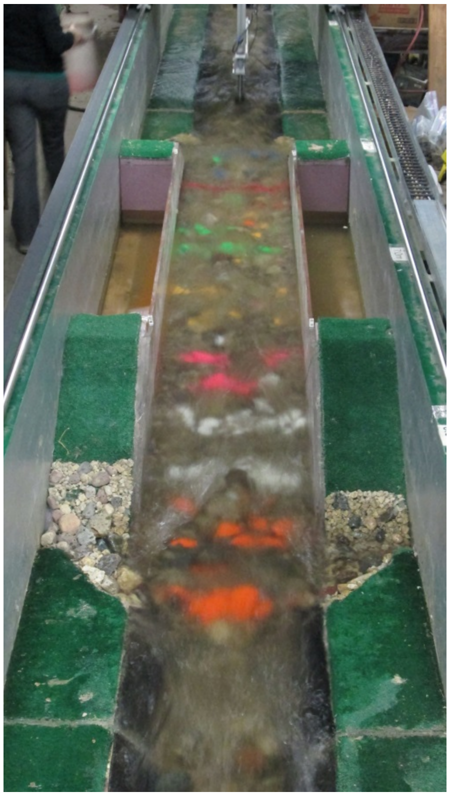
Photo 2: Rising Limb, Bankfull Flow


Photo 3: Rising Limb, Overbank Flow 1

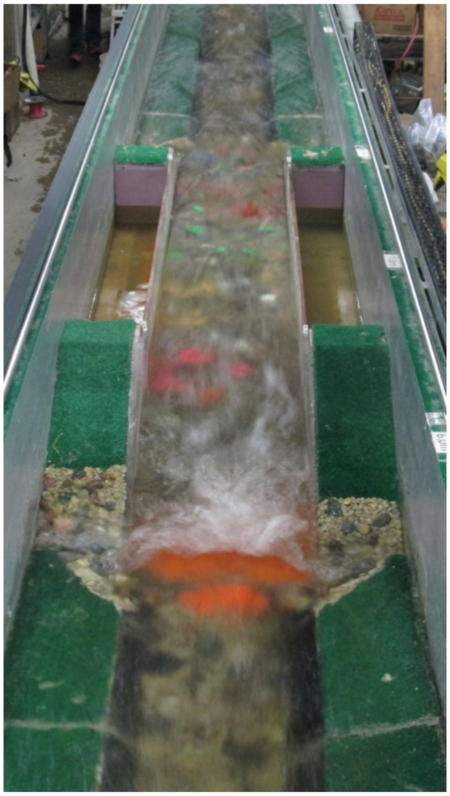
Photo 4: Overbank Flow 2


Photo 5: Falling Limb, Overbank Flow 1


Photo 6: Falling Limb, Bankfull Flow


Photo 7: Falling Limb, Base Flow


Photo 8: Drained

Appendix C

Time-Lapse Photographs of Multi-Barrel Culvert Hydrograph Experiments

A) Entrance to of Multi Barrel Culvert Run1 – no offset

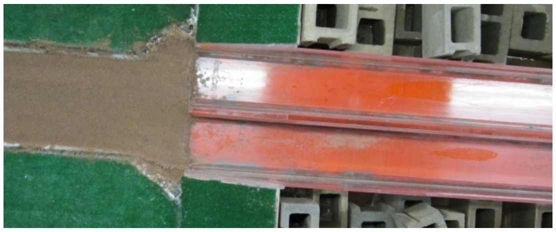
Photo 1: Pre Run

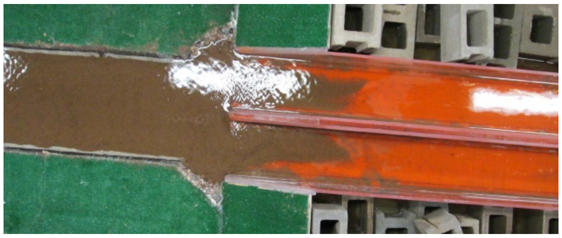
Photo 2: Base Flow


Photo 3: Bank Full Flow

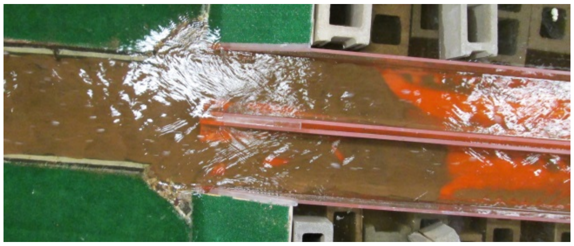
Photo 4: Overbank Flow 1

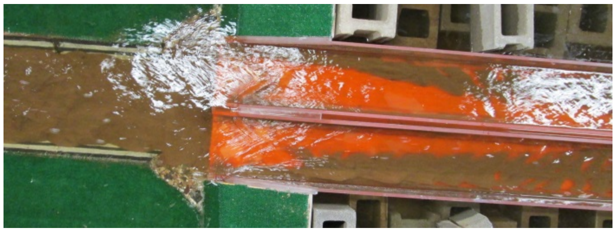
Photo 5: Overbank Flow 2

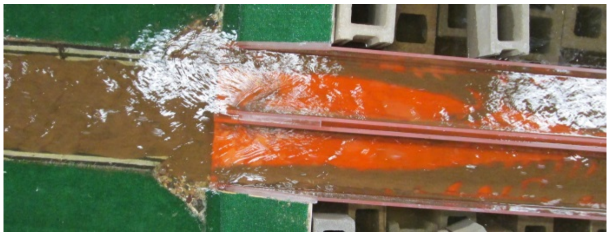
Photo 6: Overbank Flow 1 on Falling Limb

