A Study of Bankfull Culvert Design Effectiveness

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for the
Ohio Department of Transportation
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Cleveland State University

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16. Abstract

As part of the certification under the Clean Water Act 404 Nationwide Permit, the Ohio EPA mandated that the Ohio DOT install bankfull culverts in all new culvert installations subject to the permit. In addition, by embedding the culvert, the bottom of the culvert is to take on the characteristics of the natural streambed and promote the passage of fish and other aquatic organisms. The OEPA's requirement to install bankfull culverts has resulted in increased design and construction costs.

The objectives of the study were to examine the parameters which control the benefits of bankfull culverts when installed, including how the benefits alleged are affected by culvert diameter, slope and length, and the size of the stream in which the culvert is placed. Ultimately, the research was designed to determine if bankfull culverts, as currently installed, provide the benefit of allowing movement of aquatic biota better than traditional culverts, if there is any impact on flood attenuation, and if the bankfull culverts installed in Ohio have caused quantitative environmental changes or cumulative impacts (as measured by the QHEI).

The physical survey of the culverts revealed that of the 61 culverts identified by ODOT as being designed as embedded bankfull culverts (EBCs), there are only 12 that are actually embedded. ***ODOT should develop and implement a system of inspecting and verifying that culverts specified to be embedded bankfull culverts are actually installed as such.*** An important finding is that many of the culverts with greater than 1% slope had no sediment present inside of the culvert. ***The results of the survey indicate that, at the 90% confidence interval, sediments are being washed through culverts with a slope 1% or greater.*** Therefore it is recommended that EBCs should not be installed at slopes greater than 1%. Of the 12 embedded culverts, only two were found to be effectively allowing for the continuity of sedimentation patterns through the reach of a culvert. Because of the low numbers, the results found are not statistically significant. ***To better understand the functionality of culverts and the trends presented, more research is needed.*** ODOT should consider funding additional research in this area to confirm preliminary trends and provide more guidance in the design of embedded bankfull culverts.

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FINAL REPORT ON A STUDY OF BANKFULL CULVERT DESIGN EFFECTIVENESS
for the Ohio Department of Transportation - State Job Number 134465

1.0 Introduction

As part of the certification under the Clean Water Act 404 Nationwide Permit (NWP) in 2002, the Ohio Environmental Protection Agency (OEPA) mandated that the Ohio Department of Transportation (ODOT) install bankfull culverts in all new culvert installations subject to the permit. Bankfull culverts are designed to approximate the waterway's width/depth ratio at bankfull discharge and they are required to be buried or depressed approximately 10% below the grade of the waterway. The bankfull discharge is the point where the stream bank starts to overflow its banks onto the adjacent floodplain. In addition, by embedding the culvert, the bottom of the culvert is to take on the characteristics of the natural streambed and promote the passage of fish and other aquatic organisms. Throughout this report, we use the term "embedded bankfull culvert" or EBC to refer to culverts designed using bankfull discharge design and depressed culvert inverts. Specifications for ODOT's bankfull and depressed culvert designs can be found in *ODOT's Location and Drainage Design Manual,* Volume 2. An example of a bankfull, embedded culvert is shown in Figure 1.

Figure 1:
Bankfull Embedded Culvert on SR 30 Near Wooster, Ohio

The OEPA's requirement to install bankfull culverts has resulted in increased design and construction costs. Preliminary investigations conducted at Cleveland State University indicate that costs may increase by up to 34%. Despite this increased cost, a search of the literature reveals that there has been little published research conducted to determine under what physical conditions bankfull culverts are effective in establishing a natural channel bottom or in allowing for the passage of migratory aquatic species present in Ohio waterways. In fact, preliminary investigations conducted at Cleveland State University indicate limited, if any, environmental benefits in several installations, especially when installed at greater than approximately 1.5 % slope or in smaller streams subject to significant spates (large variations in flow). Currently, the OEPA's general conditions for the new NWP program would require that bankfull culverts with depressed inverts on all new culverts installed at a slope of less than 3% despite the lack of scientific evidence indicating when these culvert design techniques are appropriate and effective. More research must be done to determine the effectiveness of these culvert design techniques to justify the expenditure of funds and to assure that future regulations are developed based on sound science.

1.1 Research Approach: Traditionally, the primary function of a drainage culvert is to convey the design flow effectively. However, concerns of the environmental impacts that culverts have on streams have recently arisen. Embedded, bankfull culverts have been argued to reduce potential impacts by simulating the natural channel as well as the natural streambed. However, there has been little research that quantitatively examines their effectiveness with respect to hydraulic function or biological integrity of the stream. While hydrologic function is a relatively straightforward parameter to measure, environmental impacts and biological integrity remain much more challenging factors to quantify. Many methods have been developed to measure the overall environmental impact that *human activities* have had on streams from both a hydrologic and biological standpoint, and even though there has been an increasing amount of research done on this subject, many of the methods used to measure overall impact cannot be applied to measure the specific impact that culverts have on streams.

The overall research approach of this study was to survey existing embedded bankfull culverts installed in Ohio, to collect physical and hydraulic data, and use those data to explore any relationships between culvert design parameters (e.g. length, slope, diameter) and the distribution of sediment above and below the culvert. ***The premise of the study was that physical and hydraulic measurements would directly assess the channel conditions. By analyzing the bed material transported it is possible to understand the time-integrated results of hydraulic conditions within the culvert.*** For example, increased particle size is associated with increasing shear stress, which indicates more severe conditions within the culvert relative to a reference stream reach or standard culvert installation (Bathust et al., 1987). Further, the sediment size distribution is also an indicator of potential biological impact, as bed texture can be implicated in many morphological and habitat related functions, as well as movement of aquatic organisms (Buffington and Montgomery 1999; Miltner et al., 2004; Wood and Armitage, 1997; Washington Department of Fish and Wildlife, 2003).

To address the cost and time associated with biological sampling for assessment, the Ohio Environmental Protection Agency developed the Qualitative Habitat Evaluation Index (QHEI) to provide a qualitative assessment of physical characteristics of a sampled stream (Ohio EPA, 1989). The index consists of a list of descriptors, physical factors that affect fish and invertebrate communities, which are assigned a score based on high biological diversity and integrity. These descriptors include but are not limited to substrate type and quality, in stream cover, channel quality, riparian zone width, bank erosion, and gradient. ***This project used the QHEI as the assessment tool for cumulative environmental impact of the project. This was possible only in those locations where ODOT provided from their files copies of a QHEI that were completed before the culvert was installed. At those locations, the research team performed a "post-culvert QHEI" for comparison to the pre-culvert value.***

2.0 Objectives of the Study

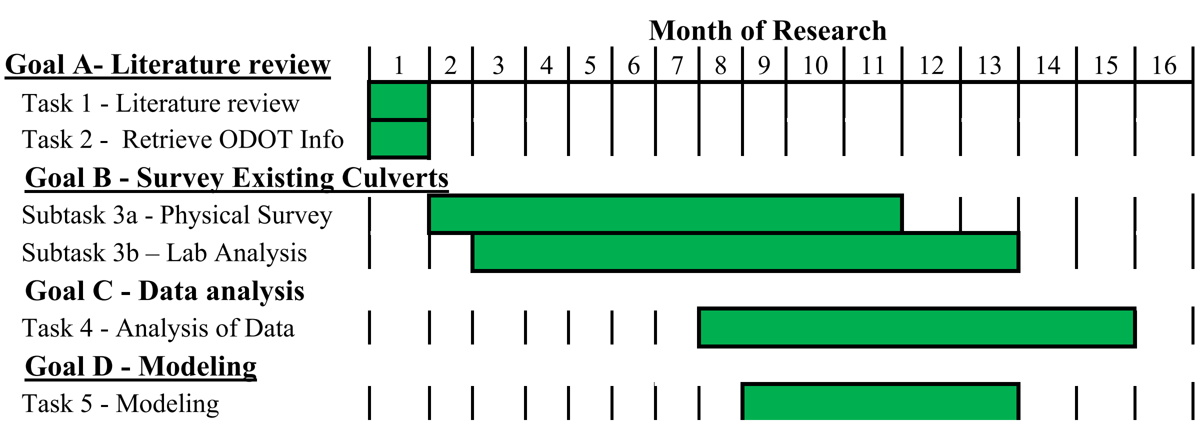
The objectives of the study were to examine the parameters that control the benefits (both hydrologic and environmental) of embedded and/or bankfull culverts when installed. Specifically, the research addressed the following questions:

1. How is the effectiveness of a bankfull culvert affected by culvert diameter, slope and length?
2. Does the size of the stream in which the culvert is placed affect culvert effectiveness?
3. Do bankfull culverts, as currently installed, provide the benefit of allowing movement of aquatic biota better than traditional culverts, and is that benefit, if any, related to stream size or culvert diameter, slope and/or length?
4. What impact, if any do bankfull culverts have on potential fish passage and flood attenuation?
5. Have the bankfull culverts installed in Ohio caused quantitative environmental changes or cumulative impacts (as measured by the QHEI) and are these changes, if any, related to stream size or culvert diameter, slope and/or length?

2.1 Work Plan

The research took 16 months (starting August 23, 2009 and ending December 23, 2010) and involved four specific research tasks: (a) a detailed literature review; (b) a survey of existing bankfull culverts installed in Ohio to collect data; (c) an analysis of the effectiveness of the installed culverts; and (d) a computer model analyses of the hydrologic impacts of bankfull culverts on velocity in the culvert and fish migration (using FishXing®) and flood attenuation (using HydroCad®). A project schedule bar chart is provided in Figure 2 that shows the time frame in which the various tasks were completed. Each specific task is detailed in Section 3 entitled "General Description of Research."

Figure 2: Research Activities and Specific Tasks from Quarterly Progress Reports



3.0 <u>General Description of Research</u>

As detailed in section 2.1 above, the project involved four specific research tasks: (a) a detailed literature review; (b) a survey of existing embedded and/or bankfull culverts installed in Ohio to collect data; (c) an analysis of the effectiveness of the culverts as installed; and (d) a computer model analyses of the hydrologic impacts of bankfull culverts on velocity in the culvert, fish migration (using FishXing®) and flood attenuation (using HydroCad®).

3.1 <u>Task A - Literature review</u>

A detailed review of the published literature on the environmental and hydrologic impacts of bankfull culverts was conducted. Both peer-reviewed and gray literature was surveyed. The results of the literature review are included throughout this report as cited literature. A complete list of the articles reviewed is contained in the bibliography.

3.2 <u>Task B - Survey of Existing Culverts</u>

According to data, maps and design drawings provided by ODOT, there were 61 bankfull/depressed culverts already installed statewide. These culverts have been installed in various, hydrologic, geologic, and topographic settings. During the project, all 61 culverts were visited and surveyed. The details of this part of the research are provided in Section 4 of this report, entitled "Results." The data collected and their relationship to the five specific objectives of the research are shown in Table 1. Hydrologic data were also collected and used in the modeling study described in Task D below.

3.2(a) <u>Methods of Data Collection During Survey</u>: At each site surveyed, grab samples of sediment and water were collected at five locations along the reach of the culvert: (1) upstream of the culvert, (2) at the culvert inlet, (3) inside the culvert, (4) at the culvert outlet, and (5) downstream of the culvert. The samples were collected working downstream to upstream so as not to have sediment entrained in the water column sample from upstream sampling activity. At some locations, sediment samples could not be collected where there was no sediment present (either inside a culvert without sediment, or in areas where no sediment deposition occurred within the stream channel). Some water samples could not be collected inside a culvert either due to the culvert being too small to enter to collect a sample, the depth of the water was too deep to enter the culvert, the stream had dried due to low summer flows, or the culvert was a control traditional culvert and only selected data was collected. After the samples were collected, a field survey was done. The surveyed locations are the top of culvert, edge of each headwall and the upstream and downstream stream profiles. Also, dimensions of the culvert were verified for the depth of the embedment and diameter of the culvert.

Table 1: Data Collected and Their Relationship to the Objectives of the Research

Data to be Collected	Objectives[1] Data Address
Culvert physical characteristics: width, length, gradient orientation with channel and depth of embedment.	These are the primary independent variables against which all other factors will be evaluated statistically. Therefore, this data serves to meet all five objectives.
Channel physical characteristics: dimensions, gradient, velocity, and flow	Objective #2; Objective #3; Objective #4
QHEI: An upstream and downstream QHEI will be conducted in those areas where pre-construction QHEIs are available.	Objective #5
Water quality: TSS, Turbidity, TOC (As detailed in the literature review, these tests give insight into stream health.)	Objective #3 Objective #5
Composite Sediment Grab Samples: taken upstream at the inlet, at the outlet, downstream, and inside culvert (As detailed in the Literature Review, these data are a primary source of evaluating both hydrologic and environmental impact. Each sample will be divided into 3 to 4 sub samples ranging from 110 -125 g each. Preliminary research has shown has been determined to be the most effective sample size for the equipment being used.)	Objective #1 Objective #2 Objective #3 Objective #5.

1 The specific objectives as detailed in section 2.0 above are:
Objective #1: Determine the relationship of culvert diameter, slope and length to effectiveness.
Objective #2: Determine effect of stream size on culvert effectiveness.
Objective #3: Determine the effect of culvert on movement of aquatic biota
Objective #4: Determine the effect of culvert on flood attenuation
Objective #5: Determine if culvert has produced any quantifiable environmental changes/impacts

3.2(b) <u>Laboratory Analysis Methods for Sediment Samples</u>: The methods for determining the total organic carbon (TOC) are based on ASTM 4129-05. Each sample was dried at 104 ^oC (219 ^oF) for 24 hours, weighed, and a loss on ignition test performed at 420 ^oC (788 ^oF) for 16 hours. Three trials were done for each sample. Grain size distribution was determined using ASTM method 6913-04(2009). The sample was sorted into particle size ranges using standard sieves #4, 10, 16, 35, 60, 140, 200, and pan. Three trials were done for each trial.

3.2(c) Laboratory Analysis Methods for Water Samples: ASTM D7315 was used to determine turbidity in water samples. Ten (10) ml samples of water were placed into a portable turbid meter. Formazin calibration was using in calibrating the turbid meter. Total Suspended Solids (TSS) at each site was determined using ASTM method D5907-09. Sample sizes for analysis were determined based on the amount of sample collected from the field. Sample sizes used for TSS ranged from five (5) ml to twenty (20) ml. After water was passed through filters, filters were dried at 104 ^{o}C (219 ^{o}F) for 24 hours and cooled in a dessicator for a minimum of one hour.

3.3 Task C - Analysis of Data

The data were analyzed statistically to determine if it were possible to identify a relationship between culvert design parameters (slope, size, length, and type) and the movement of streambed load and sediment distribution. The effects of bankfull versus traditional culvert installations were compared to approach an evaluation of the operation and environmental benefits of traditionally designed culverts and bankfull culverts. In addition to standard statistical techniques such as Linear Regression Analyses, non-statistical techniques were employed where data were not sufficient to conduct detailed statistical analyses or where the statistical analyses required were beyond the scope, time restrictions and budget of the project.

3.4 Task D - Hydrologic and Fish Modeling

Using the data collected in Task B, The computer models FishXing® and HydroCad® were used to evaluate and compare bankfull and typical culverts for their impacts on stream velocity in the culvert (which effects fish passage) and flood attenuation. In addition, an analysis of flow velocities was conducted to allow for examination of the potential for limitation of passage of other aquatic microorganisms besides fish. This examination looked only at average flow velocities in the culvert at a standard flow in the stream. Standard flood flows (2-year, 5-year and 10-year) were taken from the online US Geological Survey *stream stats* database (http://water.usgs.gov/osw/streamstats/ohio.html). For the vast majority of organisms found in Ohio waterways, there is insufficient literature and limited information on the actual velocities that might limit migration.

4.0 Results

4.1 Literature Review

The main purpose of the literature review was to determine if any other evaluations of bankfull culvert effectiveness had been published and to determine the best and most cost effective parameters to sample in order to develop a picture of the environmental impact and benefits of the embedded bankfull culvert design. A thorough literature search did not produce any available field studies of embedded bankfull culvert effectiveness or impact. However, the literature search did provide significant information on approaches to investigating culvert impacts. Table 2 provides an overview of the literature review of methods for impact assessment as well as some evaluation parameters for selection between the methods. Figure 3 presents a "decision tree" of some of the more pertinent questions and options when designing a culvert assessment-monitoring program.

4.1(a) Sediment Transport in Streams: Streams are complex and dynamic systems that change over time. A stream environment is shaped based on a variety of factors including, energy of flow, sediment load, channel morphology, channel hydraulics, and the bio-chemical processes of the stream. Of these, the energy of the flow, sediment load, and channel morphology are important with regards to changes in sedimentation patterns (Newton et al. 1997). A sediment particle in a stream can originate from land or from the channel itself (Ponce, 1989). Once a particle has been eroded from its origin, the sediment will travel down gradient under the force of flow of water until its eventual deposition. In a stream system, the energy of the flow dictates whether a particle is deposited or transported downstream (Ponce, 1989).

Although sedimentation is a naturally occurring phenomenon, human activity can increase sediment transport in streams and therefore in sedimentation. A study conducted by Miltner et al (2003) in Ohio showed that run-off resulting from poor land use planning and poorly regulated construction practices lead to declining stream health and biotic integrity within a watershed. Excess sedimentation can cause serious side effects for streams and rivers both hydrologically and biologically. The addition of excess sediments in the water can occur because of culverts mainly as a result of the erosion of fill and bank material caused when the hydraulic capacity of the culvert is exceeded or when the culvert is not properly aligned and oriented with the natural channel and bankfull width. The primary function of a drainage culvert to convey the design flow effectively can be greatly impaired or completely lost due to the presence of deposited sediments (Tsihrintzis, 1995). Wood and Armitage (1997) outlined several ways in which excess fine sediments deposited on the streambed have serious hydrological and biological consequences on a stream. For example, fine sediments can:

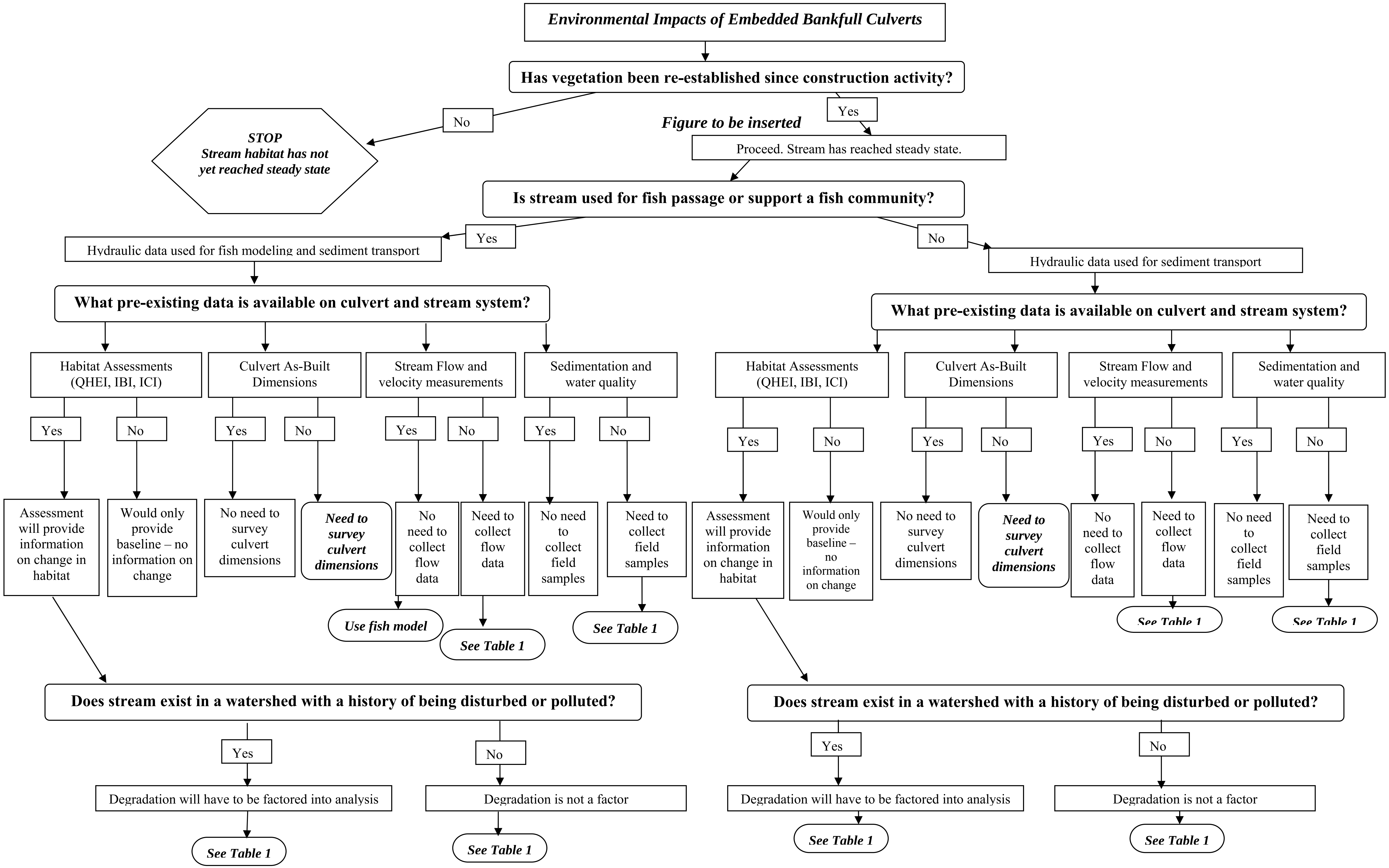
- smother the streambed killing aquatic flora changing channel morphology;
- clog small spaces between streambed particles, increase invertebrate drift and reduce available habitat for benthic organisms; and
- deposit on respiration structures of macroinvertebrates and may produce low dissolved oxygen concentrations, creating an environment not suitable for respiration.