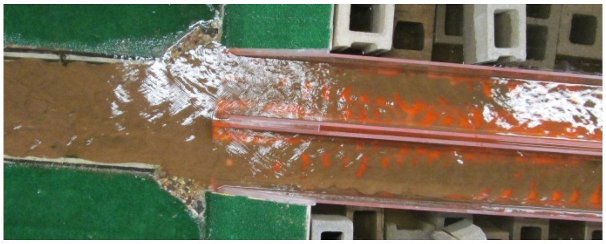
Photo 7: Bank Full Flow on Falling Limb

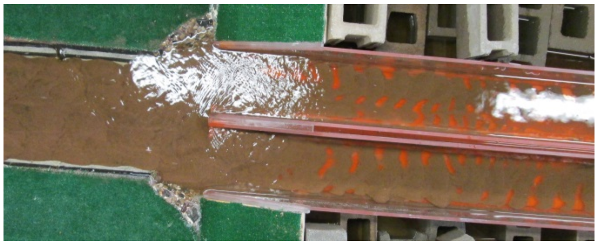
Photo 8: Base Flow on Falling Limb

B) Exit of Multi Barrel Culvert Hydrograph Run1 – no offset

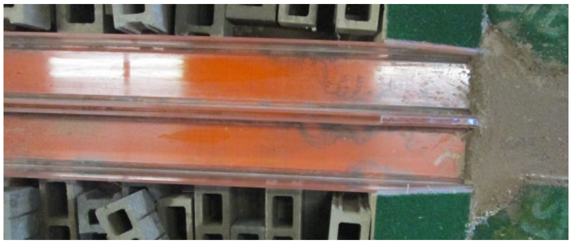
Photo 1: Pre Run


Photo 2: Base Flow


Photo 3: Bank Full Flow

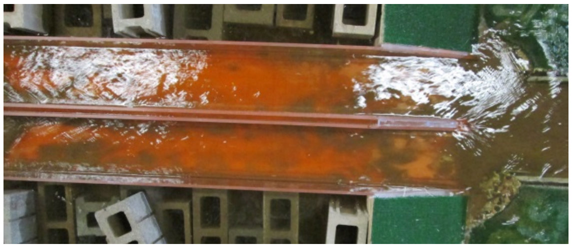
Photo 4: Overbank Flow 1

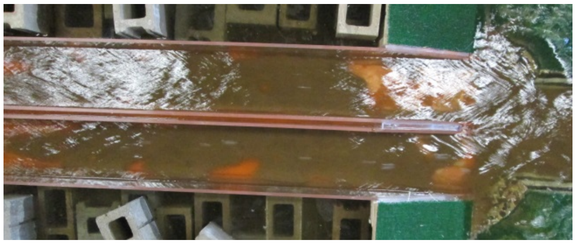
Photo 5: Overbank Flow 2

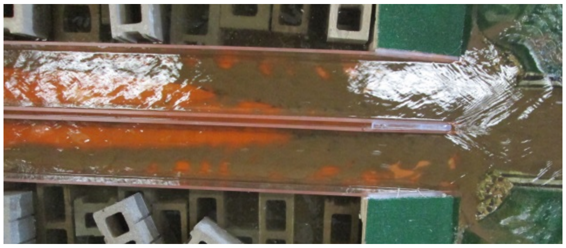
Photo 6: Overbank Flow 1 on Falling Limb

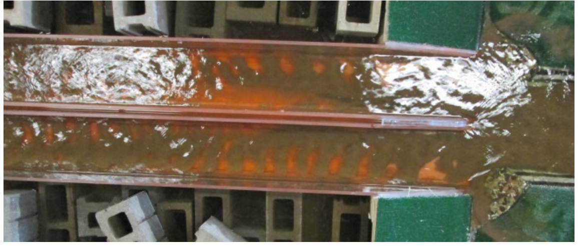
Photo 7: Bank Full Flow on Falling Limb

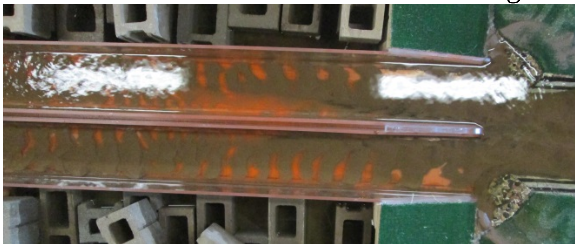
Photo 8: Base Flow on Falling Limb

C) **Entrance to of Multi Barrel Culvert Run1 – 0.5 in offset**


Photo 1: Pre Run


Photo 2: Base Flow


Photo 3: Bank Full Flow


Photo 4: Overbank Flow 1


Photo 5: Overbank Flow 2


Photo 6: Overbank Flow 1 on Falling Limb


Photo 7: Bank Full Flow on Falling Limb


Photo 8: Base Flow on Falling Limb

D) Entrance to of Multi Barrel Culvert Run1 – 1 in offset

Photo 1: Pre Run

Photo 5: Overbank Flow 2

Photo 2: Base Flow

Photo 6: Overbank Flow 1 on Falling Limb

Photo 3: Bank Full Flow

Photo 7: Bank Full Flow on Falling Limb

Photo 4: Overbank Flow 1

Photo 8: Base Flow on Falling Limb

E) Entrance to of Multi Barrel Culvert Run1 – 1 in offset on right, skewed to flow