TABLE 2: Culvert Impact Assessment Methods

Reason for Test	Parameter	Technique	Time and Cost[1] *(shortest time unit in which test can be sampled and analyzed)*	Benefit	Drawback
Changes in stream hydraulics may affect fish passage and aquatic life	Hydraulics	Velocity Measurements	Days	Detailed velocity profile used for fish modeling	Information on fish passage only, no information on habitat
		Physical & Hydraulic Measurements	Hours	View of general physical and hydraulic conditions used for fish modeling	Fish passage is implied
Changes in sedimentation may affect water quality and ability for stream to support invertebrates and Salmonids	Sediment Transport	Total Suspended Solids (TSS)	Days	Detailed information on water quality and sediment transport through water	Information on water quality only, no information on habitat
		Turbidity	Hours	Detailed information on water quality and sediment transport through water	Information on water quality only, no information on habitat
		Particle Size Distribution	Weeks	General view of habitat quality through particle size distribution in sediment	Habitat quality in terms of sediment size only
		Total Organic Carbon (sediment)	Days	General view of habitat quality through amount of TOC and fine particles in sediment	Habitat quality in terms of streambed characteristics only
Due to change in continuity of the stream, the overall habitat may be affected due to culvert	Biological Impact	Index of Biotic Integrity (IBI)	Months to a Year	Detailed view of habitat quality through diversity of biota population	Habitat quality in terms of fish populations only
		Qualitative Habitat Evaluation Index (QHEI)	Hours	General view of habitat quality in a short time through	Habitat quality in terms of physical condition only
		Invertebrate Community Index (ICI)	Months to a Year	Detailed view of habitat quality through diversity of macroinvertebrate population	Habitat quality in terms of macroinvertebrate populations & pollution sensitive macroinvertebrates

[1] Cost is driven by the human labor cost for the time required to sample and analyze data; the longer the time the more expensive a test is to perform

Figure 3: Decision Tree for Developing Culvert Monitoring Programs



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4.1(b) ***Sediment Impacts on Flora and Benthic Organisms***: In addition to the loss of hydraulic function, sediment transport and sedimentation can have adverse effects on water quality and aquatic ecosystems. Further, there is a correlation between hydraulic conditions and biological integrity. For example, the growth of aquatic macrophytes has important influences on flow velocity, flow patterns, channel roughness, and water depth (Hearne et al., 1993; Watson, 1987). Sediments in the water increase turbidity, limit light penetration reducing aquatic macrophyte growth, and impede fish passage, among other harmful effects (Davis-Colley et al., 1992; House et al., 2005; Kahler et al., 1998). When fine sediments settle, they can deposit between the larger bed particles, clogging the substrate. The process of streambed clogging is best described by Cui et al. (2008).

> *Once a fine sediment particle enters the pores of the bed material, it will either continue to move downward within the pores or become lodged within the bed matrix according to a quantifiable probability distribution. After a fine sediment particle is lodged in place, it becomes permanently fixed in place, which decreases the pore size opening and increases the probability for subsequent incoming fine sediment particles to become lodged. This process results in a decreased fine sediment fraction with depth into the deposit. Eventually, the pore spaces in the top layer of the bed material will be completely clogged with fine sediment particles (i.e., the deposit becomes saturated with fine sediment) and effectively stops additional fine sediment infiltration. Herein, a coarse sediment deposit is defined as saturated with fine sediment when the pore spaces of the deposit become so small that fine sediment can no longer advance through it.* (pg. 1421)

This change in channel morphology can have a profound impact on biota at all levels of the food chain. For primary producers, low light penetration caused by the high turbidity reduces the amount of production of primary producers. In areas with high amounts of fine deposits, the particles can actually smother in-stream fauna (Artimage & Wood, 1997). High sedimentation can affect invertebrates in a number of ways. Existing invertebrates may not be well suited to the change in substrate composition. The accumulation of fines can affect respiration, increase macroinvertebrate drift due to substrate instability, and impede filter feeding (Connolly & Pearson, 2007).

4.1(c) ***Sediment Impacts on Fish***: Fish hold both environmental and economic importance. In the United States alone, 4.3 billion dollars were generated from commercial fisheries in 2008. In the great lakes region of the United States, 16.7 million dollars were generated from fisheries in 2008 (Pritchard, 2008). Because of this, in many areas of the United States there is both an environmental and economic interest in the health of streams. Salmonids are of particular importance because of their use as a food source as well as an economic staple. It has been estimated that the average American consumes 2.0 pounds of salmon a year, and the US exports 292 million pounds of salmon worth 440.3 million dollars (Ag Marketing Resource Center, 2010).

Salmonids use stream systems for spawning, migration, and juvenile rearing. Salmonids typically build their nests in an area with high amounts of in-stream cover, low fine particulate embedment, and high food sources (Bates, 2003). Harrison (1923) showed that the deposition of high amounts of fine sediments dramatically reduce the survival rate of Salmon eggs (Harrison, 1923). In addition to reducing populations in the short-term, the lack of surviving juveniles can reduce genetic diversity within the species, thus reducing the fitness of the species as a whole (K.S, Schwartz, & Ruggiero, 2002).

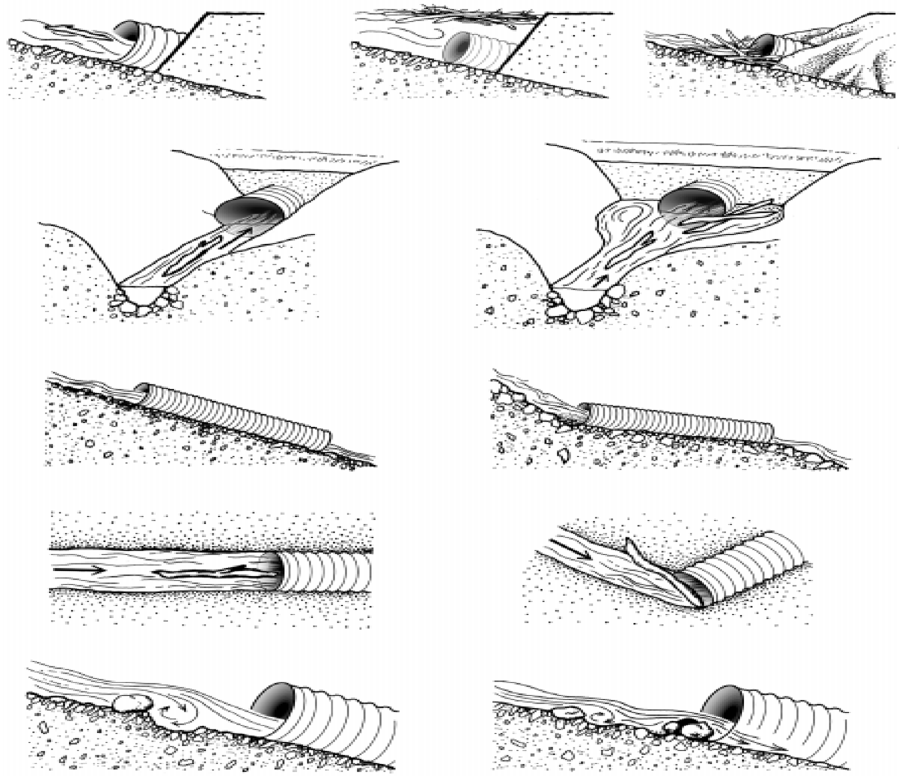
Recent studies have shown that using average velocity as a criterion for fish passage is much too simplified and abstracted a method to capture the complexity of natural channel morphology and hydraulics (House et al., 2005; Buffington and Montgomery, 1999). Migratory fish take advantage of the areas of low flow velocity created by non-uniform flow to move upstream without exceeding their fatigue limit (House et al., 2005). As a result design methods based on average velocity may restrict upstream movement of some fish species. A preliminary study conducted by the Washington Department of Fish and Wildlife beginning in 1999 and ending in 2003 measured the hydraulic and physical characteristics of 15 stream simulation culverts.

4.1(d) <u>Measuring Impact through Sediment Monitoring</u>: Based on the literature review presented in sections 4.1(a) through 4.1(c) above, it can be argued that physical and hydraulic measurements would directly assess the channel conditions presented to migratory fish and would allow for efficient and cost effective monitoring. There are several direct links between culverts and sediment transport that are well researched. Increased deposition inside the culvert results in less sediment reaching the downstream face and scouring can occur (Tsihrintzis, 1995). When scouring occurs, coarser sediment is transported immediately downstream and can create bars. However finer material is suspended and can be carried further downstream (ConnDOT, 2002).

It has been observed that culverts that best match the slope, orientation and the bankfull width are less likely to have sedimentation problems (ConnDOT, 2002). Bankfull width refers to the stream width associated with the stream stage just as the stream is about to flood and the water is at the height of the stream bank (Sherwood & Huitger, 2005). Matching the culvert width with the stream width can eliminate higher velocities associated with changes in width (Forest Service Stream Simulation Working Group, 2008).

Changes in flow geometry (width, slope and direction) from the stream to the culvert can lead to sedimentation problems. Scour can occur at both the inlet and outlet if the culvert is sized smaller than the bankfull width, thus leading to increased sediment loads downstream (ConnDOT, 2002). If the slope is less than the natural channel, it can lead to sediment deposition (Forest Service Stream Simulation Working Group, 2008). Culverts that are oriented in the same direction as the natural stream typically do not experience sedimentation problems. In a study performed by the United States Department of Agriculture (2008), researchers observed that a culvert that was not aligned with the natural channel tended to see large energy losses due to re-orientation of the flow between the culvert and stream, leading to increased sedimentation and blockage from debris. Figure 4 shows how the culvert can become blocked with debris at the inlet if the culvert is not aligned with the stream.

Figure 4 (*taken from USDA, 1998*)
Illustrations Showing How Culvert Installation Can Affect Blockage at a Culvert Inlet



The purpose of a bankfull culvert is to match the culvert width with the stream width to eliminate problems associated with sudden expansions and contractions between the stream width and culvert width (ConnDOT, 2002). By minimizing the degree of expansion or contraction through a culvert, it is expected the energy losses at the inlet and outlet of a culvert would be lower. However, research conducted at the Utah State University concluded embedded culverts have higher entrance loss coefficients than traditional culverts (Tullis, Anderson, & Robinson, 2008).

By analyzing the bed material transported it is possible to understand the hydraulic conditions within the culvert. For example, increasing particle size (coarsening) is associated with increasing shear stress which indicates more severe conditions within the culvert relative to reference reach (Bathust et al., 1987). Coarsening would also indicate a failure of the steam simulation concept since bed texture can be implicated in many morphological and habitat related functions, as well as movement of aquatic organisms (Buffington and Montgomery 1999; Miltner et al., 2004; Wood and Armitage, 1997; Washington Department of Fish and Wildlife, 2003).

It has been shown that excess sedimentation has serious side effects both hydrologic and biological to a stream/culvert system. In particular, excess fine sediments have been shown to be a major contributor to the decline of stream health and biotic integrity. An analysis of sediment particles in a stream/culvert system through a grain size distribution analysis would provide a detailed description of the amount and type of sediment located in the system. This analysis in conjunction with physical and hydraulic measurements could provide insight into the effectiveness of culvert design. ***This research project used sediment transport measurements as an important tool in evaluating the impacts, both hydrologic and environmental, of embedded bankfull culverts installed in Ohio.***

4.1(e) Measuring Impact through Biological and Habitat Monitoring: Culverts and roadway crossings create a break in the habitat continuity. In the 2008 document *Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings*, the USDA states that a culvert, where a flow blockage occurs upstream, functions as a low headwater dam. This creates a fragmented habitat that may be a factor in the population decline in fish (Forest Service Stream Simulation Working Group, 2008). In addition to migratory fish passage, culverts can also act as barriers to aquatic insects, aquatic macroinvertebrates, small mammals, and amphibians (Blakely et al., 2006; Yanes et al., 1994; Ward et al., 2008). A study performed by Yanes et al. (1994) showed that culvert dimensions, complexity of vegetation around the culvert, and the presence of detritus pools at the entrance of culverts all create obstacles to the movement of certain organisms.

In order to evaluate how the habitat around a culvert has changed since the installation of a culvert, there must have been a habitat assessment done prior to the installation of the culvert (Bouska, Paukert, & Keane, 2010). A prior assessment will provide baseline data on the status of the stream environment before the construction of the culvert and roadway. If baseline data is available, then new assessments will provide data on how the stream has responded to the addition of the culvert into the stream habitat. Assessments must be done on the upstream and downstream of the culvert. The upstream assessment will show how the stream has naturally changed since installation, and the downstream will show the natural changes in the stream combined with the effects associated with the culvert.

The abundance and diversity of macroinvertebrates are of particular importance due to their use as bio-indicators of stream health. Aquatic macroinvertebrates are important food source for fish, amphibians, birds, and other mammals and as a result, they play a critical role in the cycling of energy and nutrients through stream ecosystems (Vaughn, 2002). Aquatic macroinvertebrates are good indicators of stream health due to the fact that they are susceptible to physical and chemical disturbances such as changes in flow patterns, sediment movement, and water quality (Kahn & Colbo, 2007).

The response of benthic organisms to changes in a watershed can be used to evaluate the health of the stream environment (Khan & Colbo, 2008). Changes in sediment transport, nutrient loadings and other environmental factors will ultimately be reflected in the benthic populations. Because the changes in the environment will be reflected in the changes of the benthic habitat, environmental impact of a culvert can arguably be measured by studying how culverts affect the benthic habitat. Sampling is typically accomplished through a process known as kick seining. However, for this data to be useful in assessment, it must be collected over several different periods of the year, multiple times. As a tool for assessing the impacts of culverts, this approach would be extremely costly and not possible in the limited time allotted to the proposed study by ODOT.

The use of salamanders as bio-indicators of stream health, due to the important role they play in biological diversity, has increased. Ward et al. (2008) showed that several factors including stream gradient, sediment type, elevation, water quality, and canopy cover influence distribution and abundance of stream and streamside salamanders. However, sampling of salamanders is even more time consuming and costly than kick seining.

4.1(f) <u>Measuring Impact through Habitat Assessment Tools</u>: The Ohio EPA has a number of techniques used for habitat assessment. Two quantitative tools available are the Index of Biotic Integrity (IBI) and Invertebrate Community Index (ICI). The IBI is primarily used to evaluate the strength of the biological integrity in a study area (USEPA, 2010). The IBI is determined by measuring the populations and health of individual biota. Through this measurement, an overall picture of the strength and diversity of the community can be developed. The tool uses 12 metrics evaluating community composition, environmental tolerance, community function, and community condition (OEPA, 1987b).

The Invertebrate Community Index (ICI) is primarily used to evaluate invertebrate taxa in a study area. Similar to the IBI, organisms are counted and measured. The ICI uses 10 metrics evaluating for the same environmental conditions as the IBI (OEPA, 1987b). Both the ICI and the IBI require significant skill and experience. Reliable data are based on the ability to identify specific species as well as proper classification at the family level (Rankin, 2010). In addition to the technical skills required, the sampling period takes months to complete at each study site. A comprehensive collection must be completed in order to provide the data required for analysis.

Another tool used for habitat assessment is the Qualitative Habitat Evaluation Index (QHEI), which is a ***qualitative*** tool to assess a stream. In the QHEI, the primary focus of the evaluation is to determine the habitat quality for a fish community and to identify sources of impairment (Rankin, 2010). The limitation of QHEI is that is not as comprehensive as an IBI or ICI study. Data gathered can be very general and do not measure all aspects of the local habitat (Walton, 2010). However, the use of QHEI is beneficial if the ultimate goal of the study is to quickly and inexpensively determine a general condition of the local habitat.

The QHEI uses visual observation of the stream habitat to evaluate the quality of the fish habitat. As discussed before, features that promote a healthy fish community include a porous substrate, high sinuosity, areas of in-stream cover, a low stream gradient, wide riparian width, and good pool and riffle development (Rankin, 2010). The metrics of the QHEI are developed on these factors so there is a strong correlation between QHEI scores and IBI scores.

Metrics of the QHEI include substrate quality, in stream cover, pool and riffle development, channel morphology and sinuosity, quality of the riparian zone, and stream slope. Scores in these areas are tallied to identify the quality and functionality of the metric on the fish habitat in the stream. The total score of the QHEI range from 0 to 100, with 0 being the lowest and 100 being the highest. The QHEI is a very effective tool in determining the health of a stream; however, the tool is primarily used for evaluation for aspects important to a fish community. The effectiveness of using this tool is limited to higher order streams (Rankin, 2010).

For headwater streams (first order stream), the conditions that constitute a healthy stream differ from that of a larger order stream. For headwaters streams with drainage areas of less than one square mile (259 hectares), there is a tool available similar to the QHEI called the Headwater Habitat Evaluation Index (HHEI). The intended use of the HHEI is to determine the class of stream for streams that have a watershed of one square mile or less (Tuckerman, 2002). Similar to the QHEI, the HHEI uses visual observation and measurement of substrate quality and pool depth. However, the there are some slight differences between the two indices. The HHEI evaluates bankfull width and does not evaluate features important to fish habitat such as in-stream cover and quality of riffle or pool development (Tuckerman, 2002).

Defined by the Ohio EPA, the class of a primary headwater habitat (PHWH) is determined by the amount of annual flow throughout the year, and the amount of aquatic life present in the stream. Headwater streams can be classified as class I, class II, or class III. A class I stream is defined as a stream that has a dry annual flow and has low biotic diversity. A class II stream is defined as a stream that has intermittent flow and may have permanent pools. A class III stream has perennial flow and has fish or salamanders present at all times. By identifying the class of stream, a prediction can be made as to biological potential of the stream (Tuckerman, 2002).

4.1(g) Estimating Impact through Modeling: Fish have evolved to migrate in natural channels through the development of strategies that utilize natural channel features and their own abilities. Placing a culvert in a stream can create an impassible obstacle to fish passage. Designing culverts to simulate the natural channel has developed as a cost effective method, which provides for hydraulic function as well as allowing for the passage of migratory fish. The basic concept of the stream simulation design is that by reproducing the main characteristics of these structurally diverse and hydraulically rough channels inside the culvert, fish passage is implied, if not assured (Washington Department of Fish and Wildlife, 2003).

Traditionally, modeling fish passage has been based on research on the ability of fish to swim against certain velocities. Beyond data on Salmonids and a select few other economically important fish species, there is little to no data on the migration ability of other species, including fish that would be present in the streams of Ohio, such as minnows, darters or catfish. There is even less research on migration of other aquatic microorganisms such as macroinvertebrates or insect species which form the base of the ecosystem. Hence, the modeling exercise is of limited usefulness in estimating impact in Ohio streams and waterways.

4.2 Survey of Existing Culverts

ODOT provided 61 sites where embedded and/or bankfull culverts had been installed. The culverts were installed in various regions of Ohio with different geology, topography, and land use. Specifics on the 61 culverts are provided in Section 4.2 below. The 61 culverts listed by ODOT included 44 circular culverts, 12 box culverts, three (3) elliptical culverts and two (2) culverts that were actually arches without a constructed bottom. The culverts are located in Athens, Crawford, Meigs, Fairfield, Paulding, Ross, and Wayne counties.

For reference in this report, the culverts were grouped together by the contract under which they were installed. Each separate contract where culverts were installed was given a number from 1 to 17 and then the culvert is identified by letter starting at A. A key which maps the culvert identification used in this research to the contract under which they were installed and the ODOT plan sheet showing the culvert location and design is provided in Table 3.

Table 3
Key Mapping Culverts as Identified in Report to ODOT Plans and Contracts

Culvert ID in Report	Contract installed	Plan sheet
1A	PAU-24-0.00	441-445
1B	PAU-24-0.00	447-451
1C	PAU-24-0.00	492-496
1D	PAU-24-0.00	484-488
1E	PAU-24-0.00	478-483
1F	PAU-24-0.00	455-461
1G	PAU-24-0.00	467-473
2A	ATH-33-40.981	563
2B	ATH-33-40.981	566
2C	ATH-33-40.981	567
2D	ATH-33-40.981	568
2E	ATH-33-40.981	570
2F	ATH-33-40.981	571
2G	ATH-33-40.981	574
3A	ATH-33-30.981	852
3B	ATH-33-30.981	853
3C	ATH-33-30.981	854
3D	ATH-33-30.981	855
4A	ROS-35-26.17	197, 734-736
4B	ROS-35-26.17	213,774
4C	ROS-35-26.17	213,775
4D	ROS-35-26.17	508-509,740-742
5A	MEG-124-31.57	81,559
5B	MEG-124-31.57	85, 564
5C	MEG-124-31.57	86, 565
5D	MEG-124-31.57	91-92, 566
5E	MEG-124-31.57	103, 570
5F	MEG-124-31.57	104, 571
5G	MEG-124-31.57	106, 572
6A	MEG-124-26.66	33, 380

Culvert ID in Report	Contract installed	Plan sheet
6B	MEG-124-26.66	36, 385
6C	MEG-124-26.66	42, 391
6D	MEG-124-26.66	43, 392
6E	MEG-124-26.66	52, 404
7A	MEG-124-22.72	91, 648
7B	MEG-124-22.72	100, 751
8A	FAI-33-7.31	1339
8B	FAI-33-7.31	1402
8C	FAI-33-7.31	1360
9A	FAI-33-13.25	492
9B	FAI-33-13.25	504
9C	FAI-33-13.25	504
9D	FAI-33-13.25	510
10A	FAI-33-17.44	327
10B	FAI-33-17.44	339
11A	FAI-33-19.79	476
11B	FAI-33-19.79	484
12A	FAI-33-0.41	656
12B	FAI-33-0.41	664
12C	FAI-33-0.41	634
12D	FAI-33-0.41	636
12E	FAI-33-0.41	647
13A	WAY 30-11.86	131,481
13B	WAY 30-11.86	190, 482
13C	WAY 30-11.86	202, 487
14A	WAY 30-16.14	91, 382
14B	WAY 30-16.14	258, 395
15A	CRA/RIC 30-33.5/0.00	452, 100, 442
15B	CRA/RIC 30-33.5/0.00	452, 420, 451A
16A	CRA 30-24.0	446
17B	CRA 30-15.865	297

Figure 5: Locations of EBCs in Ohio

Figure 5 shows the location of the culverts by county along with the number of culverts in each county. ***Because the arched culverts (culverts 1F and 1G in Paulding County) did not have constructed bottoms, these two culverts were eliminated from further analysis and were not surveyed. Therefore, a total of 59 culverts were included in the survey.***

The data collected on the 59 culverts are summarized in tables for each county below, and a complete set of the survey data for all culverts can be found in Appendix A.

***4.2(a) <u>Athens County</u>*:** In southern Athens County and northern Meigs County there were 11 culverts designated by ODOT as EBC. The culverts in the region are culverts 2A through 2G, and 3A through 3D located on US Highway 33. The culverts designated in the "2 series" were constructed under contract ATH-33-40.981 and are located in the Hocking Watershed (HUC: 05030204) (USGS, 2009). The culverts in the "3 series" were constructed under contract ATH-33-30.981 and are located in the Upper-Ohio Shade Watershed (HUC: 05030202) (USGS, 2009). The area surrounding the culverts is mainly forested land, with high hills, and low population density. There are some small family farms in the area surrounding the culverts. The area of the county with the highest population density is the city of Athens with an estimated 2000 population of 21,342 (US Census Bureau, 2010)

The culvert surveys were performed in April 2010 and the QHEIs were performed in August 2010. Table 4 is a summary of the results from the field survey in Athens County. As can be seen from Table 4, the field survey found that the vast majority of the culverts were sized as indicated in the initial design; except that Culvert 2B was installed with a diameter of five feet as opposed to the designed six feet, and Culvert 3D was installed with a slope 5.64% as opposed to the design slope of 3.86%. The length and slope of culvert 2F were unable to be surveyed because of a large, steep drop-off from the highway embankment to the culvert.

It is also noted that none of these culverts have sediment accumulating in the culvert, and therefore, none of these culverts are embedded. Some unique installation methods were observed at the culvert sites in Athens. In culverts 2A, 2B, and 2D the culverts were installed with a concrete bottom. Hence, at these culverts sediments appear to be washing through the culvert and there is no deposition occurring in the culvert.

Table 4: Athens County Field Survey Results

Culvert	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m])	As-built Diameter [ft [m])	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m])	Notes	Pre-construction QHEI done?
2A	2	512 [156]	462.6 [141.0]	5.9 [1.8]	6 [1.8]	1.15%	1.12%	0 [0]	Culvert bottom lined with 2 in of concrete	Yes
2B	1	452 [138]	453.1 [138.1]	5.9 [1.8]	5 [1.5]	2.90%	2.95%	0 [0]	Culvert bottom lined with 5 in of concrete	No
2C	1	535 [163]	494.0 [150.6]	3.5 [1.1]	3.5 [1.1]	8.24%	7.79%	0 [0]		No
2D	1	853 [260]	823.0 [250.9]	5.5 [1.7]	5.5 [1.7]	2.09%	1.95%	0 [0]	Culvert bottom lined with 11 in of concrete	Yes
2E	1	540 [165]	534.5 [163.0]	4.5 [1.4]	4.5 [1.4]	3.56%	3.39%	0 [0]		No
2F	1	640 [195]	not measured (nm)	3.5 [1.1]	3.5 [1.1]	4.23%	nm	0 [0]		No
2G	1	410 [125]	408.5 [124.5]	2.5 [0.8]	2.5 [0.8]	6.69%	6.34%	0 [0]		No
3A	1	750 [229]	749.9 [228.6]	5.9 [1.8]	6 [1.8]	3.16%	3.55%	0 [0]	Concrete pad at outlet	No
3B	3	825 [252]	823.1 [251.0]	12.0 [3.7]	12 [3.7]	0.60%	0.66%	0 [0]	Concrete pad at outlet	Yes
3C	1	312 [95]	313.8 [95.7]	4.5 [1.4]	4.5 [1.4]	3.19%	3.33%	0 [0]	Concrete pad at outlet	Yes
3D	1	251 [77]	253.9 [77.4]	5.5 [1.7]	5.5 [1.7]	3.86%	5.64%	0 [0]	Concrete pad at outlet	Yes

Figure 6: Culvert 2A in Meigs County showing concrete lining on bottom of culvert

Figure 6 shows the installation of culvert 2A. In culverts 3A, 3B, 3C, and 3D there was a concrete pad placed at the outlet of the culvert, raised above the bottom of the culvert. In the culverts lined with concrete, there were no sediments present inside the culvert. Perching has occurred at many of the culverts in Athens County. Culverts 2A, 2B, 2C, 2D, 2E, 3A, 3C, and 3D are all perched. For culverts 3A, 3C, and 3D it appears perching has occurred due to the concrete pad that is placed at the outlet.

Finally, one other observation was made at the culvert 2E. As shown in Figure 7, water entering the culvert was clear; however the water exiting had a red-brown color. This was the only culvert surveyed in this entire study where there was a change in watercolor through the reach of the culvert. This may indicate that the culvert is corroding inside or that there are internal leaks and fine sediments are eroding from around the culvert. ***In either case, this culvert should be inspected to determine the source of the color change.***

Figure 7: Change in Watercolor in Culvert 2E

Water entering culvert 2E

Water exiting culvert 2E

4.2(b) ***Crawford County***: In Crawford County four culverts were surveyed. They are all located on US Highway 30 and are all located in the Sandusky Watershed (HUC: 04100011) (USGS, 2009). In addition, one traditional culvert was randomly selected for a control sample. The area is mainly flat, rural and the land is primarily used for agriculture. Culverts 15A, 15B (installed under contract CRA/RIC 30-33.5/0.00) and 16A (installed under contract CRA 30-24.0), are located near Crestline, OH. Culvert 17B (installed under contract CRA 30-15.865) is located near Bucyrus, OH.

Culverts 15B, 15A, and the randomly selected control culvert were surveyed in October 2009, and culverts 16A and 17B were surveyed in July 2010. The QHEI for culverts 16A and 17B were performed in July 2010. The results of the field surveys are presented in Table 5. Culverts 15B and 15A were installed in series (15B upstream to 15A downstream). Culvert 15B was installed on a service road and 15A was installed on the highway. Only culvert 17B was installed exactly as designed. Culverts 15A, 15B, and 16C were installed with different slopes. Culvert 15B and 17B had no embedment present at the time of sampling and at 15B the outlet was perched above the downstream. Aside from the perching of 15A, there were no other noted unique features about these culverts.

Table 5: Crawford County Field Survey Results

Site	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m])	As-built Diameter [ft [m])
15A	2	246 [75]	248.7 [75.8]	7.4 [2.3]	8 [2.4]
15B	2	118 [36]	121.0 [36.9]	7.4 [2.3]	8 [2.4]
16A	2	315 [96]	320.4 [97.7]	11.8 [3.6]	12 [3.7]
17B	4	463 [141]	461.1 [140.6]	6.4 [2.0]	6 [1.8]

Site	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m])	Notes	Pre-construction QHEI done?
15A	0.34%	0.15%	1 [0.3]	Outlet perched	No
15B	0.35%	0.43%	0 [0.0]		No
16A	0.34%	1.71%	3 [0.9]		Yes
17B	0.62%	0.62%	0 [0.0]		Yes

***4.2(c) Fairfield County*:** In Fairfield County 16 culverts were surveyed. Culverts 8A, 8B, and 8C (installed under contract FAI-33-7.31), 9A, 9B, 9C, and 9D (installed under contract FAI-33-13.25), 10A and 10B (installed under contract FAI-33-17.44), and 11A and 11B (installed under contract FAI-33-19.79), are all located on US Highway 33 near Lancaster in the Hocking Watershed (HUC: 05030204) (USGS, 2009). Culverts 12A through 12E (installed under contract FAI-33-0.41) are located in the Upper Scioto Watershed (HUC: 05060001) (USGS, 2009), near Canal-Winchester near the entrance and exit ramps from US 33 to Diley Rd. Culverts 12A and 12B are located on Eichorn Rd which is just north of the ramps. Culverts 12D and 12C are located on Diley Rd just south of the ramps. Culvert 12E passes underneath the westbound entrance ramp to US 33. The culverts are located very close to the boundary of the Berea Escarpment.

In the year 2000, the population of Canal-Winchester was 4,478. The area around the site 12 culverts appears to be urbanizing. When field trips were made, it appeared many new homes and suburban communities had recently been built. The sites 8, 9, 10, and 11 culverts are located in central and southeast Fairfield County. US 33 in this area forms an outer-belt around the city of Lancaster. The population of Lancaster in 2000 was 35,335 (US Census Bureau, 2010). The land use around culverts 8A, 8B, 9A, 9B, 9C, 9D, and 10A is mainly agricultural and the area has low population density. There are some rolling hills in the area. Around sites 10B, 11A, and 11B there are more steep hills and valleys. There are some small family farms near these culverts, and the population density is low.

The culverts in Fairfield County were surveyed in May 2010. Table 6 shows the results of the field study. Follow-up QHEIs were performed in July 2010. Culverts 8A, 9A, 11A, 11B, 12A, and 12B, are all box culverts. Of these box culverts, 8A and 12B were installed as designed. Culvert 12A was surveyed 17 feet longer than designed. Culverts 9A, 11A, and 11B all had installed slopes differing from the design slope. Culverts 8B, 8C, 9B, 9C, 9D, 10A, 10B, 12C, 12D, and 12E are all circular culverts. Culvert 12C was installed 27 feet shorter than designed. Culverts 9B, 10A, 11A, 12C, and 12D all have different slopes than designed. Culverts 8B, 8C, 9C, 12B, and 12E were installed as designed.

Culverts 9C and 9B are in series with 9C being immediately upstream of culvert 9B. At 11B, it appears the stream has begun scouring the inlet due to a change in orientation from the stream to the culvert. The site 12 culverts are in series starting at 12A, then in order to 12B, 12E, 12D and finally 12C. Culvert 12D also has another culvert immediately upstream that was not included in the survey. Because the upstream reach of is so close to the upstream culvert, there was not sufficient distance for the stream to re-establish itself. Therefore, no samples were taken upstream of 12D and no follow-up QHEI was performed for culvert 12D. Follow-up QHEIs were performed at culverts 8B, 8C, 9B & C, 9D, 10A, 10B, 11A, 11B, and 12C.

Table 6: Fairfield County Field Survey Results

Culvert	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m])	As-built Diameter [ft [m])	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m])	Pre-construction QHEI done?
8A	4	236 [72]	237.3 [72.3]	Box 8' H x 18' W [2.4m x 5.5m]	Box 8' x 18' [2.4m x 5.5m]	0.12%	0.16%	0 [0.0]	No
8B	3	143 [44]	143.3 [43.7]	14 [4.3]	14 [4.3]	0.87%	0.79%	1 [0.3]	Yes
8C	2	203 [62]	205.8 [62.7]	7 [2.1]	7 [2.1]	0.87%	0.82%	2 [0.6]	No
9A	4	192 [59]	190.8 [58.2]	Box 10' H x 20' W [3.0m x 6.1m]	Box 10' x 20' [3.0m x 6.1m]	0.28%	0.44%	varies	Yes
9B	3	312 [95]	312.1 [95.2]	7 [2.1]	7 [2.1]	0.70%	1.23%	1.75 [0.5]	No
9C	3	90 [27]	89.5 [27.3]	6 [1.8]	6 [1.8]	0.70%	0.64%	1.17 [0.4]	No
9D	2	224 [68]	225.4 [68.7]	9 [2.7]	9 [2.7]	0.19%	0.17%	0.58 [0.2]	Yes
10A	1	280 [85]	280.6 [85.5]	5 [1.5]	5 [1.5]	2.51%	4.77%	0.5 [0.2]	No
10B	3	259 [79]	261.3 [79.7]	10.5 [3.2]	10.5 [3.2]	0.40%	0.37%	0.58 [0.2]	Yes
11A	4	54 [16]	52.2 [15.9]	Box 8' H x 21' W [2.4m x 6.4m]	Box 8' x 21' [2.4m x 6.4m]	0.48%	0.10%	5.167 [1.6]	No
11B	4	264 [80]	261.8 [79.8]	Box 9' H x 18' W [2.7m x 5.5m]	Box 9' x 18' [2.7m x 5.5m]	0.36%	0.49%	0 [0.0]	No
12A	2	58 [18]	75.5 [23.0]	Box 8' H x 8' W [2.4m x 2.4m]	Box 8' x 8' [2.4m x 2.4m]	0.12%	0.09%	1.75 [0.5]	No
12B	2	55 [17]	55.6 [17.0]	Box 8' H x 8' W [2.4m x 2.4m]	Box 8' x 8' [2.4m x 2.4m]	1.38%	1.42%	2.17 [0.7]	No
12C	3	210 [64]	173.2 [52.8]	20 [6.1]	20 [6.1]	0.07%	0.04%	1.25 [0.4]	Yes
12D	4	276 [84]	276.2 [84.2]	8 [2.4]	8 [2.4]	0.37%	0.59%	1.75 [0.5]	Yes
12E	4	125 [38]	109.7 [33.5]	10.5 [3.2]	10.5 [3.2]	0.16%	0.14%	3.17 [1.0]	No

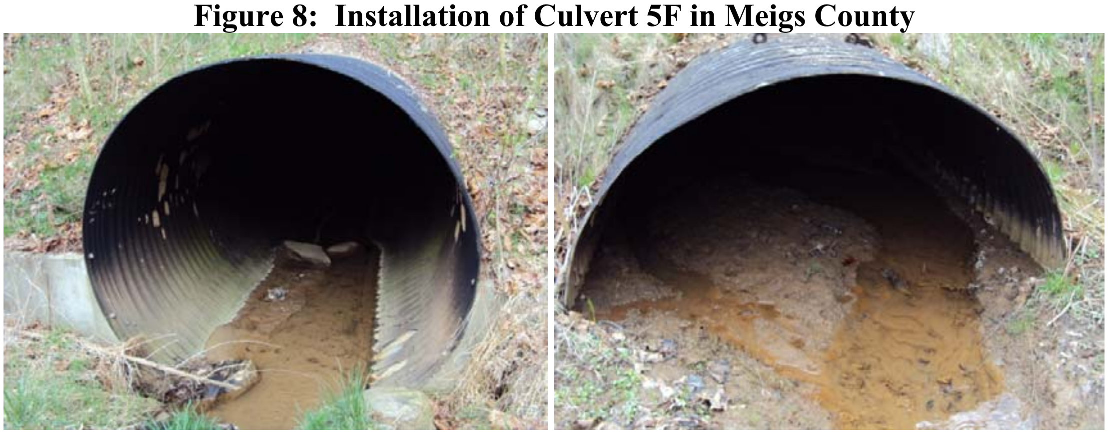
Nm = not measured   Unknown = Design parameter not known

4.2(d) ***<u>Meigs County</u>*:** There were 14 culverts were surveyed in Meigs County. Culverts in Meigs County are 5A through 5G were installed under contract MEG-124-31.57; 6A through 6E were installed under contract MEG-124-26.66; and culverts 7A, and 7B were installed under contract MEG-124-22.72. All of the culverts are located in southeastern Meigs County on US Highway 33 except culverts 6C and 6E. Culvert 6C is located at the intersection of the on-ramp to US 33 and Racine-Bashan Rd. Culvert 6E is located on Township Road 29 Connector in Sutton Township. These culverts are located in Upper Ohio-Shade Watershed (HUC: 05030202) (USGS, 2009). The area around the culverts is sparsely populated with a number of townships in the area. These townships include, Sutton, Chester, and Lebanon. The region is dominated with many hills and valleys with a sandy soil observed during field analysis.

The culverts in Meigs County were surveyed in April 2010 and in July and August of 2010, follow-up QHEIs were performed on those culverts with pre-construction QHEIs. Table 7 shows the results of the field survey. A traditional culvert was also randomly selected in this county to serve as a control. Because of an equipment malfunction the information for culvert 5F is incomplete. The survey found some differences between the as-built dimensions and the installed dimensions. It was found the lengths for culverts 5C, 5D were installed shorter than designed, and the length of 7A was installed longer than designed. Culverts 5D and 5G were installed with a diameter of 10" instead of the designed 12". Culverts 5D, 5G, 6B, and 6D all have slopes different than the design.

The culverts in Meigs County showed much variation in terms of how they are operating in the field. At culvert 5A some scouring is occurring at the inlet. Fine particles are being washed out and only the rocks are remaining. Culverts 5C and 5B have no embedment at the inlet but the outlet is significantly embedded. At 5D, there were low amounts of sediment particles in the stream. The streambed is comprised mostly of rock. Because of this, there was no embedment of the culvert as the rocks are not naturally moved into the culvert by normal stream flow. No sample was taken downstream of culvert 5D because there is another culvert immediately downstream and the stream does not re-establish itself after the culvert. Culvert 5E is not embedded at the inlet of the culvert, but is embedded at the outlet of the culvert. Culvert 5F has some embedment at the inlet, but is embedded 50% at the outlet. At the outlet, culvert 5F was embedded deep enough so the stream could pass through the culvert and also formed a channel through the embedment where the water made little contact with the culvert itself. Figure 8 shows the inlet and outlet of culvert 5F.

Figure 8: Installation of Culvert 5F in Meigs County



Culvert 5F Inlet | Culvert 5F Outlet

Table 7: Meigs County Field Survey Results

Culvert	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m])	As-built Diameter [ft [m])	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m])	Pre-construction QHEI done?
5A	2	535 [163]	535.3 [163.2]	6 [1.8]	6 [1.8]	2.56%	2.52%	1 [0.3]	Yes
5B	1	378 [115]	378.2 [115.3]	5 [1.5]	5 [1.5]	4.64%	4.53%	1.83 [0.6]	Yes
5C	1	310 [95]	297.8 [90.8]	4 [1.2]	4 [1.2]	5.38%	5.22%	2.75 [0.8]	Yes
5D	2	500 [152]	478.2 [145.8]	10 [3.0]	12 [3.7]	2.19%	1.95%	0 [0.0]	No
5E	2	615 [188]	615.9 [187.8]	12 [3.7]	12 [3.7]	0.69%	0.68%	2.42 [0.7]	Yes
5F	1	650 [198]	Not measured [nm]	8 [2.4]	8 [2.4]	1.18%	nm	4 [1.2]	No
5G	2	523 [159]	524.2 [159.8]	10 [3.0]	12 [3.7]	0.25%	0.18%	0.4167 [0.1]	Yes
6A	1	295 [90]	296.1 [90.3]	4 [1.2]	4 [1.2]	2.20%	2.42%	0 [0.0]	Yes
6B	1	264 [80]	265.6 [81.0]	3.5 [1.1]	3.5 [1.1]	5.00%	4.07%	0.92 [0.3]	No
6C	2	85 [26]	85.6 [26.1]	Ellipse 5.67' H x 8.17' W [1.73m x 2.49m]	Ellipse 5.67' x 8.17' [1.73m x 2.49m]	0.80%	0.75%	2.83 [0.9]	Yes
6D	1	389 [119]	388.0 [118.3]	6 [1.8]	6 [1.8]	8.50%	7.46%	0 [0.0]	Yes
6E	2	108 [33]	108.2 [33.0]	Ellipse 4.83' H x 7.58' W [1.47m x 2.31m]	Ellipse 4.83' x 7.58' [1.47m x 2.31m]	0.60%	0.54%	0.67 [0.2]	Yes
7A	1	413 [126]	428.8 [130.7]	5 [1.5]	5 [1.5]	3.07%	2.86%	0 [0.0]	Yes
7B	4	477 [145]	473.4 [144.3]	21 [6.4]	21 [6.4]	0.27%	0.39%	2.5 [0.8]	Yes

Figure 9: Culvert 7A in Meigs County

As shown in Figure 9, culvert 7A is not embedded and the outlet is perched ***four feet*** above the water level downstream. Culvert 7B is located on Nease Creek. The depth of flow in the culvert was so great at the time of collection, that water and sediment samples could not be collected from the interior of the culvert.

Culvert 6A had no embedment of the culvert and the culvert is perched above downstream of the culvert. In addition, the culvert is not aligned with the stream at the outlet of the culvert. There were heavy amounts of erosion present at the outlet of the culvert. It appears the source of this erosion is due to the misalignment of the culvert with the stream resulting in water exiting the culvert eroding the land before traveling further downstream.

At culvert 6B, the inlet is not embedded but the outlet is embedded 26% of the culvert diameter.

Culvert 6C is an elliptical culvert. The culvert is embedded throughout the reach of the culvert, but the inlet shows heavy sedimentation from what appears to be the erosion of the highway embankment. Culvert 6D had no embedment and downstream of the culvert, the streambed is flat rock with no sediments present. Culvert 6E is an elliptical culvert with some scouring occurring at the inlet.

4.2(f) ***Paulding County*****:** There were five culverts surveyed in Paulding County (1A through 1F installed under contract PAU-24-0.00). As noted above, there were two arches installed under this contract (1F and 1G) that behave like bridges so they were not surveyed. The culverts are all located on US Highway 24 in southwestern Paulding County near Antwerp, three miles east of the Indiana border, and are in the Upper Maumee Watershed (HUC: 04100005) (USGS, 2009). The area is mainly used for agriculture and has a low population density. The population of Antwerp, OH in 2000 was 1,740 (US Census Bureau, 2010). The area is very flat and near the culverts there were very few trees and shrubs. The area adjacent to all of the culverts is mainly row crops with no riparian zone.

The survey of the Paulding culverts was done in November 2009, with the follow-up QHEIs performed in July 2010. The results of the field study are presented in Table 8.

Table 8: Paulding County Field Survey Results

Culvert	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m])	As-built Diameter [ft [m])
1A	3	512 [156]	510.7 [155.7]	Box 9' H x 14' W [2.7m x 4.3m]	Box 9' x 14' [2.7m x 4.3m]
1B	3	256 [78]	253.9 [77.4]	Box 9' H x 14' W [2.7m x 4.3m]	Box 9' x 14' [2.7m x 4.3m]
1C	3	78 [24]	76.3 [23.3]	Box 12' H x 20' W [3.7m x 6.1m]	Box 12' x 20' [3.7m x 6.1m]
1D	3	156 [48]	154.2 [47.0]	Box 9' H x 14' W [2.7m x 4.3m]	Box 9' x 14' [2.7m x 4.3m]
1E	3	96 [29]	93.1 [28.4]	Box 9'H x 16' W [2.7m x 4.9m]	Box 9'H x 16' [2.7m x 4.9m]

Culvert	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m])	Pre-construction QHEI done?
1A	0.05%	0.03%	0.55 [0.2]	No
1B	0.06%	0.19%	0.6 [0.2]	No
1C	0.38%	0.37%	1 [0.3]	No
1D	0.06%	0.16%	0.7 [0.2]	Yes
1E	0.31%	0.45%	0.25 [0.1]	No

The culverts are in series along North Creek, flowing from 1E to 1A, 1D, 1B and further downstream 1C. Culverts 1E, 1A, 1D, and 1B are physically located close enough such that the downstream sample for one is the same as the upstream sample for the next culvert downstream. Culverts 1A, and 1C were installed as designed. Culverts 1B, 1D, and 1E were installed with slopes slightly greater than the design slopes. Each of the culverts is embedded and the only notable observation is that the stream is very turbid. The source of this turbidity is unclear but on both trips to the culverts, the stream was very turbid through the entire stream .