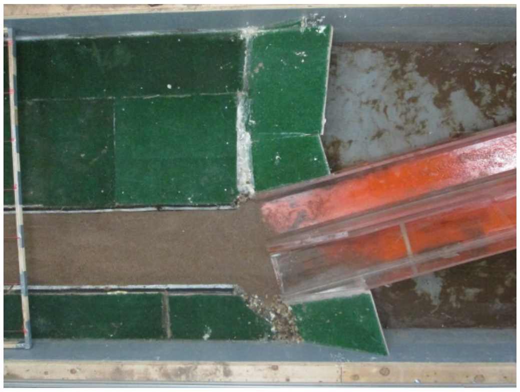
Photo 1: Pre Run

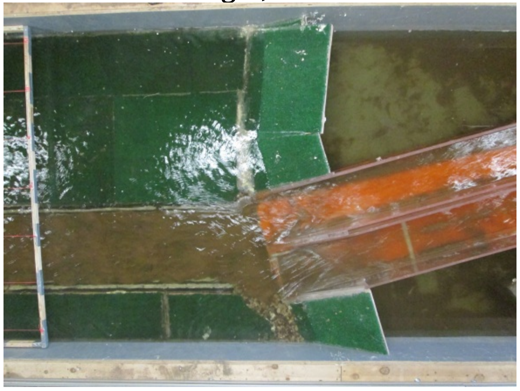
Photo 5: Overbank Flow 2

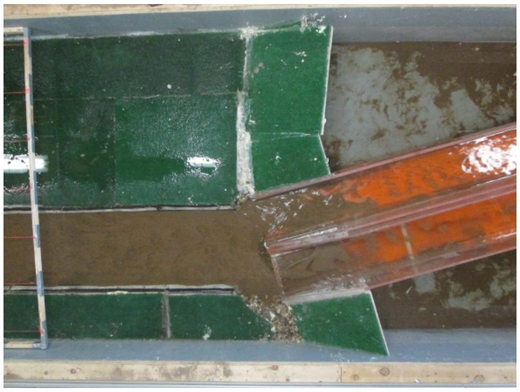
Photo 2: Base Flow

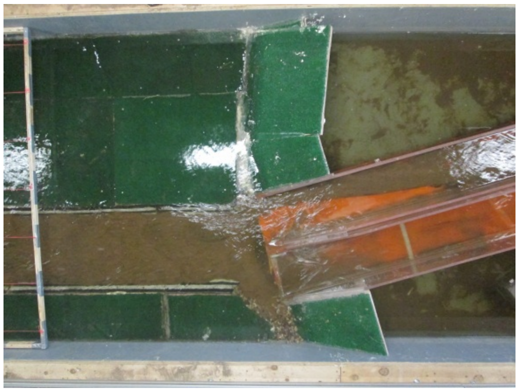
Photo 6: Overbank Flow 1 on Falling Limb