4.2(g) ***Ross County*****:** There were four culverts surveyed in Ross County (4A through 4D installed under contract ROS-35-26.17). The culverts are located in southeastern Ross County on US Highway 35 south of Chillicothe and are located in the Lower Scioto Watershed (HUC: 05060002) (USGS, 2009). The area around culverts 4A, 4B, and 4C has many steep hills and valleys. Speaking with local residents, the land is primarily used for logging. At the time of collection, new pine trees had begun growing and were approximately 20 to 30 feet in height. It was observed that approximately two miles upstream of culverts 4B and 4C entire hillsides had been cleared, and no trees were present. Culvert 4D is located on relatively flat terrain where a small family farm was adjacent downstream of the culvert.

Culverts 4A, 4B, 4C, and 4D were surveyed in March 2010 with the follow-up QHEIs performed in July 2010. The results of the field study are presented in Table 9. Culvert 4D is a box culvert and the other culverts are circular culverts. Culvert 4A was installed with a shorter length and a greater slope than designed. The other culverts were installed as designed. Culvert 4A is perched above the downstream water level. Culverts 4B and 4C had concrete pads installed at both the inlet and outlet of the culvert, which was observed to accelerate the water velocity upon entry into the culvert, thereby increasing scour in the culvert. Neither of these culverts had sediments deposited in the culvert. Immediately upstream of culvert 4D there is a double barrel culvert installation. Because there is not sufficient distance between the double-barrel culvert and culvert 4D to perform a QHEI, there was no follow-up QHEI performed upstream of culvert 4D.

Table 9: Ross County Field Survey Results

Culvert	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m])	As-built Diameter [ft [m])
4A	4	390 [119]	219.2 [66.8]	12 [3.7]	12 [3.7]
4B	1	368 [112]	372.1 [113.4]	5 [1.5]	5 [1.5]
4C	1	295 [90]	289.7 [88.3]	5 [1.5]	5 [1.5]
4D	2	84 [26]	84.0 [25.6]	Box 8' H x 14' W [2.4m x 4.3m]	Box 8' x 14' [2.4m x 4.3m]

Culvert	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m])	Notes	Pre-construction QHEI done?
4A	0.77%	1.46%	0 [0.0]	Outlet is perched	Yes
4B	1.63%	1.62%	0 [0.0]	Concrete pad at inlet and outlet	Yes
4C	2.04%	1.94%	0 [0.0]	Concrete pad at inlet and outlet	Yes
4D	0.60%	0.71%	1.833 [0.6]	1.833	Yes

4.2(h) *Wayne County*: There were five culverts surveyed in Wayne County. Culverts 13A, 13B, and 13C, were installed under contract WAY 30-11.86 and culverts 14A, and 14B were installed under contract WAY 30-16.14. All five culverts are located on US Highway 30 east of the State Route 83 interchange in the Walhonding Watershed (HUC: 5040003) (USGS, 2009). The culverts are located south of Wooster, Ohio. In 2000, the population of Wooster was 24, 811 (US Census Bureau, 2010). The area around the culverts had a combination of flat terrain mixed with hills and valleys.

The culverts in Wayne County were surveyed in October 2009. Because there were no pre-construction QHEIs performed at these sites, no follow-up QHEIs were performed at these culverts for this study. The results of the field study are presented in Table 10. Culverts 14A and 14B are located in series flowing from A to B. There is wetland area between the two culverts. Because of the close proximity of the culverts the downstream sample of 14A is the same as the upstream sample for 14B. Culvert 13C was surveyed but the culvert bends under the embankment so it is impossible to determine the length or slope of the culvert from the survey performed. Culvert 14A is located on a stream that appears to serve as field drainage for the local crops. Because of this, samples were collected but no survey was performed. Culverts 13A, 13B, and 14B were installed as designed. In addition, a traditional culvert was randomly selected in this area and sampled to serve as a control. The control culvert is circular with a diameter of 6 feet, is located approximately 1000 feet east of 14A downstream, has no embedment and the outlet is perched.

Table 10: Wayne County Field Survey Results

Culvert	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m]]	As-built Diameter [ft [m]]
13A	1	163 [50]	162.9 [49.6]	4 [1.2]	4 [1.2]
13B	1	286 [87]	284.0 [86.6]	4 [1.2]	4 [1.2]
13C	4	560 [171]	Not measured [nm]	9 [2.7]	9 [2.7]
14A	2	282 [86]	[nm]	7 [2.1]	nm
14B	2	144 [44]	144.6 [44.1]	Ellipse 5.67' H x 8.83' W [1.73m x 2.69m]	Ellipse 5.67' x 8.83' [1.73m x 2.69m]

Culvert	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m]]	Pre-construction QHEI done?
13A	0.30%	0.30%	0 [0.0]	No
13B	3.00%	2.94%	0.541 [0.2]	No
13C	2.50%	nm	2.67 [0.8]	No
14A	1.14%	nm	0 [0.0]	No
14B	0.34%	0.31%	3.33 [1.0]	No

At site 13A, the diameter of the culvert was too small to collect a sediment sample from inside of the culvert. At 13B and 13C, scouring has occurred at the inlet so there was no embedment at the entrance but deposition is occurring inside and at the outlet of the culvert. At 13C, the outlet is significantly embedded (over 30% of the diameter). At 14A, there was little sediment present at the inlet, inside, or at the outlet of the culvert. Culvert 14B is an elliptical culvert. The inlet showed signs of scouring but the interior and the outlet of the culvert was significantly embedded.

4.3 Laboratory Results

Laboratory analyses were performed on sediment and water samples collected in the field. After samples were collected in the field, they were placed on ice and transported to the laboratory at Cleveland State University. The samples were stored in a refrigerator until testing. Tests were performed as soon as after collection trips. Water samples were analyzed to determine the Total Suspended Solids (TSS) and Turbidity of each sample. Some examples of the data are presented in this section. Due to the large amount of data collected, the full set of data is provided on CD attached to this document.

4.3(a): <u>Total Organic Carbon</u>: Fine-particulates can also be indirectly determined by measuring the total organic carbon (TOC) of the bed sediments. In 1999, Sutherland tested streambed sediments for the TOC present in different particle sizes. The study showed that the highest percentage of TOC was present in the fine particles (Sutherland, 1999). Therefore, the percentage of TOC in the sediment sample correlates to the percentage of fine particles present in the bed load.

For determining TOC in sediments, Shumacher proposes a number of techniques for the evaluation of TOC in sediment. These techniques range from semi-quantitative methods using burn on ignition measuring the change in weight of a sample to quantitative using oxidation and measuring the CO_2 released (Schumacher, 2002).

The burn-on-ignition method outlined in Chapter 3 was used to determine the TOC of the sediment. A representative 20-gram sample of sediment was placed into a crucible and baked in a furnace at 420° C for 16-18 hours. In some instances, less than 20-grams were placed into a crucible due to the low amount of available sediment collected in the stream. There were three trials performed for each test. A summary of the results for the TOC is provided in Appendix B.

4.3(b): <u>Particle Size Distribution Analyses</u>: The remainder of the collected sample was used for sieve analysis. After cohesive particles were broken apart, the sample was separated using the No. 10 sieve. The particles that remained on the sieve were washed to clean the rocks and gravel from the smaller cohesive particles than remained on the rocks. Sieve sizes used for analysis were No. 4 (4.750 mm), No. 10 (2.000 mm), No. 16 (1.180 mm), No. 35 (0.050 mm), No. 60 (0.025 mm), No. 140 (0.106 mm), and No. 200 (0.075 mm). The sieves were shaken for three minutes each trial, and three trials were run for each sample. The results were used to produce a particle-size distribution for each sample. Particle size distribution graphs for the sediments tested are provided in Appendix C.

One of the primary objectives of this study was to determine how if an embedded bankfull culvert was impacting the environment and how that impact is related to such design parameters as length, diameter, slope or stream size (order). In order to accomplish this task, ***impact*** of the culvert must be defined and measured. As discussed above in the sections on the results of the literature review (Sections 4.1(a) through 4.1(d) ***sediment transport measurements are an important tool in evaluating the impacts, both hydrologic and environmental, of embedded bankfull culverts installed in Ohio.*** By using data collected from the sieve analysis, particle size distributions were created for each culvert. The particle size distributions of sediments at the inlet, inside the culvert, at the outlet, and downstream of the culvert were compared to the distribution upstream of the culvert in order to identify how sedimentation patterns are changing through the culvert. These were used to determine whether the culvert was impacting sediment transport, and thereby, the environment of the stream downstream of the culvert. This analysis is discussed in detail in Section 4.5(a) below.

4.3(c): Turbidity and Total Suspended Solids: Turbidity was collected using a LaMotte portable turbidimeter model 2020. Ten (10) ml (0.34 oz) of water were placed into a test tube and then in the meter. Five trials were run for each water sample. To prepare for Total Suspended Solids (TSS) testing, 11 µm filter papers were dried in an oven at 110 °C (230 ^{o}F) for two hours and then allowed to cool in a dessicator for one hour. After cooling, a filter was weighted and then placed in a vacuum-flask set-up. Depending on the amount of water collected in the field, either 20 ml (0.68 oz), 15 ml (0.51 oz), 10 ml (0.34 oz), or 5 ml (0.17 oz) were poured through the filter. The filter was then dried again at 110 °C (230 ^{o}F) overnight. After cooling in the dessicator, the filter re-weighed. Three trials were performed for each water sample. A summary of the results for the turbidity and TSS is provided in Appendix D.

4.4 Derived Data

4.4(a) *Sheer Stress in the Culvert:* As described above (Section 1.1), shear stress is a major factor in the transport of sediment particles. Sedimentation is a function of shear stress, gravity, and buoyancy on a particle (Ponce, 1989). Because of this, the energy of the flow will dictate the amount of sedimentation and deposition. When the shear stress of the water becomes larger than the critical shear stress of a particle, the particle will move downstream. In comparing the culverts, it is necessary to determine what effect the peak flows have on sedimentation patterns. To determine the shear stress within a culvert, methods are available to determine shear stress from the flow rate.

In addition, the concept of shear stress includes two important design parameters of the culvert; ***slope*** and ***diameter***. The energy of the flow through a culvert is dependent on the volumetric flow rate, as well as the cross-sectional area of the culvert itself. The dimensions relating to the shear stress of the flow include the width (diameter) of the culvert, and slope. As shown in Equation 1 developed by the Forest Service Stream Simulation Working Group (2008), sheer stress can be calculated by using the hydraulic radius, slope of the culvert and the unit weight of water.

$$\tau = R*S*\gamma \quad \tau = R*S*\gamma \qquad \text{Equation 1}$$

where:

τ = sheer stress (lb/ft^2 or N/m^2)
R = hydraulic radius (ft or m)
S = Slope (ft/ft or m/m)
γ = unit weight of water (lb/ft^3 or N/m^3)

Typically, hydraulic radii are determined by selecting a flow, then iteratively solving Manning's Equation to find a depth of flow that results in a hydraulic radius that produces the selected flow. Because of the number of culverts in the study, it was decided use a method developed by Mangin (2010), in which Manning's equation was manipulated so the depth of flow in a culvert can be calculated for a given flow (see Equations 2 and 3) below.

$$Q^* = \frac{Q}{\sqrt{gD^5}} \qquad \text{Equation 2}$$

$$d = 0.32*D*\left(\left(\frac{Q}{\sqrt{S_o}}\right)\left(\frac{K_s}{D}\right)^{1/6} + 0.64\right) \qquad \text{Equation 3}$$

where:

Q^* = non-dimensional flow rate
Q = flow rate (ft^3/s or m^3/s)
g = gravitational constant (32.2 ft/s or 9.81 m/s)
D = diameter of the culvert (ft or m)
d = depth of flow in culvert (ft or m)
S_o = slope of channel (ft/ft or m/m)
K_s = absolute roughness (ft or m)

Using Equations 2 and 3, one can calculate a depth (d) that results from any given flow through the culvert. If the depth of flow (d) equals the diameter (D) of the culvert (culvert flowing full), the area (A) and wetted perimeter (P) are easily calculated based on circular geometry, and the hydraulic radius (R) is:

$$R = \frac{D}{4} \qquad \text{Equation 4}$$

If the depth in the culvert means the culvert is only partially full, the hydraulic radius is calculated using methods produced by Bengtson (2010) as shown in equations 5 through 9 below.

$$h = 2r - d \qquad \text{Equation 5}$$

$$\Theta = 2 \arccos\left(\frac{r-h}{2}\right) \qquad \text{Equation 6}$$

$$A = \pi r^2 - \left(\frac{r^2(\Theta - \sin\Theta)}{2}\right) \qquad \text{Equation 7}$$

$$P = r*\Theta \qquad \text{Equation 8}$$

$$R = \frac{A}{P} \qquad \text{Equation 9}$$

where:

h= circular segment height (ft or m)
r = radius of culvert (ft or m)
θ = central angle (radians)
A = cross sectional area of water (ft^2 or m^2)
P = wetted perimeter (ft or m)

Knowing the hydraulic radius, one can then calculate the sheer stress using Equation 1 above.

As can be seen from the derivation, the hydraulic radius, and therefore the sheer stress, is a function of the depth of flow in the culvert. To ensure valid comparisons between culverts, one must have comparable flows for each culvert. ***For this study, we chose to calculate the sheer stress in the culverts produced by the 2-year, 5-year, and 10-year peak flows as determined by the USGS Stream Stats Ohio.*** These flows were selected as they represent flows that are regularly encountered by the culverts and therefore include similar flow conditions over time that would produce the time-integrated sedimentation results represented by the sediment samples taken. This allowed us to examine the correlation between sheer stress and the observable effects on sedimentation patterns. A flow rate could not be determined for culverts 2G because the stream is so small and USGS has no data for such streams. Appendix E contains a table of the 2-year, 5-year and 10-year flows and the resulting shear stresses from these flows for each of the culverts surveyed.

4.4(b) ***<u>Culvert Classification by Operation</u>:*** Another important factor for analysis is to determine whether the culvert as installed is actually operating as an embedded bankfull culvert (EBC). Using the field survey and observation data, a determination was made as to the "operational mode" that each installation represented. A culvert was designated as operating as a "***non-embedded culvert***" when the culvert had ***no sediments in the culvert***. A culvert was designated as operating an "***embedded bankfull culvert***" when it had sediment in the bottom of the culvert for the ***entire length*** of the culvert. It was also observed that some culverts had sediments along some portions of the culvert, but in other portions, sediments had been scoured away, and in at least one instance (culvert 15A), even though there were sediments in some portion of the culvert, the downstream end (outlet) of the culvert was perched, and therefore the culvert cannot be classified as embedded. Culverts that had this ***mixed deposition/embedment profile or that had sediment deposition but had a perched outlet*** were defined as operating a "***hybrid culvert.***" Table 11 shows the classification of the 59 culverts surveyed during this study.

It should be noted that an embedded bankfull culvert design, as specified by ODOT, requires that the culvert be embedded by 10% of its diameter. For this study, even if the percentage of embedment was less than the specified 10% (as measured by the maximum depth of sediment in the culvert), the culvert was still classified as functioning as an embedded bankfull culvert as long as there were sediments along the entire length of the culvert. The percentage depth of embedment for those culverts classified as operating as embedded culverts is presented in Table 12.

Table 11: Field Classification of Operation of Culverts Surveyed

Type of Culvert	Operating as Embedded	Operating as Hybrid	Operating as Non-Embedded	Totals
Circular	12	10	22	**44**
Box	9	1	2	**12**
Elliptical	3	0	0	**3**
				59

Table 12: Percentage Embedment of Culverts Classified as Operating as Embedded Bankfull Culverts in the Field

Culvert	Maximum % Embedment	Culvert	Maximum % Embedment
5F	50.0%	9C	19.5%
5G	3.5%	9D	6.4%
6B	26.3%	12C	6.3%
7B	11.9%	12D	21.9%
8B	7.1%	12E	30.2%
8C	28.6%	16A	25.0%

4.5 Analysis of Data

As can be seen from the data above, box and elliptical culverts appear to be much more frequently embedded throughout the entire length of the culvert. However, it must be noted that there are very few box culverts, and even fewer elliptical culverts, included in the sample. A statistical analysis of percent embedment versus culvert type (circular, box and elliptical) ***did NOT show a significant difference by type due to the small number of box and elliptical culverts***. Because there are such few box and elliptical culverts in the sample – the data on these two types of culverts are not sufficient for further analyses and these culverts are dropped from further discussion.

4.5(a) *Relationship of Embedment to Culvert Design Parameters*: With respect to circular culverts, less than 28% of the culverts are embedded the entire length. To determine whether there were specific design parameters that correlated with those 12 circular culverts that are embedded, the relationship between culvert and stream characteristics on the depth of embedment in the culvert was examined. The Shields diagram for the initiation of motion compares the shear stress and Reynolds number required to move a particle at a specific size (Ponce, 1989). The equation for the boundary Reynolds number for the Shields diagram accounts for shear velocity, mean particle diameter, and kinematic viscosity of water.

Using the factors from the Reynolds number as a base, a linear regression was performed to determine if an equation could be developed to predict the percentage of embedment in a culvert as a function of the upstream particle size, length of the culvert, and shear stress in the culvert. Diameter and slope of the culvert are included in the shear stress term in the analysis. The regression model developed was:

$$Y = \alpha X_1 + \beta X_2 + \gamma X_3 + C \qquad \text{Equation 10}$$

where:

Y= deepest percentage of culvert embedment
X_1 = length of culvert (ft or m)
X_2 = shear stress (lb/ft^{2}or Pa)
X_3 = D_{50} of the upstream sediment
α, β, γ and C = are constants determined by regression

Multiple regression analyses were performed using the 2 year, 5 year, or 10 year peak shear stresses. The best correlation was found using shear stresses for the 5-year peak flow. When all culverts were compared, there is little correlation between length, shear stress, and mean particle size on the embedment of a culvert. However when the 12 embedded circular culverts were analyzed, the R^2 is 0.297 and the equation for the regression is:

$$Y = 0.004*X_1 + 7.83*X_2 - 1.05*X_3 + 10.64$$

From this model, it can clearly be seen that the shear stress and upstream particle size do play a significant role in the ultimate level of sediment that is deposited in the culvert. This would be expected as the ability of sediment to be transported INTO the culvert and then be deposited is a function of the particle sizes present upstream of the culvert, and the shear stress developed by flow in the stream to move those particles. It is important to note however, that the correlation is not exceedingly strong, and additional research would be necessary to validate and confirm these results.

This analysis also leads to one possible recommendation regarding the installation of bankfull culverts. As currently specified in the ODOT manual, there is no sediment placed in the culvert, nor are there baffles or any other physical obstruction placed in the culvert to aid in sediment deposition. The above data may indicate such steps might be beneficial in helping circular culverts that are initially installed below the bottom level of the stream collect sediments and truly become embedded.

4.5(b) ***Culvert Impact as Measured by Sediment Transport***: One of the primary objectives of this study was to determine how embedded bankfull culverts may or may not be impacting the environment of the stream in which they are installed, especially as compared to traditional culverts. As discussed above in the sections on the results of the literature review (Sections 4.1(a) through 4.1(d) ***sediment transport measurements are an important tool in evaluating the impacts, both hydrologic and environmental, of embedded bankfull culverts installed in Ohio.*** By using data collected from the sieve analysis, particle size distributions were created for each culvert. The particle size distributions of sediments at the inlet, inside the culvert, at the outlet, and downstream of the culvert were compared to the distribution upstream of the culvert in order to identify how sedimentation patterns are changing through the culvert. These were used to determine whether the culvert was impacting sediment transport, and thereby, the environment of the stream downstream of the culvert.

An effective culvert that minimizes impact allows for conveyance of the storm flow (Tsihrintzis, 1995) and does not change sedimentation patterns throughout the reach of a stream (ConnDOT, 2002). Based on this, we measured the impact of an EBC through the ability to allow for storm passage while ***allowing for unaltered sedimentation patterns in the stream through the culvert***. Particle size distributions of a culvert that is having minimal impact on the stream show little change from the upstream to the points along the culvert. Conversely, ***a culvert that is impacting the stream disrupts sedimentation patterns***, either causing increased sediment loads to be transported downstream, or causing changes in particle deposition at the inlet and/or outlet of the culvert. The particle size distributions that show significant variation from the upstream distribution to the inlet, outlet and downstream reaches of the culvert are typical of culverts that are may be having significant impact on the stream ecosystem.

It is critical to understand that the changes in particle size distributions, while indicative of potential impact, do not prove an impact on the stream ecology, either negative or positive. ***Actual impact can only be measured through extensive biological studies that were well beyond the scope and budget of this project.*** However, the literature does support the conclusion that changes in sediment deposition patterns do have negative environmental impacts.

In order to do a full statistical analysis on culvert impact under this definition, a non-parametric statistical approach is needed such as the Kolmogorov-Smirnov goodness of fit test (Holcomb, 2010, Scheaffer & McClave, 1995). The test compares how close two distributions are. By comparing the two functions, the maximum difference between the two functions at a confidence level can be calculated. The maximum difference is compared to the actual distance, and a determination of fitness can be made (Scheaffer & McClave, 1995). By using this test, it would be possible to determine if the distributions of sediment particle sizes are statistically different between the upstream sample to the various downstream and culvert samples.

However, a full statistical analysis is beyond the scope of this project, and therefore a non-statistical approach was used. Particle size distributions were compared based on the change measured between the upstream sample and the samples from the rest of the culvert site for each of the seven sieve sizes used to develop the distribution. If the change in percent passing at a given sieve size was less than 20% between two distributions, the culvert is not affecting the transport of sediments that are retained on that sieve size. If the change was greater than 20%, the culvert is impacting transport for that sieve size.

For a culvert to be designated as having "***minimal impact***" all seven sieve sizes must have a change of less than or equal to 20%. A culvert is designated as having ***minor impact*** if one to three sieve sizes have a change greater than 20%. If four or more sieve sizes have a change greater than 20% the culvert is designated has having ***potentially significant impact***. Figure 10 shows the particle size distributions of a culvert designated as "***having minimal impact***"; Figure 11 the particle size distributions of a culvert designated as having "***minor impact***"; and Figure 12 shows the particle size distributions of a culvert designated as "***potentially having significant impact***" on the stream.

Figure 10: Particle Size Distributions from a Culvert Designated as Having Minimal Impact (Culvert 5F)

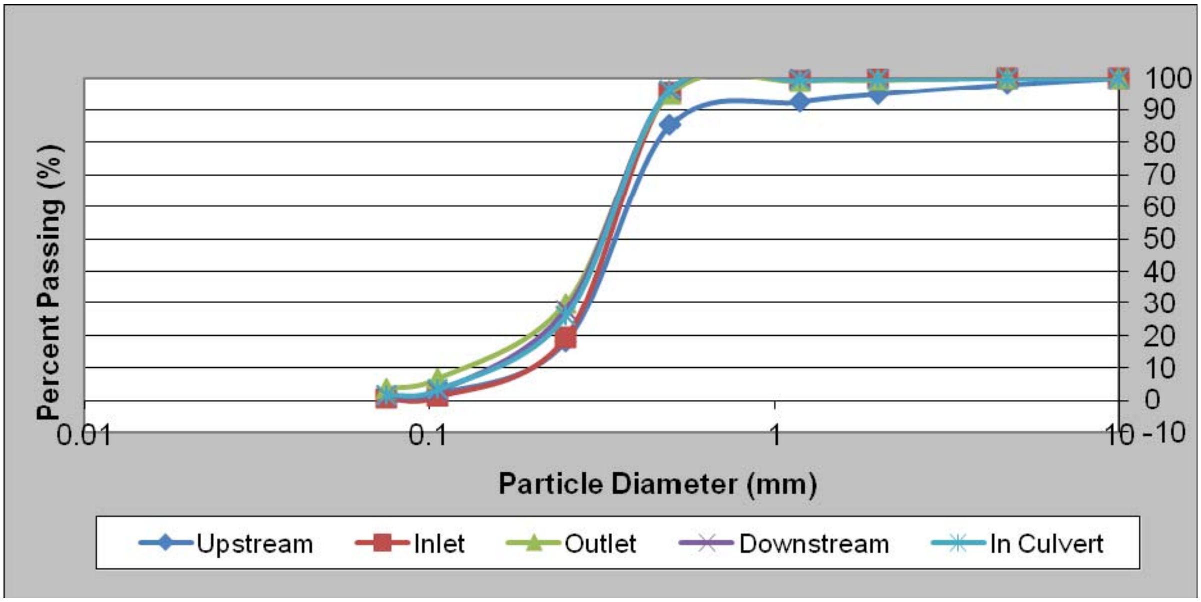


Figure 11: Particle Size Distributions from a Culvert Designated as Having Minor Impact (Culvert 2F)

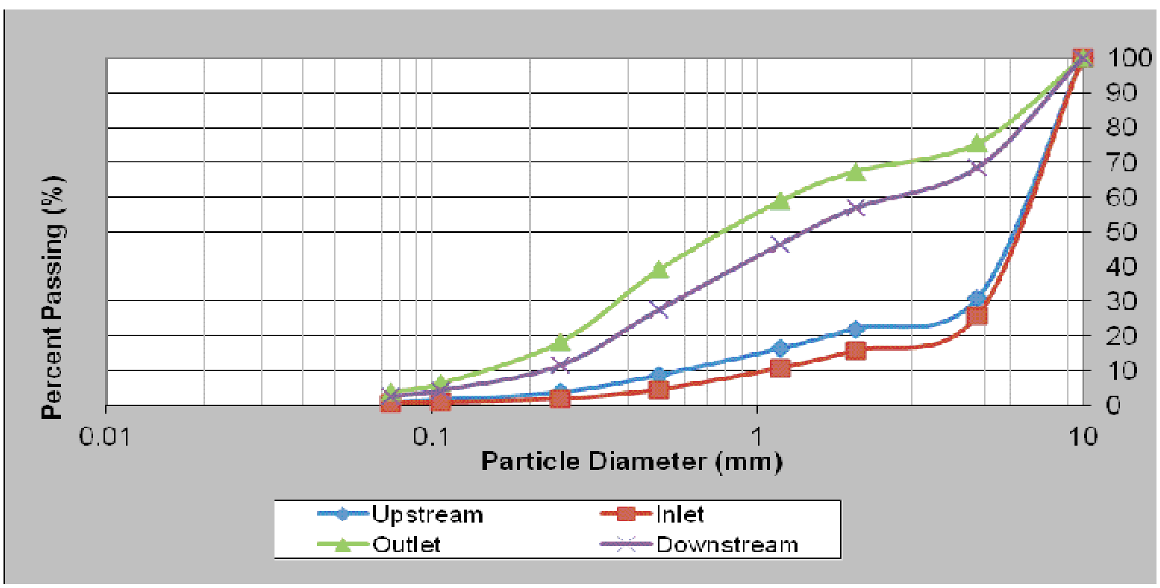
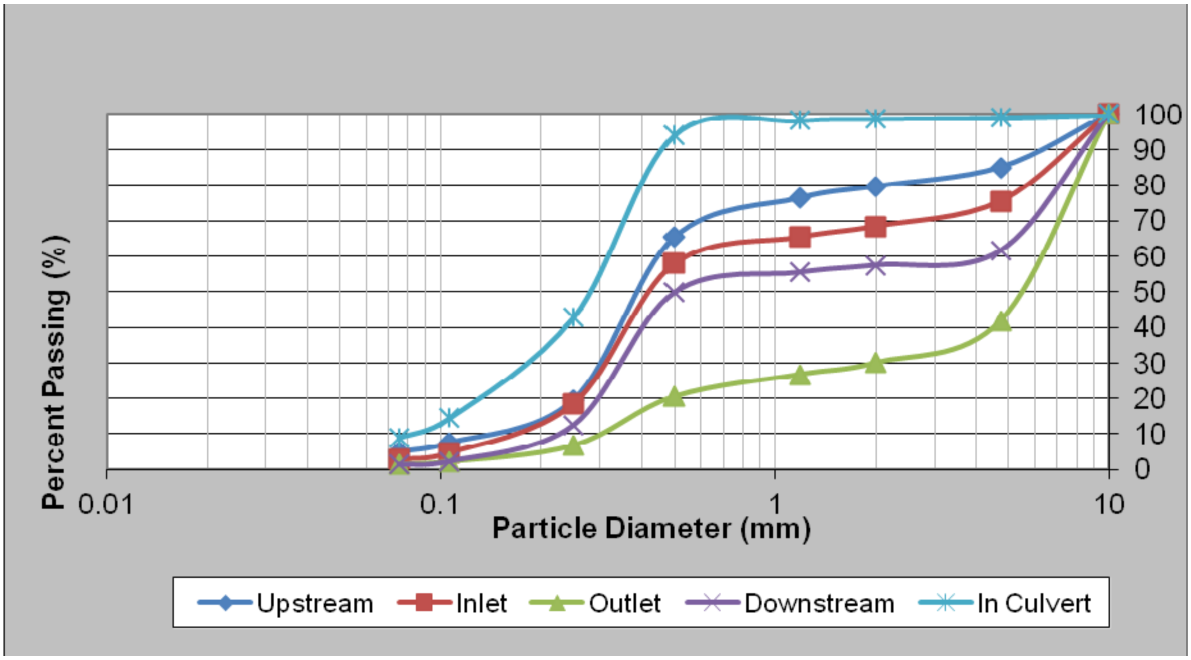


Figure 12: Particle Size Distributions from a Culvert Designated as Having Potentially Significant Impact (Culvert 5G)



This approach was used to determine the level of impact a culvert was having on the stream. This analysis was performed for all 44 circular culverts surveyed as well as the three randomly selected control culverts (culverts installed as non-embedded, non-bankfull culverts). For those circular culverts classified in Table 11 above as operating as embedded culverts or hybrid culverts, the analysis incorporates the sediment particle size distribution for ***each sample point*** along the reach of the culvert. For those culverts classified as operating as non-embedded culverts and for the three control culverts, the analysis was performed by comparing the changes f***rom upstream to the inlet*** and ***from the outlet to the downstream***. If there is less than 20% change between the upstream and the inlet, and there is less than 20% change between the outlet and the downstream, then the non-embedded culvert is also designated as "having minimal impact."

Exceptions to the definition of impact occur in culverts 4A, 2D, and 17B, where one or more portions of the reach above or below the culvert had sediments that were scoured away. In these culverts, because sediments were not present to be sampled, particle size distributions cannot be compared. However, because the hydraulics of the culverts has caused sediments to be scoured away, the culvert is clearly not allowing for the continuity of sedimentation patterns, and therefore the culverts were designated as “potentially having significant impact." Table 13 shows the results of this impact assessment by the operational field classification of the culverts. ***It is interesting to note that those culverts that are NOT embedded actually have a higher percentage of culverts that are assessed to be having "minimal" or "minor" impact than the culverts which are embedded.***

Table 13: Impact Analysis of Circular Culverts by Field Classification

Culverts Classified as Embedded in Field Survey		Culverts Classified as Hybrid in Field Survey		Culverts Classified as Non-Embedded in Field Survey	
Site	**Impact**	**Site**	**Impact**	**Site**	**Impact**
5F	Minimal	13C	Minimal	2C	Minimal
12E	Minimal	10A	Minor	2E	Minimal
8B	Minor	5A	Potentially Significant	2F	Minimal
9D	Minor	5B	Potentially Significant	2G	Minimal
5G	Potentially Significant	5C	Potentially Significant	3C	Minor
6B	Potentially Significant	5E	Potentially Significant	4A	Potentially Significant
7B	Potentially Significant	9B	Potentially Significant	4B	Potentially Significant
8C	Potentially Significant	10B	Potentially Significant	4C	Potentially Significant
9C	Potentially Significant	13B	Potentially Significant	5D	Potentially Significant
12C	Potentially Significant	15A	Potentially Significant	6A	Potentially Significant
12D	Potentially Significant			6D	Potentially Significant
16A	Potentially Significant			7A	Potentially Significant
				13A	Potentially Significant
				14A	Potentially Significant
				2A	Potentially Significant
				2B	Potentially Significant
				2D	Potentially Significant
				3A	Potentially Significant
				3B	Potentially Significant
				3D	Potentially Significant
				15B	Potentially Significant
				17B	Potentially Significant

4.5(c) Relationship of Culvert Classification to Assessed Impact**:** Using a Chi-Squared test for association, an attempt was made to see if the field classification of a culvert was related to the amount of impact the culvert appeared to be having. The results yield a χ^2 of 0.057 (P=0.972). Likewise, the Chi-Squared test was run to determine if the amount of impact was related to the order of stream on which the culvert was installed. The result is a χ^2 of 0.386 (P = 0.825). These results there is no statistical correlation between whether or not the culvert has sediments along its bottom (field classification) or stream order on the potential impact of a culvert when using sediment transport as an indication of impact.

4.5(d) Similarities of Culverts having Minimal or Minor Impact**:** Only eleven (11) culverts out of the 44 circular culverts analyzed had minimal or minor impacts on sediment transport. (Four (4) embedded, two (2) hybrid, and five (5) non-embedded). Because the number of culverts having minimal or minor impact as determined by this study is low, none of the factors that were examined (diameter, length , slope, stream order, upstream particle sizes and shear stress) showed statistically significant correlation with impact. Thus, no parameter can be conclusively linked to the culverts having minimal impact. However, there are some trends that were common amongst the culverts having minimal impact.

Four culverts that were classified as non-embedded culverts (those having NO sediments inside the culvert and/or those which were perched) were found to have minimal impact on sediment transport in the stream (2C, 2E, 2F, and 2G) and one (3C) was found to have minor impact. By examining the physical dimensions of these culverts, it was seen that each of these is located in a first order stream, have a slope greater than 3%, a length over 300 ft (91 m), and a diameter of less than five (5) feet (1.5 m). While the shear stress could not be determined for 2G because there are no USGS flow data for that stream, the remaining culverts all have a 2-year flow of less than 26 cfs (0.7 m^3/sec) and a resulting shear stress of less than 2.2 lb/ft^2 (105 Pa). As previously stated, the shear stress is a major factor in the movement in sediment particles. ***It appears from this data that on smaller (1st order) streams, which tend to have smaller flows and steeper slopes actually are less impacted by non-embedded, more traditionally designed culverts.*** Table 14 presents the as-built dimensions of non-embedded culverts that were having minimal impact on the stream sediment transport.

Table 14: Properties of Non-Embedded Culverts Having Minimal or Minor Impact

Site	Stream Order	As-built Length (ft [m])	As-built Diameter [ft [m]]	As-built Slope [%]	Two Year Flow (cfs [m^3/sec])	Shear from 2-year flow (lb/ft^2 [Pa])
2C	1	494.0 [150.6]	3.5 [1.1]	7.79%	13.7 [0.4]	2.19 [104.8]
2E	1	534.5 [163.0]	4.5 [1.4]	3.39%	25.9 [0.7]	1.46 [69.8]
2F	1	nm	3.5 [1.1]	nm	19.1 [0.5]	1.21 [58.1]
2G	1	408.5 [124.5]	2.5 [0.8]	6.34%	No flow data	
3C	1	313.8 [95.7]	4.5 [1.4]	3.33%	25.5 [0.7]	1.50 [71.6]

The two embedded culverts (5F and 12E) are having minimal impact while two additional embedded culverts (8B and 9D) are having only minor impacts. These four culverts all have diameters of 8 ft (2.4 m) or larger, the slopes are all less than 1%, the culvert is embedded 6% or greater and , the 2-year peak shear stress is less than 1 lb/ft^2 (50 Pa). T***hese data seem to indicate that in streams with slopes of less than 1%, embedded culverts have minimal impact and that larger diameters (which, combined with the low slope produce low shear stresses) may be the key to successful accumulation of sediment in the culvert.*** Table 15 shows the physical properties of the embedded culverts having minimal or minor impact on sediment transport.

Table 15: Properties of Embedded Culverts Having Minimal or Minor Impact

Site	Stream Order	As-built Length (ft [m])	As-built Diameter [ft [m]]	As-built Slope [%]	% Embedded	Two Year Flow (cfs [m^3/sec])	Shear from 2-year flow (lb/ft^2 [Pa])
5F	1	nm [nm]	8 [2.4]	nm	50.0%	25.9 [0.7]	0.74 [35.3]
12E	4	109.7 [33.5]	10.5 [3.2]	0.14%	30.2%	100 [2.8]	0.17 [8.3]
8B	3	143.3 [43.7]	14 [4.3]	0.79%	7.1%	183 [5.2]	1.03 [49.5]
9D	2	225.4 [68.7]	9 [2.7]	0.17%	6.4%	135 [3.8]	0.23 [11.1]

4.5(e) ***<u>Sediment Accumulation in Culverts Installed as "Embedded"</u>*****:** The relationship of slope to the accumulation of sediment in the culvert is an important result of this study. ***Many of the culverts with slopes greater than 1% had no sediment present inside of the culvert***. In the ODOT culvert design manual, it is stated that a depressed culvert should fill naturally with stream sediments. Of the 27 culverts that have a slope of 1% or greater, only 8 culverts had sediment present inside the culvert (29.6%). Though the culvert was initially depressed below the stream, once water enters the culvert the water velocity accelerates because the roughness of the culvert was less than the natural stream. A general linear model was used to determine if a correlation exists between culverts with a slope greater than 1% and culverts with no sediment present in the culvert. ***The analysis shows that at the 90% confidence interval, sediments are being washed through culverts with a slope 1% or greater (P = 0.06).***

4.5(f) ***<u>The Effect of Embedment Depth on Sedimentation Patterns</u>*****:** From the literature review, it was shown that embedded culverts provide a natural stream bottom for aquatic organisms to migrate through (Forest Service Stream Simulation Working Group, 2008). Though states have specified culverts should be depressed in the stream, the amount of embedment differs from state to state. For example, the State of Ohio specifies culverts should be depressed 10% (ODOT, 2010) into the stream where the State of Washington specifies culverts should be embedded 20% (Bates, 2003). Because of the non-uniform depths specified it is important to attempt to determine the effect of the depth of embedment has on the impact of the culvert as measured by sedimentation patterns.

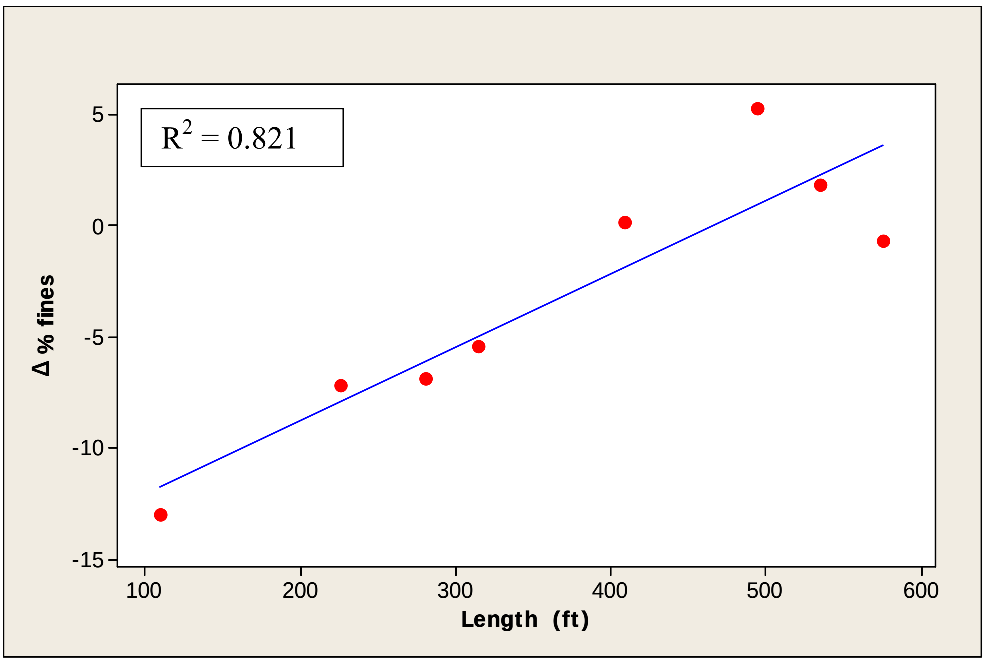
As noted in Section 4.3(a) above, Total Organic Carbon (TOC) is correlated with fine particulate matter in sediments. TOC in the sediments was measured in all sediment samples collected. In addition to the particle distribution data, this TOC data can be used to more precisely examine the impact of fine particulate transport. For analysis, the change in TOC (ΔTOC) from the upstream to the downstream was calculated. The closer the ΔTOC is to zero, the less impact the culvert is having on fine particle transport upstream to downstream through the culvert. The ΔTOC was compared to the percentage of embedment by producing a scatter plot comparing percentage of embedment with ΔTOC. Both the percentage of the inlet embedment and percentage of embedment at the maximum embedment depth in the culvert were compared to ΔTOC. Both scatter plots result in R^2 values less than 0.06. ***Therefore, there appears to be no clear statistical correlation in the data collected between the depth of embedment and the ability of the culvert to allow for sediment transport.***

4.5(g) ***<u>The Effect of Culvert Design Parameters on Sedimentation Patterns</u>*****:** One of the objectives of this study is to determine if the impact of the culvert (as measured by impact on sedimentation) is linked to standard design parameters such as length, slope, and diameter. As with the examination of embedment effects discussed in 4.5(f) above, ΔTOC from the upstream to the downstream was used as a more precise gauge of transport than the non-statistical evaluation of particle size distribution graphs. Scatter plots were produced with length, slope, and diameter as the independent variable and ΔTOC as the dependent variable. Using a linear regression trend line as the statistical measure of correlation, the data show little to no correlation between length, slope, and diameter and the change in the change of TOC from the upstream to the downstream of the culvert. The R^2 for each of these scatter plots respectively are 0.021, 0.02, and 0.056.

Even though strongly correlated, TOC is still only an indirect measure of fines in the sediments**.** Therefore, in addition to TOC, analyses were performed on the change in fines measured in the sieve analysis (a direct measure of percent fines). Fines are defined as particles passing the No. 200 sieve. ***When all circular culverts are considered, there was no correlation found between the change in percent passing the No. 200 sieve and the length, diameter, slope, and sheer stress from the 2-year, 5-year, and 10-year peak flows.***

However, if only culverts having minimal impact are considered, (including non-embedded, hybrid and embedded) some correlation is found. The strongest correlation found was the increase in the percentage of fine particles as the length of the culvert increases. The R^2 value of this correlation is 0.821. The graph of the change in the percentage of fines versus length is shown in Figure 13.

Figure 13: Correlation between the Change in % Fines vs. Length in Functioning Culverts



Another strong positive correlation was found between the percentage of fines and culvert slope. The R^2 value for the correlation between the change in the percentage of fines and slope is 0.65.

There is a weaker inverse correlation between the percentage of fines and culvert diameter. The R^2 value for the change in the percentage of fines and diameter is 0.361. For sheer stress, similarly weak correlations were found. The R^2 value for the change in the percentage of fines versus the sheer stresses from the 2-year, 5-year, and 10-year flows are 0.325, 0.286, 0.265 respectively.

4.5(h) ***<u>Instantaneous Sediment Transport through the culvert</u>*****:** The change in Total Suspended Solids and Turbidity from upstream to downstream of the culverts provides insight to the instantaneous sediment transport at the time of collection. As one would expect, there is a positive (albeit weak) relationship between ΔTSS and instantaneous sheer, as sediment transport is a function of sheer stress in the system. The linear regression of ΔTSS versus instantaneous sheer stress in culverts that are having minimal impact on sediment transport has an R^2 value of 0.536. If all culverts are analyzed together, there are no correlations found.