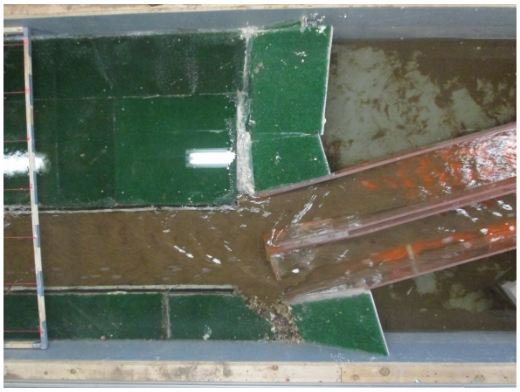
Photo 3: Bank Full Flow

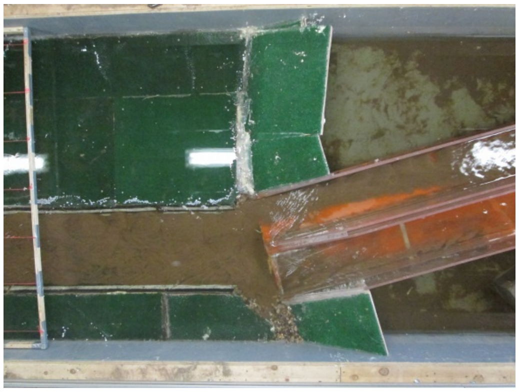
Photo 7: Bank Full Flow on Falling Limb

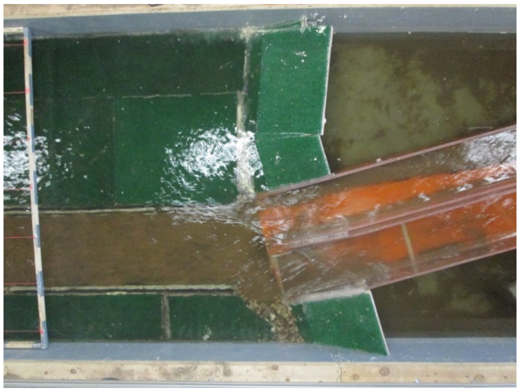
Photo 4: Overbank Flow 1

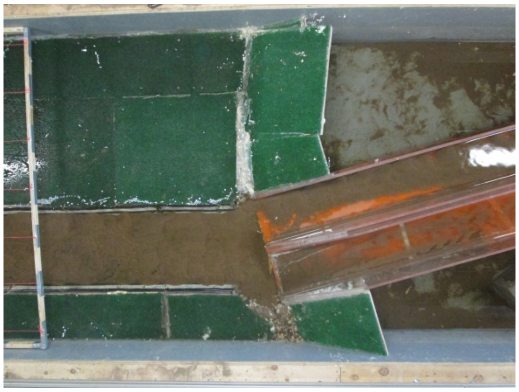
Photo 8: Base Flow on Falling Limb

F) Entrance to of Multi Barrel Culvert Run1 – No offset, skewed to flow

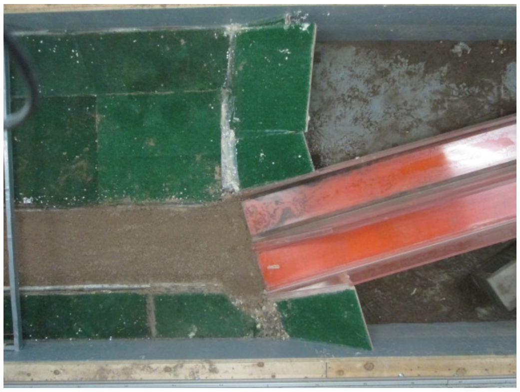
Photo 1: Pre Run

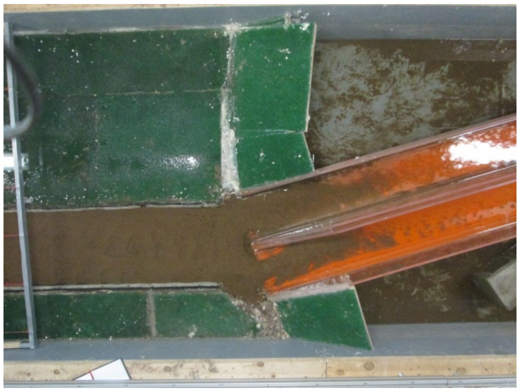
Photo 2: Base Flow

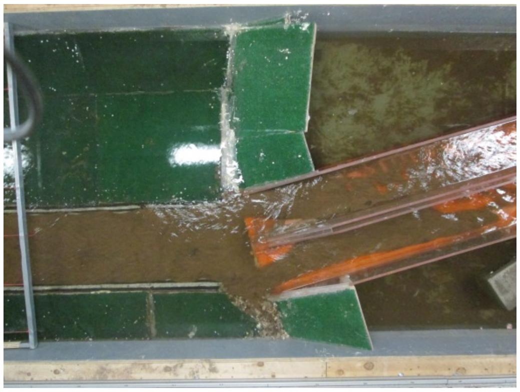