4.6 QHEI Results

Prior to highway construction and culvert installation, QHEIs were performed at 28 sites. The pre-construction QHEIs were performed by ODOT and the Ohio EPA. As part of the field survey, follow up QHEIs were performed at these sites. QHEIs were done both upstream and downstream of the culvert except at sites 4D, and 12D, where upstream QHEIs were not performed due to the fact there is another culvert immediately upstream of those culverts. Of the 28 culverts where QHEIs were performed, 22 culverts are circular culverts. Two of these culverts had incomplete pre-construction QHEI collection in the field so there these culverts were not included in the analysis. Therefore, a total 20 culverts were analyzed using QHEI. **Only five of the culverts where a QHEI was performed were classified as embedded in the field survey, and none of these five were determined to be having minimal impact under the definitions of this study.**

Comparing the upstream post-construction QHEI scores with the pre-construction reflects the natural change that has occurred in the stream since the culvert was installed, because it is arguable that the culvert does not affect upstream conditions. To investigate the effect of the culvert on the local stream environment, the upstream and downstream scores were compared against each other. Because the upstream scores represent the natural change of the stream, and the downstream scores represent the natural change ***plus*** the change caused by the culvert, subtracting the two scores should yield a measure of the change caused by the culvert. Table 16 provides a summary of the QHEI data for the 20 culverts for which complete pre-construction QHEIs were available and post construction QHEIs could be collected. The table also shows the field classification of the culvert as well as the estimate of impact the culvert is having on the sediment transport in the stream as defined in this report.

Of the 20 sites surveyed, 11 sites have lower upstream QHEI scores after culvert installation, meaning that the stream has naturally degraded since the installation of the culvert. It can also be seen that at three of the five culverts that were classified as embedded, there has been a degradation of the stream environment attributed to the culvert. For the non-embedded culverts, seven (7) of the 15 sites have experienced degradation due to the culvert. A statistical analysis of the change in QHEI scores showed no statistical correlation to any of the design parameters, the extent of embededness nor the field classification of the culvert. ***None of the culverts originally assessed were found in this study to be having minimal impact. Therefore, there are no QHEI data on culverts having the least impact on sediment transport in the stream.***

Table 16: Net change in QHEI scores from Upstream to Downstream

Site	Operating as	Pre-Construction QHEI	Survey QHEI Upstream	Survey QHEI Downstream	Natural change	Change w/culvert	ΔQHEI associated with culvert	Impact (Minimal, Minor or Potentially Significant)
8B	Embedded	56	77.5	68	21.5	12	-9.5	Minor
9D	Embedded	36	33.5	47	-2.5	11	13.5	Minor
12C	Embedded	39.25	51.25	49	12	9.75	-2.25	Potentially Significant
5G	Embedded	48	59	47.5	11	-0.5	-11.5	Potentially Significant
5A	hybrid	47	52	42	5	-5	-10	Potentially Significant
5B	hybrid	39.5	48	42.25	8.5	2.75	-5.75	Potentially Significant
5C	hybrid	58	49	41.5	-9	-16.5	-7.5	Potentially Significant
5E	hybrid	52.5	50.5	58.5	-2	6	8	Potentially Significant
3C	Non-embedded	53	29	40	-24	-13	11	Minor
2A	Non-embedded	67	39.5	65	-27.5	-2	25.5	Potentially Significant
2D	Non-embedded	54	64	69	10	15	5	Potentially Significant
3B	Non-embedded	67	45	58	-22	-9	13	Potentially Significant
3D	Non-embedded	57	54.5	48.5	-2.5	-8.5	-6	Potentially Significant
4A	Non-embedded	57	89	66	32	9	-23	Potentially Significant
4B	Non-embedded	47	52	50	5	3	-2	Potentially Significant
4C	Non-embedded	50.5	50	62.4	-0.5	11.9	12.4	Potentially Significant
6A	Non-embedded	57	46.5	44.5	-10.5	-12.5	-2	Potentially Significant
6D	Non-embedded	59	33.5	47.5	-25.5	-11.5	14	Potentially Significant
7A	Non-embedded	41.5	49	49	7.5	7.5	0	Potentially Significant
17B	Non-embedded	70	49.5	46	-20.5	-24	-3.5	Potentially Significant

4.7 Flood Attenuation Modeling

One specific objective set forth by ODOT in this project was a request to determine what, if any, impact bankfull culverts have on flood attenuation. The addition of a culvert into a stream has the potential to disrupt natural flow patterns. Culverts are designed to convey a specific storm (Tsihrintzis, 1995). When flow events exceed the design storm, ponding may occur upstream of the culvert. To determine what effect an EBC has on the height of ponding during the 100 yr flood, hydrologic modeling was performed. The software selected for the hydrologic modeling was HydroCAD® published by HydroCAD® Software Solutions.

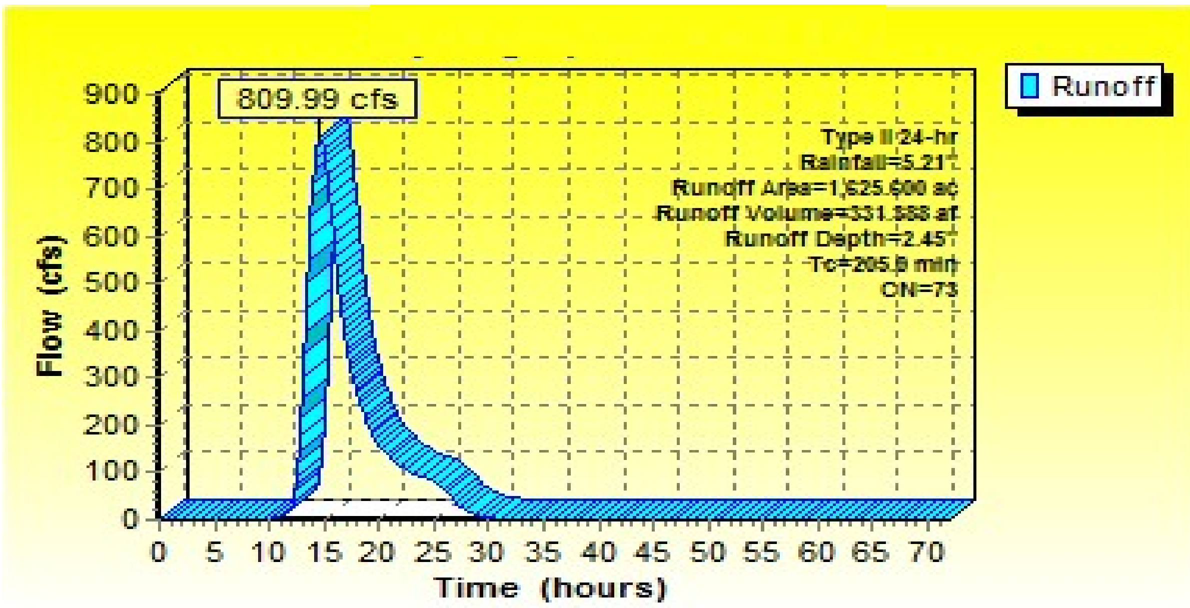
For the analysis, site 7B was selected because the site featured a culvert that featured no exceptional qualities or irregularities, and the percentage of the embedment of the culvert closely matches the ODOT EBC design on 10%. Culvert 7B is embedded 11.9% of the culvert diameter (2.5 feet). Also, all pertinent information for the model was collected during field collection at the culvert. The SCS TR-20 method was used to quantify the flows during the 100-year storm event. The routing method for selected the reach and ponding at the culvert was the dynamic-storage-indication method. This method was selected because the height of the headwater will rise as the water ponds behind the culvert, changing the amount of flow passing through the culvert. The inputs to the model are provided in Table 17.

Table 17: Stream and Watershed Characteristics Input into HydroCAD

Parameter	Input Value	Source
Storm Type	SCS Type II	Kuo, 2010
100-year storm	5.21 in (808 cfs)	NOAA
Soil Condition	AMC 2	USDA, Natural Resources Conservation Service
Dominant Hydrologic Soil Group	C	USDA, Natural Resources Conservation Service
Land Use	Woods, fair condition	Field Observation
CN	73	Kuo, 2010
Area	1625.5 acres	USGS, stream stats
Stage-Area Storage Relationship		Calculated from USGS contour maps
Slope	0.0027	Field Measurement
Diameter	21 ft	Field Measurement
Embedment Depth	2.5 ft	Field Measurement
Length	473 ft	Field Measurement

After the inputs from table 5.6 were entered into the software, the analysis was run. The 100-year peak flow for the stream at the culvert location is 808 cfs (22.9 m^3/sec) (USGS, 2010). Since the time of concentration (T_c) is not known at this location, iterations of the flood attenuation were run in the model, changing the T_c until the peak flow in the stream hydrograph matched as close as possible the 100-year flow for the stream. Figure 14 shows the hydrograph for the stream with no culvert.

Figure 14: Hydrograph of Site 7B with No Culvert (Base Case)



After T_c was determined for the stream, the culvert was introduced in the stream using the surveyed data and the model was run again. Two trials were run in the model, one with a traditional culvert with no embedment and the other with and embedded bankfull culvert 2.5 feet of embedment (12%). The results of the simulation are summarized in Table 18. Figure 15 shows the hydrograph for the culvert with no embedment and Figure 16 shows the hydrograph for the culvert with the embedment as measured in the field.

Table 18: Results of Hydrologic Modeling for the 100-year storm at Site 7B

	Traditional Culvert	EBC
Maximum flow passing through culvert (cfs and m^3/sec)	805.3 (22.8)	797.3 (22.6)
Depth of Ponding (ft and m)	12.57 (3.83)	12.86 (3.92)

It can be seen the embedment of the culvert has minimal effect on the ponding depth. The embedded culvert increases the depth of ponding by 0.29 ft (8.8 cm). The conclusion of this analysis is there is no significant increase in storage in ponding when the culvert is embedded approximately 12% of the culvert diameter.

Figure 15: Hydrograph of Site Culvert 7B with No Embedment

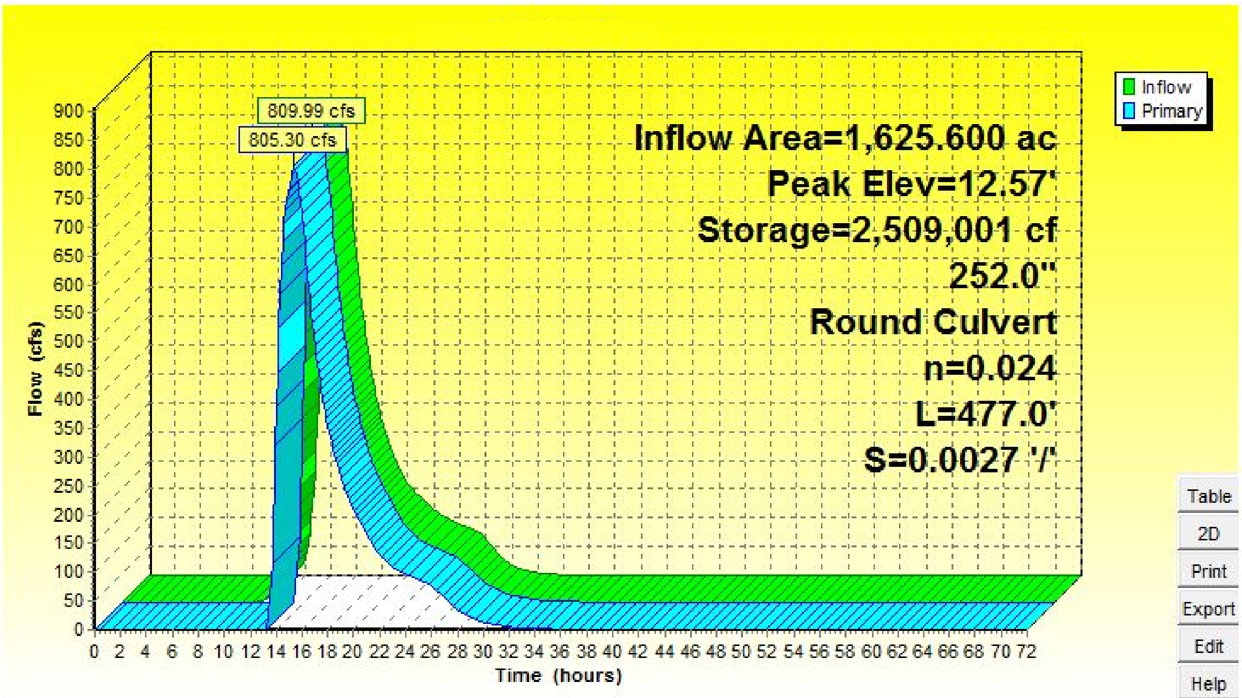
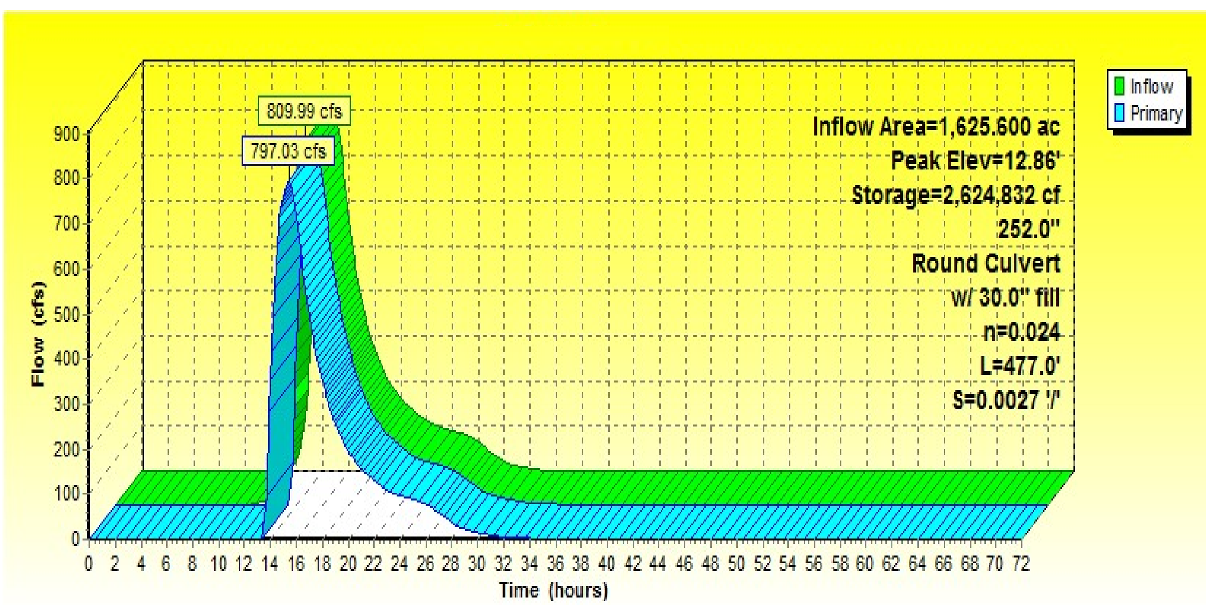


Figure 16: Hydrograph of Site Culvert 7B with 2.5 ft of Embedment



4.8 Fish Passage Modeling

Traditionally, modeling fish passage has been based on research on the ability of fish to swim against certain velocities. Beyond data on Salmonids and a select few other economically important fish species, there is little to no data on the migration ability of other species, including fish that would be present in the streams of Ohio, such as minnows, darters or catfish. There is even less research on migration of other aquatic microorganisms such as macroinvertebrates or insect species which form the base of the ecosystem. Hence, the modeling exercise is of limited usefulness in estimating impact in Ohio streams and waterways.

However, to examine the potential application of modeling in this regard, the US Forest Service's fish passage model FishXing® was used to analyze one of the embedded bankfull culverts. This software is intended to assist engineers, hydrologists, and fish biologists in the evaluation and design of culverts for fish passage. It is free and available for download at http://www.stream.fs.fed.us/fishxing/index.html.

To be consistent with the hydrologic exercise, Culvert 7B was selected for modeling. The model contains various biological data concerning species of fish. For the modeling exercise, a brown trout was selected as the fish species, as this species is present in Ohio and data were available in the model for this species. It is important to note that the presence of Brown Trout was not noted or researched in any of the streams on which the culverts surveyed were located. Table 19 shows the biological data in the model for this species.

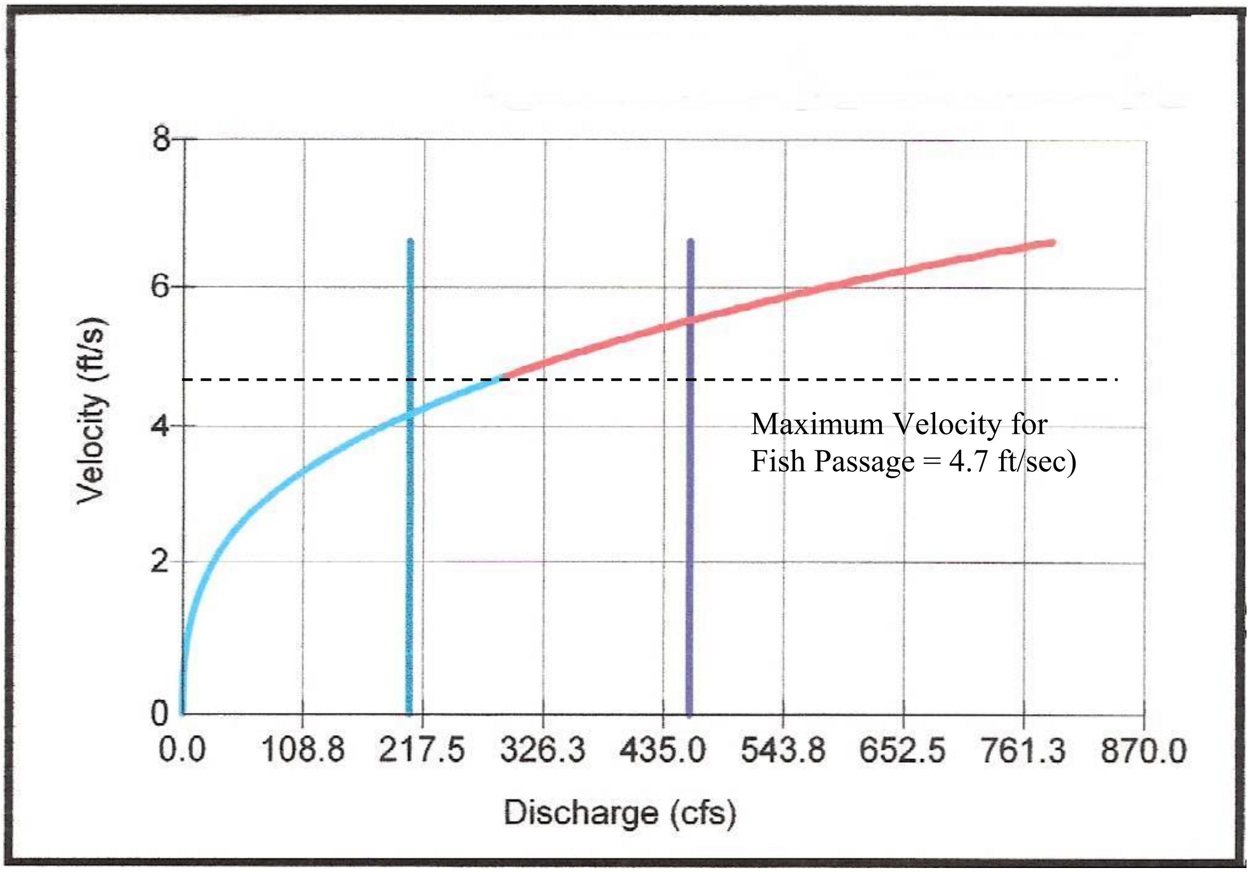
Table 19: Biological Data for Adult Brown Trout Fish from FishXing®

Minimum Water Depth:	4.8 ft (1.5 m)		Burst Swimming Speed:	9 ft/s (2.7 m/sec)
Prolonged Swimming Speed:	5 ft/s (1.5 m/sec)		Burst Time to Exhaustion:	5 s
Prolonged Time to Exhaustion:	30 min		Jumping Speed:	9 ft/s (2.7 m/sec)

The culvert was modeled with the three flows (and corresponding depths) associated with the 2-year, 5-year and 10-year peak flow. Figure 17 shows the limits of the acceptable migration velocity through the culvert. As can be seen, this culvert would allow passage of the Brown Trout adult well past the 2-year peak flow of 205 cfs (5.8 m^3/sec). Therefore, this culvert should not be an impediment to fish passage under normal flow conditions.

The data on flows contained in Appendix E could be used to conduct similar analyses for all the culverts surveyed. However, until there is reliable biological data on the prolonged swimming speeds of the various fish species, macroinvertebrates, and/or insect species of interest in the stream, this exercise would be of limited value.

Figure 17 : Fish Passage Acceptable Velocities with Flow in Culvert 7B (Produced by FishXing®)



5.0 Conclusions and Recommendations

5.1 Observational Conclusions

The purpose of this section is to illustrate field conditions that may be contributing a culvert's impact on sediment transport and the failure of sediments to naturally accumulate in the culvert so that it becomes embedded. These observations are not intended as conclusions, but rather to show trends that were observed but not measured or could not be statistically validated.

The first major observation is the variation between culvert installations performed under different contracts. Only twelve (12) of the circular culverts surveyed actually have accumulated sediment in the culvert (are embedded). This represents less than 28% of the circular culverts studied. For culverts that were found not to be embedded, it appears that changes may have been made during the installation of the culvert. These changes are resulting in conditions that prevent the culvert from operating accumulating sediments within the culvert. For example, culverts 2A, 2B, and 2D in Athens County were installed with a concrete lining on the bottom of the culvert. This concrete lining is causing the stream sediments to pass through the culvert without depositing, leaving no natural bottom in the culvert. In these culverts, there was no stream material present and the culvert. In culverts 3A, 3B, 3C, and 3D, there were large concrete pads placed at the outlet of the culvert. It is assumed this pad was put in place in order to capture sediments. It is logical that the presence of a concrete pad might create an obstruction where suspended sediments and sediment particles traveling along the bed load would become trapped inside the culvert by the pad. Overtime sediments would continue to accumulate until an equilibrium point is met between the movement of sediments and the depth of the bed load. However what is occurring is some sediments are trapped immediately upstream of the pad but no other sediments are trapped in the culvert.

An important observation is that many of the culverts with slopes greater than 1% slope had no sediment present inside of the culvert. In the ODOT culvert design manual, it is stated that a depressed culvert should fill naturally with stream sediments. However, in most of the culverts, there is no sediment accumulation occurring even though the culvert was depressed below the stream bottom. The data appear to indicate that once water enters the culvert the water velocity accelerates because the culvert slope is greater than the stream slope upstream and because the roughness of the culvert is less than the natural stream. This trend was confirmed statistically by analyzing the correlation between culverts with a slope greater than 1% and the absence of sediment in the culvert. The analysis showed that ***at the 90% confidence interval, sediments are being washed through culverts with a slope 1% or greater*** (P = 0.06).

Increased water velocities exiting the culvert can also scour the channel bottom downstream of the culvert causing the culvert to become perched. It was observed that out of the 59 culverts sampled, 12 were perched. In most instances, the perching is a few inches and can be attributed to scouring. However, in the case 7A, the culvert outlet is perched four feet above the downstream water surface level. The extreme height of the perch of 7A leads one to suspect this culvert was installed at this height.

It also was noted in some perched culverts that highway drainage was directed towards the stream in which the culvert is present. The drainage is carrying sediment from the fill material in the embankment. In the case of culvert 6C, the embankment of the upstream face is a rock cliff with little no vegetation on the embankment. It appears the fill material upstream of the culvert was being heavily eroded during storm events and depositing at the inlet of the culvert. The observation of erosion from embankments has also been show by Cerda (2004), who found erosion rates of embankments were higher for embankments with no vegetation than embankments with vegetation. As discussed above, the health of a stream can be negatively affected by the increase of sediments.

Another issue with culvert placement is that in two cases surveyed (3C and 12D), an embedded bankfull culvert (EBC) has been placed immediately downstream of a traditional culvert. In this case, it is almost impossible to determine the effect of the culvert on the stream because the stream is unable to transition back into its natural state before entering the EBC. ***It is unclear if an EBC is needed in these cases because the traditional culvert is already in place upstream of the EBC location.*** The purpose of an EBC is to minimize the disruption of sedimentation patterns in a stream. However, with a traditional culvert upstream of an EBC, the purpose of an EBC in the stream is defeated.

5.2 Conclusions From Data Analysis

A general linear model analysis showed there is no correlation between stream order and whether a culvert becomes embedded or not. However, this finding is limited because of the 44 circular culverts surveyed only 12 culverts are currently embedded. This represents less than 28% of the circular culverts surveyed. ***This may be attributed to the large number of culverts installed on with slopes greater than 1% as there is a correlation at the 90% confidence interval between a culvert slope greater than 1% and no embedment within a culvert.***

The limited number of culverts that currently have sediments in the culvert (and therefore meet the definition of embedded) does not give a large enough sample for statistical significance to be determined. It was observed that the two of the embedded culverts which show minimal impact on sediment transport both had over 30% embedment at its highest level in the culvert. However, examination of those culverts that are having minimal impact on sediment transport (both embedded and non-embedded) does reveal important trends. ***It appears from the data that on smaller (1st order) streams, which tend to have smaller flows and steeper slopes actually are less impacted by non-embedded, more traditionally designed culverts. The data also seem to indicate that in streams with slopes of less than 1%, embedded culverts have minimal impact and that larger diameters (which, combined with the low slope produce low shear stresses) may be the key to successful accumulation of sediment in the culvert.***

By providing a deeper natural channel bottom, more surface area of the culvert is covered by natural sediment and thus the Manning's channel roughness is increased from the roughness of the culvert to the roughness of the natural bottom. Typical Mannings' n values for steel culverts range from 0.011 to 0.018 and natural channels range from 0.025 and 0.05 (Kuo, 2010). By increasing the channel roughness, there is more friction from the channel against the flow and suspended particles. When the friction of the channel increased against suspended particles and the flow, particles velocities are reduced and the fall velocity exceeds the velocity of the stream and the particle settles out.

An important trend that holds for functioning culverts is that the change in total suspended sediment is correlated with instantaneous sheer stress in the culvert. This finding is supported by the research that once the sheer stress becomes larger than the critical sheer stress, a particle will begin to move. As the sheer stress continues to increase, the more particles will become mobilized. This fact provides a simple test that can be applied in future studies of the functionality of culverts.

The results of the QHEI analysis show that of the 20 circular culverts surveyed, only 5 culverts are operating as embedded culverts in the field. Of these five, three resulted in lower QHEI scores attributed to the culvert. Similarly, seven of the 15 non-embedded culverts resulted in lower QHEI scores attributed to the culvert. More than half of the streams surveyed have experienced upstream degradation since the time of construction. On top of this, 60% of the streams surveyed in which EBCs are located experienced additional degradation because of the culvert and construction activities. Because there are only five culverts being compared, the results are not statistically significant.

5.3 Recommendations

It is critical to understand that the recommendations which follow are based on extremely limited data. Because of the low number of embedded culverts and the even fewer number of culverts showing minimal impact on sediment transport, the results presented are not statistically significant. Trends were identified and an attempt to identify similarities in the physical parameters of the culverts having the least impact on sediment transport, and therefore theoretically, the least impact on the environment. Based on the results presented, there were no statistical correlations found between the type of culvert and the impact of a culvert. Of the 12 embedded culverts, only two were found to be effectively allowing for the continuity of sedimentation patterns through the reach of a culvert.

***Recommendation 1*:** ODOT should develop and implement a system of inspecting and verifying that culverts specified to be embedded bankfull culverts are actually installed as such.

Basis for recommendation: The physical survey of the culverts revealed that of the 59 culverts identified by ODOT as being designed as embedded bankfull culverts (EBCs), there are only 12 that are actually embedded. Many of the culverts are having stream sediments washed through the culvert and the streambed on either side of the culvert is now at the level of the bottom of the culvert.

***Recommendation 2*:** Embedded bankfull culverts should not be installed at slopes greater than 1%.

Basis for recommendation: An important observation is that many of the culverts with slopes greater than 1% slope had no sediment present inside of the culvert. In the ODOT culvert design manual, it is stated that a depressed culvert fills naturally with stream sediments. However, the results of the survey conducted that, ***at the 90% confidence interval, sediments are being washed through culverts with a slope 1% or greater***.

***Recommendation 3*:** ODOT should consider funding additional research in this area to confirm preliminary trends and provide more guidance in the design of embedded bankfull culverts.

Basis for recommendation: To better understand the impacts of culverts and the trends presented in this report, more research is needed on sedimentation through culverts. There is little research available detailing sedimentation through culverts (Singley & Hotchkiss, 2010), and more research is needed beyond this project to determine conclusively why culverts that are not impacting sediment transport behave the way they do and why those culverts which do impact transport seem to have no predictable characteristics. Future studies are needed to determine if conditions improve at those sites where culverts are impacting sediment transport or which are not currently accumulating sediment in the culvert over time, or if the culvert has already reached an equilibrium point with the stream. It is very hard to determine how the stream has reacted to the presence of culverts that are not impacting sediment transport, because there are no pre-culvert QHEI data for these streams. ***Continued evaluation of these culverts is needed in order to determine how a functioning EBC affects the health of a stream.***

Finally, there is little longitudinal data available on these culverts. Future studies on these culverts, especially the EBCs and culverts operating as hybrid culverts, will provide data on how sedimentation patterns are changing over time. Because streams are dynamic and always changing over time, it may be useful to measure the response of a culvert as stream conditions change over time.

6.0 Implementation Plan

First, and most importantly, the Ohio Department of Transportation should immediately develop and implement a system of inspecting and verifying that culverts specified to be embedded bankfull culverts are actually installed as such (***Recommendation 1***). Because this is an internal ODOT requirement, the steps to implementation are moderately straightforward. Initial efforts should include discussions with ODOT contractors to explore the reasons that culverts, when installed, are not being installed according to the design requirements of embedded bankfull culverts.

The remaining recommendations are not sufficiently supported by the data to be implemented at this time. Before ODOT begins the process of changing the design criteria for Embedded Bankfull Culverts, they should ensure that the trends identified in this research, especially with regard to the slope of the culvert (Recommendation 2) are verified by sufficient sample in the field. This may require sampling embedded bankfull culverts outside the State of Ohio to ensure enough functioning EBCs are available for the study.

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APPENDIX A
Summary of Physical Data Collected During Survey of Culverts

Of the **Draft** Final Report on

A Study of Bankfull Culvert Design Effectiveness

By: Mark A. Tumeo, Ph.D., J.D.
Joe Pavlick, MS Student

for the
Ohio Department of Transportation
Office of Research and Development

State Job Number 134465

May 16, 2011 (draft)

Cleveland State University

Site	County	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m]]	As-built Diameter [ft [m]]	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m]]	Notes	Contract installed	Plan sheet
1A	Paulding	3	512 [156]	510.7 [155.7]	Box 9' H x 14' W [2.7m x 4.3m]	Box 9' x 14' [2.7m x 4.3m]	0.05%	0.03%	0.55 [0.2]		PAU-24-0.00	441-445
1B	Paulding	3	256 [78]	253.9 [77.4]	Box 9' H x 14' W [2.7m x 4.3m]	Box 9' x 14' [2.7m x 4.3m]	0.06%	0.19%	0.6 [0.2]		PAU-24-0.00	447-451
1C	Paulding	3	78 [24]	76.3 [23.3]	Box 12' H x 20' W [3.7m x 6.1m]	Box 12' x 20' [3.7m x 6.1m]	0.38%	0.37%	1 [0.3]		PAU-24-0.00	492-496
1D	Paulding	3	156 [48]	154.2 [47.0]	Box 9' H x 14' W [2.7m x 4.3m]	Box 9' x 14' [2.7m x 4.3m]	0.06%	0.16%	0.7 [0.2]		PAU-24-0.00	484-488
1E	Paulding	3	96 [29]	93.1 [28.4]	Box 9'H x 16' W [2.7m x 4.9m]	Box 9'H x 16' [2.7m x 4.9m]	0.31%	0.45%	0.25 [0.1]		PAU-24-0.00	478-483
2A	Athens	2	512 [156]	462.6 [141.0]	5.9 [1.8]	6 [1.8]	1.15%	1.12%	0 [0]	Culvert bottom lined with 2 in of concrete	ATH-33-40.981	563
2B	Athens	1	452 [138]	453.1 [138.1]	5.9 [1.8]	5 [1.5]	2.90%	2.95%	0 [0]	Culvert bottom lined with 5 in of concrete	ATH-33-40.981	566
2C	Athens	1	535 [163]	494.0 [150.6]	3.5 [1.1]	3.5 [1.1]	8.24%	7.79%	0 [0]		ATH-33-40.981	567
2D	Athens	1	853 [260]	823.0 [250.9]	5.5 [1.7]	5.5 [1.7]	2.09%	1.95%	0 [0]	Culvert bottom lined with 11 in of concrete	ATH-33-40.981	568
2E	Athens	1	540 [165]	534.5 [163.0]	4.5 [1.4]	4.5 [1.4]	3.56%	3.39%	0 [0]		ATH-33-40.981	570
2F	Athens	1	640 [195]	nm [nm]	3.5 [1.1]	3.5 [1.1]	4.23%	nm	0 [0]		ATH-33-40.981	571
2G	Athens	1	410 [125]	408.5 [124.5]	2.5 [0.8]	2.5 [0.8]	6.69%	6.34%	0 [0]		ATH-33-40.981	574
3A	Athens	1	750 [229]	749.9 [228.6]	5.9 [1.8]	6 [1.8]	3.16%	3.55%	0 [0]	Concrete pad at outlet	ATH-33-30.981	852
3B	Athens	3	825 [252]	823.1 [251.0]	12.0 [3.7]	12 [3.7]	0.60%	0.66%	0 [0]	Concrete pad at outlet	ATH-33-30.981	853
3C	Athens	1	312 [95]	313.8 [95.7]	4.5 [1.4]	4.5 [1.4]	3.19%	3.33%	0 [0]	Concrete pad at outlet	ATH-33-30.981	854
3D	Athens	1	251 [77]	253.9 [77.4]	5.5 [1.7]	5.5 [1.7]	3.86%	5.64%	0 [0]	Concrete pad at outlet	ATH-33-30.981	855

Site	County	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m]]	As-built Diameter [ft [m]]	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m]]	Notes	Contract installed	Plan sheet
4A	Ross	4	390 [119]	219.2 [66.8]	12 [3.7]	12 [3.7]	0.77%	1.46%	0 [0.0]		ROS-35-26.17	197, 734-736
4B	Ross	1	368 [112]	372.1 [113.4]	5 [1.5]	5 [1.5]	1.63%	1.62%	0 [0.0]		ROS-35-26.17	213,774
4C	Ross	1	295 [90]	289.7 [88.3]	5 [1.5]	5 [1.5]	2.04%	1.94%	0 [0.0]		ROS-35-26.17	213,775
4D	Ross	2	84 [26]	84.0 [25.6]	Box 8' H x 14' W [2.4m x 4.3m]	Box 8' x 14' [2.4m x 4.3m]	0.60%	0.71%	1.833 [0.6]		ROS-35-26.17	508-509,740-742
5A	Meigs	2	535 [163]	535.3 [163.2]	6 [1.8]	6 [1.8]	2.56%	2.52%	1 [0.3]		MEG-124-31.57	81,559
5B	Meigs	1	378 [115]	378.2 [115.3]	5 [1.5]	5 [1.5]	4.64%	4.53%	1.83 [0.6]		MEG-124-31.57	85, 564
5C	Meigs	1	310 [95]	297.8 [90.8]	4 [1.2]	4 [1.2]	5.38%	5.22%	2.75 [0.8]		MEG-124-31.57	86, 565
5D	Meigs	2	500 [152]	478.2 [145.8]	10 [3.0]	12 [3.7]	2.19%	1.95%	0 [0.0]		MEG-124-31.57	91-92, 566
5E	Meigs	2	615 [188]	615.9 [187.8]	12 [3.7]	12 [3.7]	0.69%	0.68%	2.42 [0.7]		MEG-124-31.57	103, 570
5F	Meigs	1	650 [198]	nm [nm]	8 [2.4]	8 [2.4]	1.18%	nm	4 [1.2]		MEG-124-31.57	104, 571
5G	Meigs	2	523 [159]	524.2 [159.8]	10 [3.0]	12 [3.7]	0.25%	0.18%	0.4167 [0.1]		MEG-124-31.57	106, 572
6A	Meigs	1	295 [90]	296.1 [90.3]	4 [1.2]	4 [1.2]	2.20%	2.42%	0 [0.0]		MEG-124-26.66	33, 380
6B	Meigs	1	264 [80]	265.6 [81.0]	3.5 [1.1]	3.5 [1.1]	5.00%	4.07%	0.92 [0.3]		MEG-124-26.66	36, 385
6C	Meigs	2	85 [26]	85.6 [26.1]	ellipse 5.67' H x 8.17' W [1.73m x 2.49m]	ellipse 5.67' x 8.17' [1.73m x 2.49m]	0.80%	0.75%	2.83 [0.9]		MEG-124-26.66	42, 391
6D	Meigs	1	389 [119]	388.0 [118.3]	6 [1.8]	6 [1.8]	8.50%	7.46%	0 [0.0]		MEG-124-26.66	43, 392
6E	Meigs	2	108 [33]	108.2 [33.0]	ellipse 4.83' H x 7.58' W [1.47m x 2.31m]	ellipse 4.83' x 7.58' [1.47m x 2.31m]	0.60%	0.54%	0.67 [0.2]		MEG-124-26.66	52, 404
7A	Meigs	1	413 [126]	428.8 [130.7]	5 [1.5]	5 [1.5]	3.07%	2.86%	0 [0.0]		MEG-124-22.72	91, 648
7B	Meigs	4	477 [145]	473.4 [144.3]	21 [6.4]	21 [6.4]	0.27%	0.39%	2.5 [0.8]		MEG-124-22.72	100, 751

Site	County	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m]]	As-built Diameter [ft [m]]	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m]]	Notes	Contract installed	Plan sheet
8A	Fairfield	4	236 [72]	237.3 [72.3]	Box 8' H x 18' W [2.4m x 5.5m]	Box 8' x 18' [2.4m x 5.5m]	0.12%	0.16%	0 [0.0]		FAI-33-7.31	1339
8B	Fairfield	3	143 [44]	143.3 [43.7]	14 [4.3]	14 [4.3]	0.87%	0.79%	1 [0.3]		FAI-33-7.31	1402
8C	Fairfield	2	203 [62]	205.8 [62.7]	7 [2.1]	7 [2.1]	0.87%	0.82%	2 [0.6]		FAI-33-7.31	1360
9A	Fairfield	4	192 [59]	190.8 [58.2]	Box 10' H x 20' W [3.0m x 6.1m]	Box 10' x 20' [3.0m x 6.1m]	0.28%	0.44%	varies [varies]		FAI-33-13.25	492
9B	Fairfield	3	312 [95]	312.1 [95.2]	7 [2.1]	7 [2.1]	0.70%	1.23%	1.75 [0.5]		FAI-33-13.25	504
9C	Fairfield	3	90 [27]	89.5 [27.3]	6 [1.8]	6 [1.8]	0.70%	0.64%	1.17 [0.4]		FAI-33-13.25	504
9D	Fairfield	2	224 [68]	225.4 [68.7]	9 [2.7]	9 [2.7]	0.19%	0.17%	0.58 [0.2]		FAI-33-13.25	510
10A	Fairfield	1	280 [85]	280.6 [85.5]	5 [1.5]	5 [1.5]	2.51%	4.77%	0.5 [0.2]		FAI-33-17.44	327
10B	Fairfield	3	259 [79]	261.3 [79.7]	10.5 [3.2]	10.5 [3.2]	0.40%	0.37%	0.58 [0.2]		FAI-33-17.44	339
11A	Fairfield	4	54 [16]	52.2 [15.9]	Box 8' H x 21' W [2.4m x 6.4m]	Box 8' x 21' [2.4m x 6.4m]	0.48%	0.10%	5.167 [1.6]		FAI-33-19.79	476
11B	Fairfield	4	264 [80]	261.8 [79.8]	Box 9' H x 18' W [2.7m x 5.5m]	Box 9' x 18' [2.7m x 5.5m]	0.36%	0.49%	0 [0.0]		FAI-33-19.79	484
12A	Fairfield	2	58 [18]	75.5 [23.0]	Box 8' H x 8' W [2.4m x 2.4m]	Box 8' x 8' [2.4m x 2.4m]	0.12%	0.09%	1.75 [0.5]		FAI-33-0.41	656
12B	Fairfield	2	55 [17]	55.6 [17.0]	Box 8' H x 8' W [2.4m x 2.4m]	Box 8' x 8' [2.4m x 2.4m]	1.38%	1.42%	2.17 [0.7]		FAI-33-0.41	664
12C	Fairfield	3	210 [64]	173.2 [52.8]	20 [6.1]	20 [6.1]	0.07%	0.04%	1.25 [0.4]		FAI-33-0.41	634
12D	Fairfield	4	276 [84]	276.2 [84.2]	8 [2.4]	8 [2.4]	0.37%	0.59%	1.75 [0.5]		FAI-33-0.41	636
12E	Fairfield	4	125 [38]	109.7 [33.5]	10.5 [3.2]	10.5 [3.2]	0.16%	0.14%	3.17 [1.0]		FAI-33-0.41	647

Site	County	Stream Order	Design Length (ft [m])	As-built Length (ft [m])	Design Diameter [ft [m]]	As-built Diameter [ft [m]]	Design Slope [%]	As-built Slope [%]	As-built Deepest Embedment [ft [m]]	Notes	Contract installed	Plan sheet
13A	Wayne	1	163 [50]	162.9 [49.6]	4 [1.2]	4 [1.2]	0.30%	0.30%	0 [0.0]		WAY 30-11.86	131,481
13B	Wayne	1	286 [87]	284.0 [86.6]	4 [1.2]	4 [1.2]	3.00%	2.94%	0.541 [0.2]		WAY 30-11.86	190, 482
13C	Wayne	4	560 [171]	nm	9 [2.7]	9 [2.7]	2.50%	nm	2.67 [0.8]		WAY 30-11.86	202, 487
14A	Wayne	2	282 [86]	nm	7 [2.1]	nm	1.14%	nm	0 [0.0]		WAY 30-16.14	91, 382
14B	Wayne	2	144 [44]	144.6 [44.1]	ellipse 5.67' H x 8.83' W [1.73m x 2.69m]	ellipse 5.67' x 8.83' [1.73m x 2.69m]	0.34%	0.31%	3.33 [1.0]		WAY 30-16.14	258, 395
15A	Crawford	2	246 [75]	248.7 [75.8]	7.4 [2.3]	8 [2.4]	0.34%	0.15%	1 [0.3]		CRA/RIC 30-33.5/0.00	452, 100, 442
15B	Crawford	2	118 [36]	121.0 [36.9]	7.4 [2.3]	8 [2.4]	0.35%	0.43%	0 [0.0]		CRA/RIC 30-33.5/0.00	452, 420, 451A
16A	Crawford	2	315 [96]	320.4 [97.7]	11.8 [3.6]	12 [3.7]	0.34%	1.71%	3 [0.9]		CRA 30-24.0	446
17B	Crawford	4	463 [141]	461.1 [140.6]	6.4 [2.0]	6 [1.8]	0.62%	0.62%	0 [0.0]		CRA 30-15.865	297

APPENDIX B
Summary of the Results for Total Organic Carbon

Of the **Draft** Final Report on

A Study of Bankfull Culvert Design Effectiveness

By: Mark A. Tumeo, Ph.D., J.D.
Joe Pavlick, MS Student

for the
Ohio Department of Transportation
Office of Research and Development

State Job Number 134465

May 16, 2011 (draft)