Photo 3: Bank Full Flow

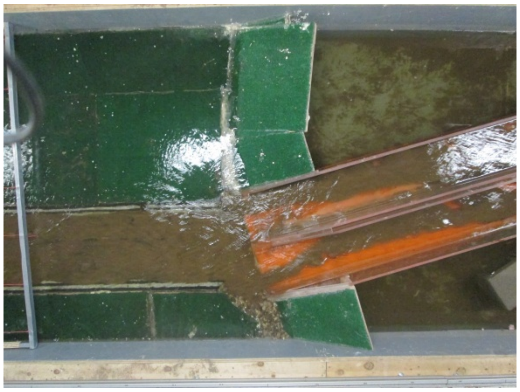
Photo 4: Overbank Flow 1

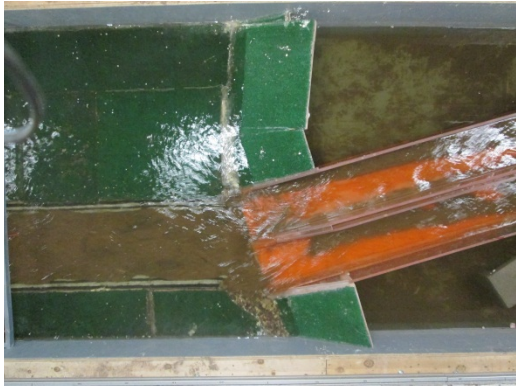
Photo 5: Overbank Flow 2

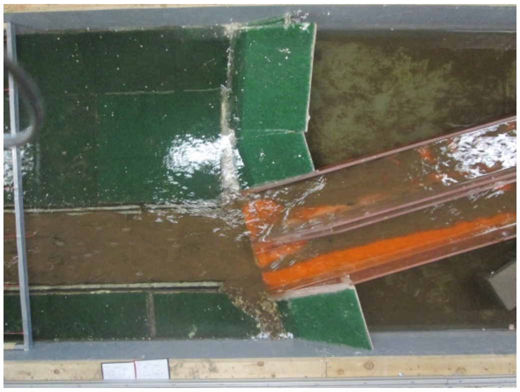
Photo 6: Overbank Flow 1 on Falling Limb

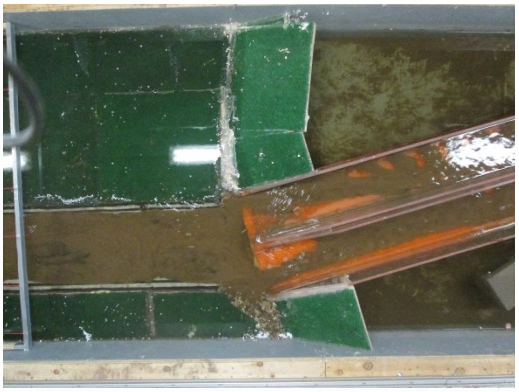
Photo 7: Bank Full Flow on Falling Limb

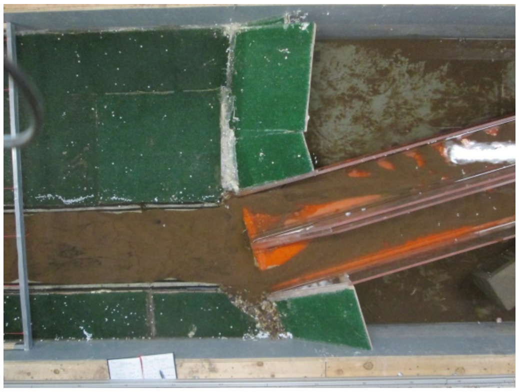
Photo 8: Base Flow on Falling Limb

G) Entrance to of Multi Barrel Culvert Run1 – 1 in offset in left barrel, skewed to flow

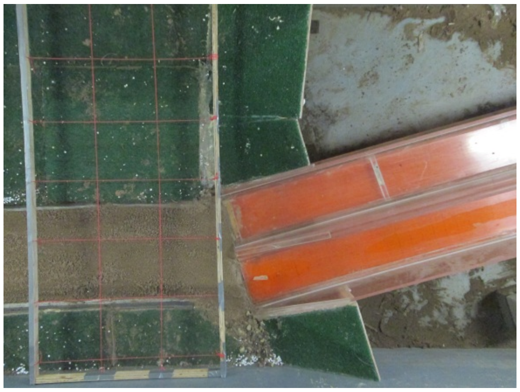
Photo 1: Pre Run

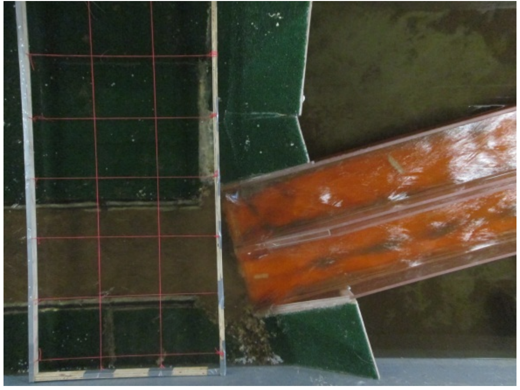
Photo 5: Overbank Flow 2

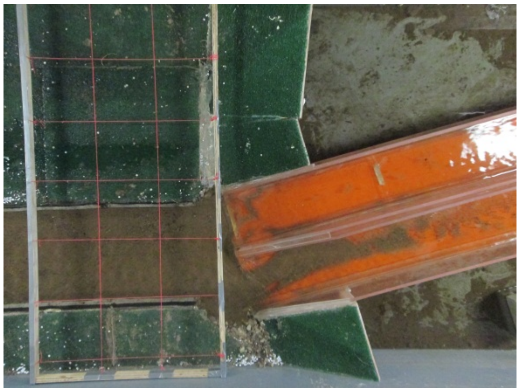
Photo 2: Base Flow

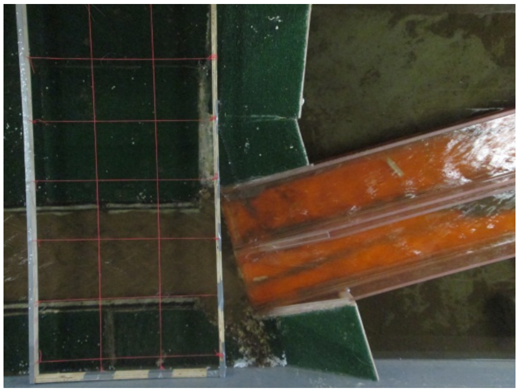
Photo 6: Overbank Flow 1 on Falling Limb

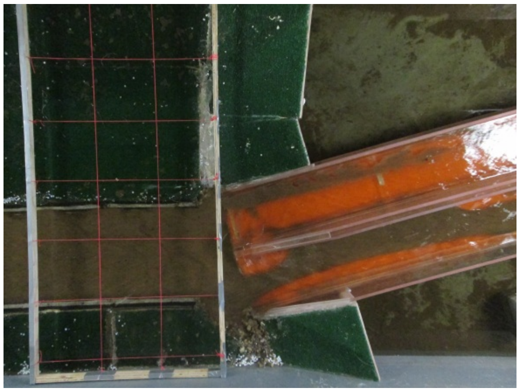
Photo 3: Bank Full Flow

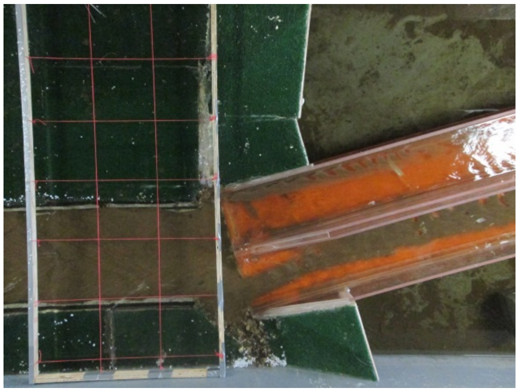
Photo 7: Bank Full Flow on Falling Limb

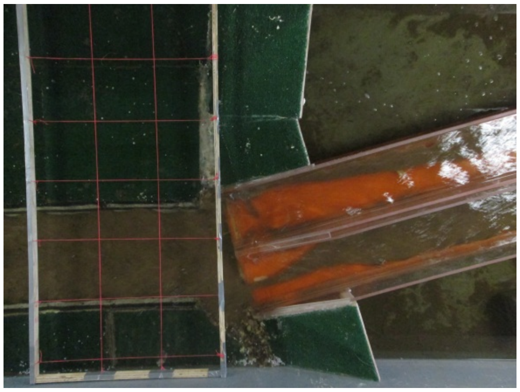
Photo 4: Overbank Flow 1

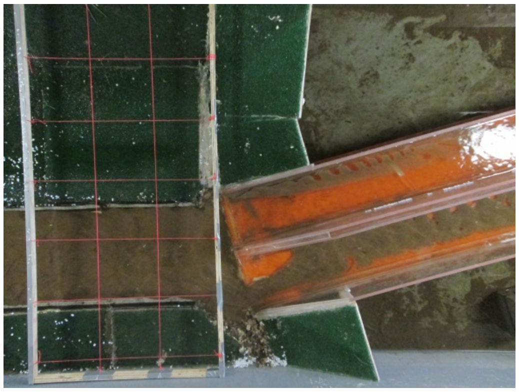
Photo 8: Base Flow on Falling Limb