Cleveland State University

Summary of Total Organic Carbon Data Collected During Survey

	Upstream		Inlet		In Culvert		Outlet		Downstream	
	Avg (%)	Std Dev	Avg (%)	Std Dev	Avg (%)	Std Dev	Avg (%)	Std Dev	Avg (%)	Std Dev
1A	2.57	0.070	3.87	0.446	4.74	0.143	3.18	0.118	2.38	0.433
1B	2.65	0.089	5.84	0.086	3.82	0.205	2.55	0.126	2.55	0.110
1C	2.44	0.620	2.60	0.281	1.73	0.215	2.60	0.063	2.34	0.080
1D	2.38	0.433	2.68	0.278	2.73	0.283	2.57	0.212	2.64	0.315
1E	3.83	0.120	3.18	0.327	4.51	0.278	2.95	0.246	2.57	0.070
2A	1.20	0.051	1.51	0.115	no sample	no sample	1.57	0.117	1.76	0.206
2B	2.81	0.078	2.45	0.261	no sample	no sample	1.91	0.062	2.30	0.154
2C	2.56	0.430	2.02	0.129	no sample	no sample	1.97	0.474	2.36	0.282
2D	1.45	0.071	no sample	no sample	no sample	no sample	1.53	0.078	1.51	0.114
2E	1.44	0.216	1.30	0.073	no sample	no sample	1.67	0.152	1.61	0.071
2F	1.02	0.230	0.94	0.342	no sample	no sample	0.44	0.146	0.62	0.103
2G	2.23	0.194	1.93	0.124	no sample	no sample	4.26	0.118	6.61	1.006
3A	1.54	0.143	no sample	no sample	no sample	no sample	1.09	0.028	1.65	0.272
3B	5.25	0.190	3.39	0.164	no sample	no sample	2.74	0.353	2.13	0.274
3C	5.25	0.190	3.39	0.164	no sample	no sample	2.74	0.353	2.13	0.274
3D	2.31	0.247	1.73	0.041	no sample	no sample	no sample	no sample	1.42	0.274
4A	4.82	0.276	4.14	0.398	no sample	no sample	no sample	no sample	4.93	0.542
4B	3.67	0.238	no sample	no sample	no sample	no sample	no sample	no sample	4.91	0.163
4C	3.61	0.089	no sample	no sample	no sample	no sample	no sample	no sample	7.43	0.173
4D	7.87	0.364	6.21	0.297	5.89	0.253	8.45	0.192	6.29	0.531
5A	3.24	0.044	2.93	0.304	2.87	2.175	7.21	0.311	4.74	0.266
5B	5.23	0.498	2.83	0.212	2.53	0.406	2.61	0.258	5.86	0.321
5C	3.34	0.609	2.94	0.429	no sample	no sample	2.05	0.055	1.21	0.219
5D	1.26	0.254	1.25	0.492	no sample	no sample	1.09	0.212	no sample	no sample
5E	1.80	0.131	2.02	0.178	1.86	0.085	3.51	0.093	1.70	0.030
5F	0.40	0.071	0.24	0.044	0.61	0.008	1.55	0.120	0.62	0.025
5G	2.17	0.423	1.39	0.296	0.86	0.063	2.62	0.062	1.38	0.336
5H	1.38	0.399	1.23	0.123	no sample	no sample	1.22	0.253	1.41	0.146
6A	1.26	0.110	1.49	0.422	no sample	no sample	1.30	0.059	1.81	0.412
6B	0.93	0.117	0.80	0.142	no sample	no sample	0.71	0.076	0.55	0.072
6C	0.77	0.096	0.73	0.325	0.83	0.030	0.84	0.095	1.05	0.063
6D	2.84	0.208	2.47	0.365	no sample	no sample	1.58	0.070	no sample	no sample
6E	2.08	0.151	1.65	0.063	3.33	0.538	2.09	0.219	1.60	0.070

Summary of Total Organic Carbon Data Collected During Survey

	Upstream		Inlet		In Culvert		Outlet		Downstream	
	Avg (%)	Std Dev	Avg (%)	Std Dev	Avg (%)	Std Dev	Avg (%)	Std Dev	Avg (%)	Std Dev
7A	3.24	0.339	2.91	0.357	no sample	no sample	2.93	0.379	2.14	0.294
7B	4.99	0.087	5.38	0.155	no sample	no sample	4.24	0.081	2.38	0.101
8A	1.06	0.069	1.15	0.138	1.65	0.061	1.04	0.025	0.94	0.188
8B	0.82	0.174	1.39	0.603	0.88	0.163	0.79	0.046	1.01	0.469
8C	1.08	0.091	2.46	0.770	2.35	0.062	0.92	0.189	1.56	0.053
9A	1.02	0.113	1.94	0.153	0.81	0.166	1.14	0.196	0.88	0.094
9B	1.34	0.748	2.70	0.289	3.08	0.110	1.47	0.283	1.56	1.120
9C	1.56	0.169	1.46	0.111	5.49	0.489	5.77	0.318	5.12	0.748
9D	3.63	0.143	5.46	0.202	6.43	0.117	6.98	0.084	9.04	0.949
10A	3.27	0.135	1.92	0.336	1.69	0.169	1.03	0.040	1.04	0.041
10B	4.56	0.233	7.23	0.205	1.21	0.518	0.98	0.026	0.47	0.060
11A	0.85	0.440	0.64	0.044	1.38	0.253	1.11	0.658	0.88	0.663
11B	1.47	0.273	3.01	0.091	no sample	no sample	1.16	0.101	0.38	0.025
12A	1.82	0.259	1.75	0.111	5.33	0.133	3.93	0.087	4.40	0.610
12B	1.30	0.135	3.43	0.113	4.52	0.039	2.68	0.179	3.38	0.009
12C	0.55	0.063	1.69	0.126	4.43	0.472	3.49	0.314	1.94	0.144
12D	no sample	no sample	2.01	0.163	1.92	0.151	1.02	0.078	2.58	0.844
12E	7.50	0.230	6.91	0.399	6.66	0.159	6.69	0.346	4.92	0.150
12F	no sample	no sample	4.24	0.169	no sample	no sample	7.28	0.076	no sample	no sample
13A	3.27	0.325	3.17	1.007	no sample	no sample	2.33	0.065	6.59	0.664
13B	2.23	0.913	no sample	no sample	2.11	0.323	3.29	0.429	5.50	0.164
13C	2.70	0.248	3.07	0.278	2.91	0.072	2.63	0.106	2.88	0.268
14A	3.30	0.603	no sample	no sample	no sample	no sample	3.42	0.314	2.32	0.706
14B	4.42	0.706	3.43	0.376	5.07	1.106	2.32	0.413	4.00	0.690
14C	no sample	no sample	2.72	0.544	no sample	no sample	2.57	0.235	no sample	no sample
15A	3.19	0.241	1.63	0.178	2.83	0.111	4.76	1.646	2.41	0.310
15B	3.45	0.236	5.38	0.374	no sample	no sample	3.94	0.226	3.19	0.241
16A	2.52	0.556	2.77	0.248	2.54	0.090	2.53	0.082	2.40	0.431
17A	10.56	1.101	6.69	0.532	3.00	0.265	5.61	0.702	9.08	0.104
17B	4.52	0.127	2.81	0.097	no sample	no sample	2.69	0.240	2.61	0.119

APPENDIX C
Particle Size Distribution Graphs for the Sediments Tested

Of the **Draft** Final Report on

A Study of Bankfull Culvert Design Effectiveness

By: Mark A. Tumeo, Ph.D., J.D.
Joe Pavlick, MS Student

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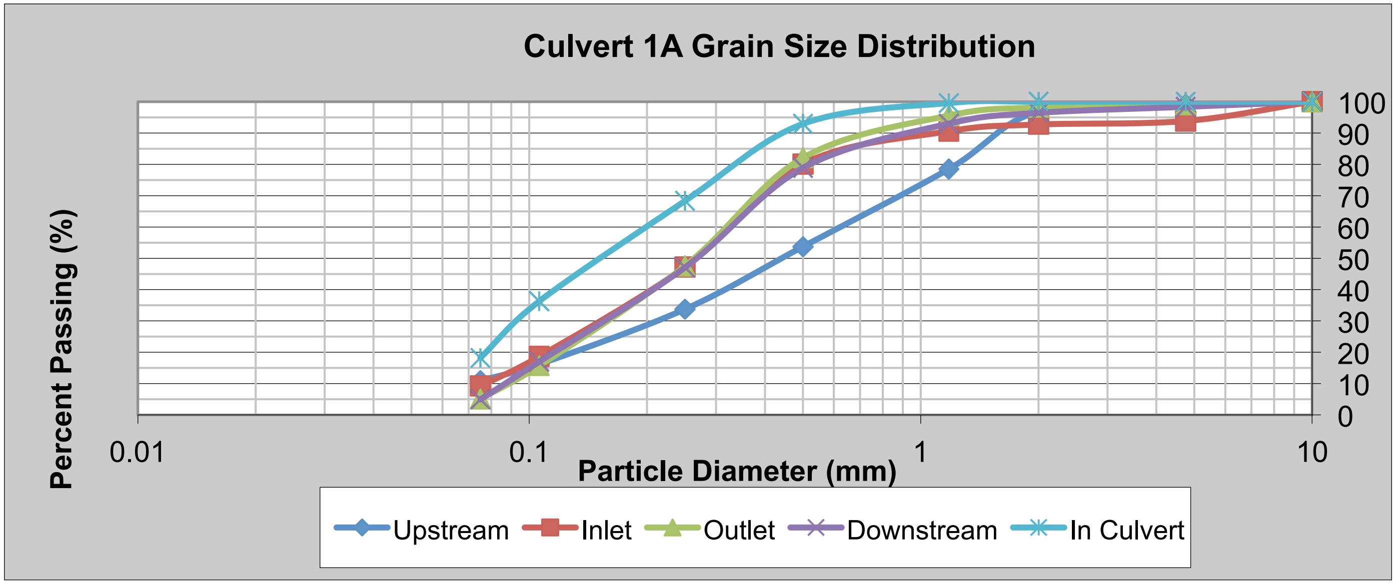
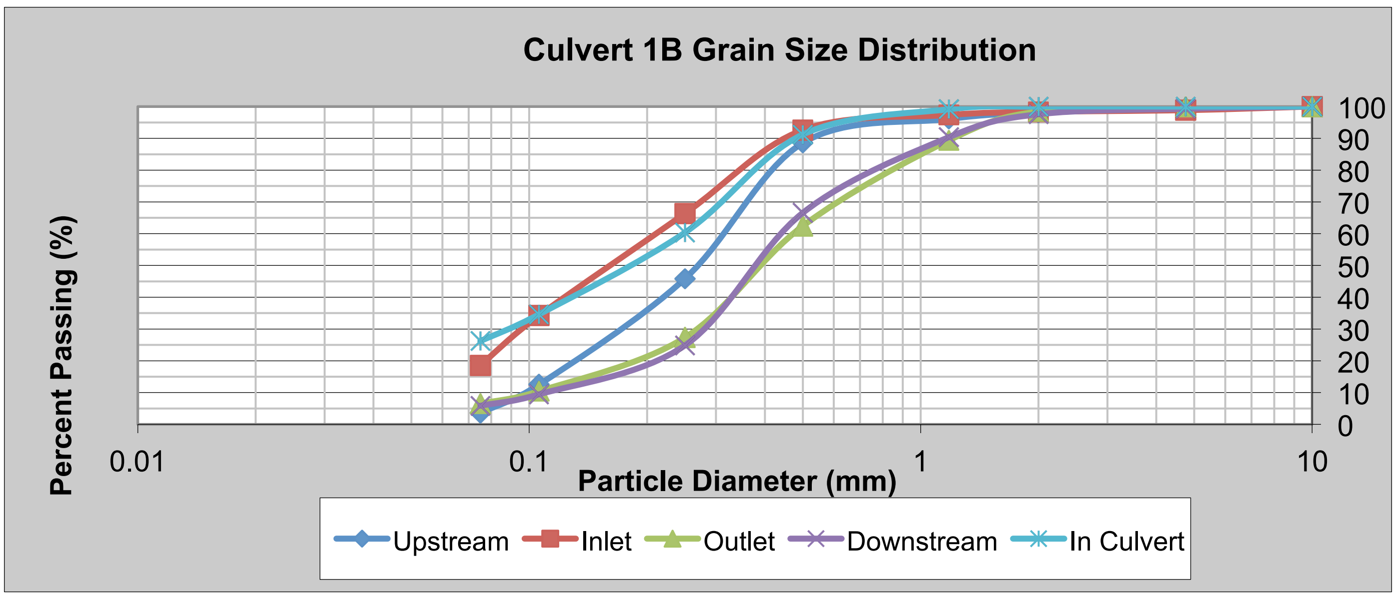
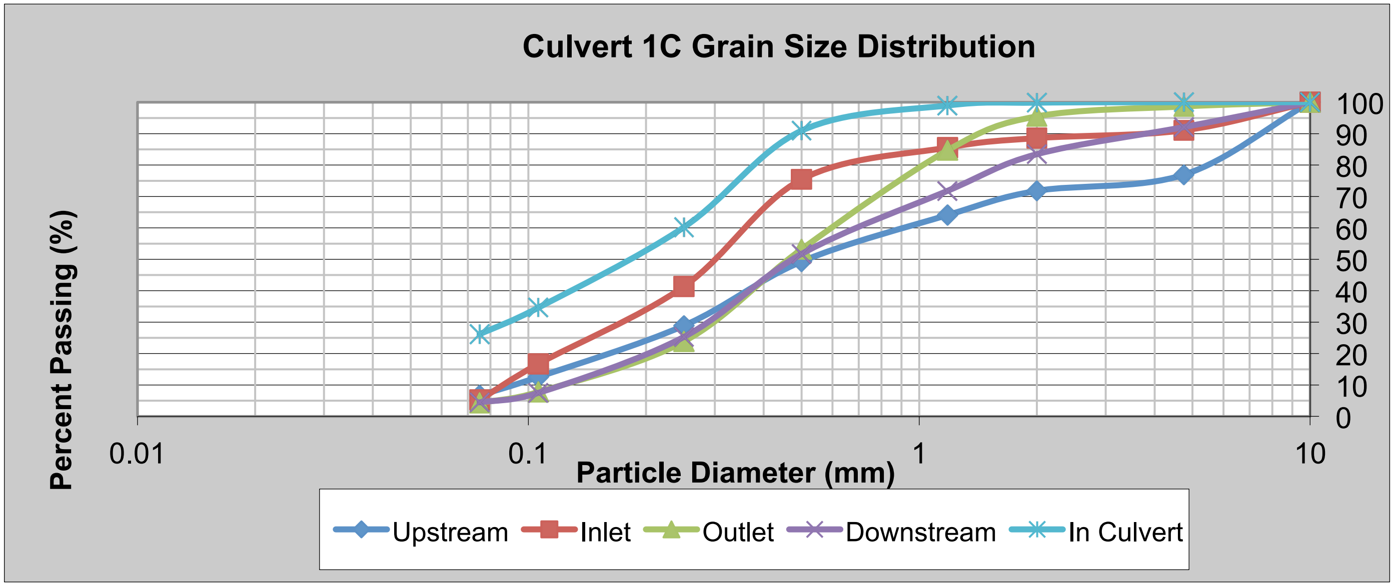
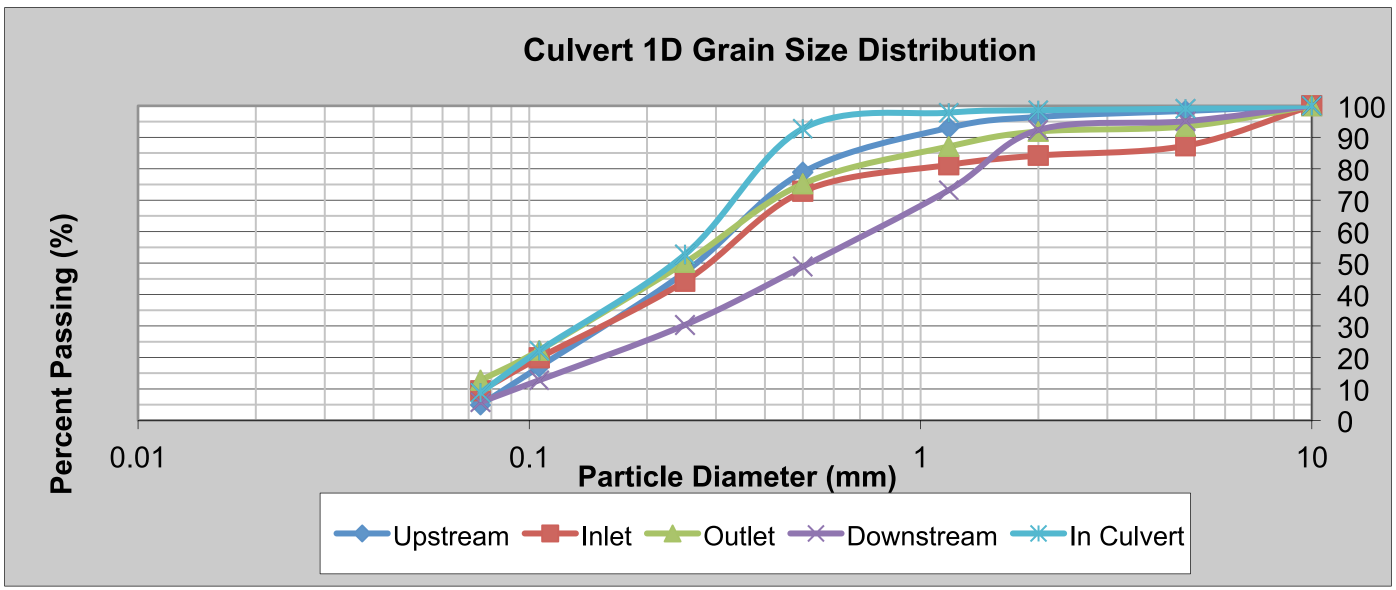
Cleveland State University


Culvert 1A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

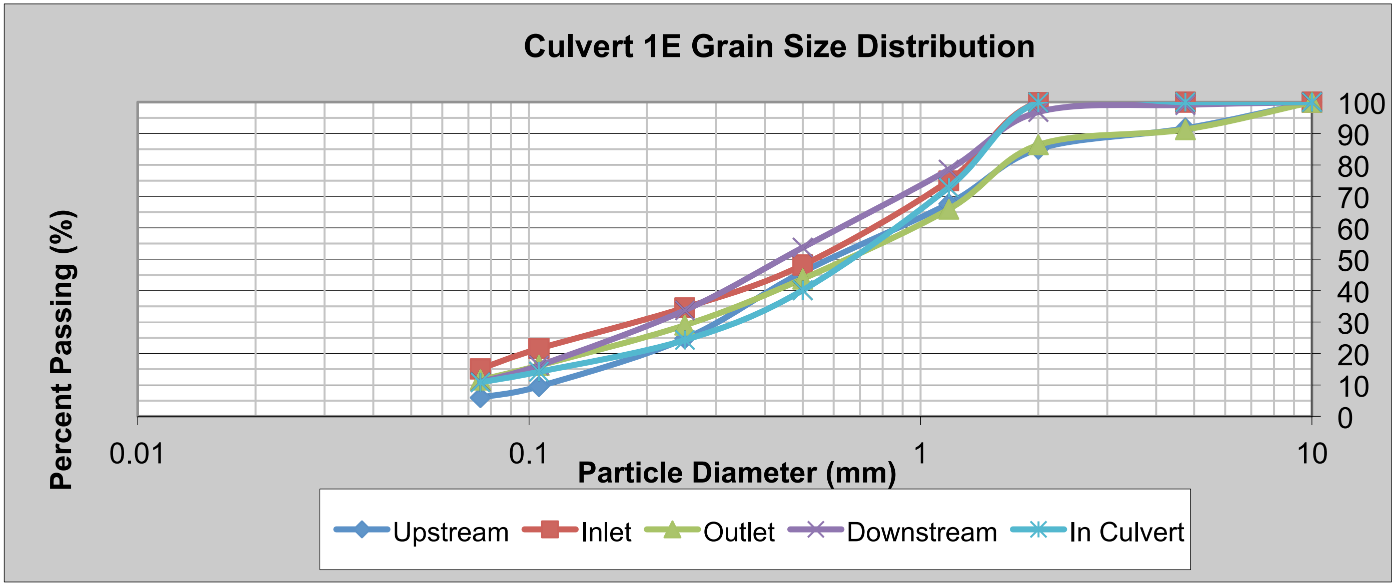

Culvert 1B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert



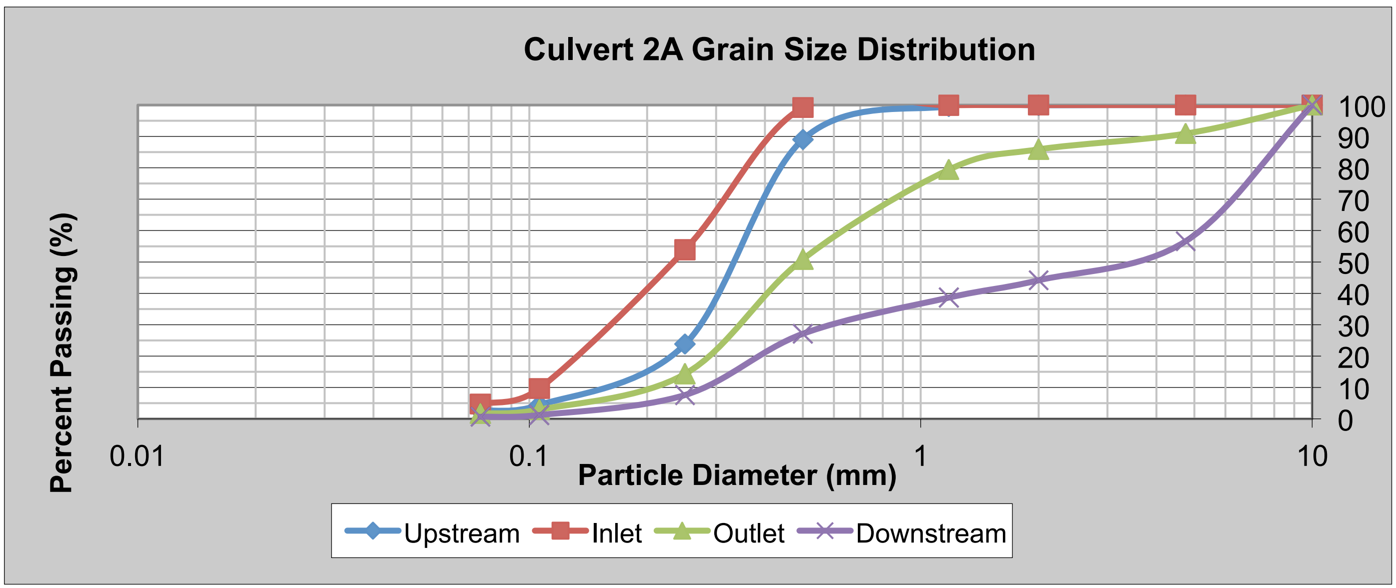
Culvert 1C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert



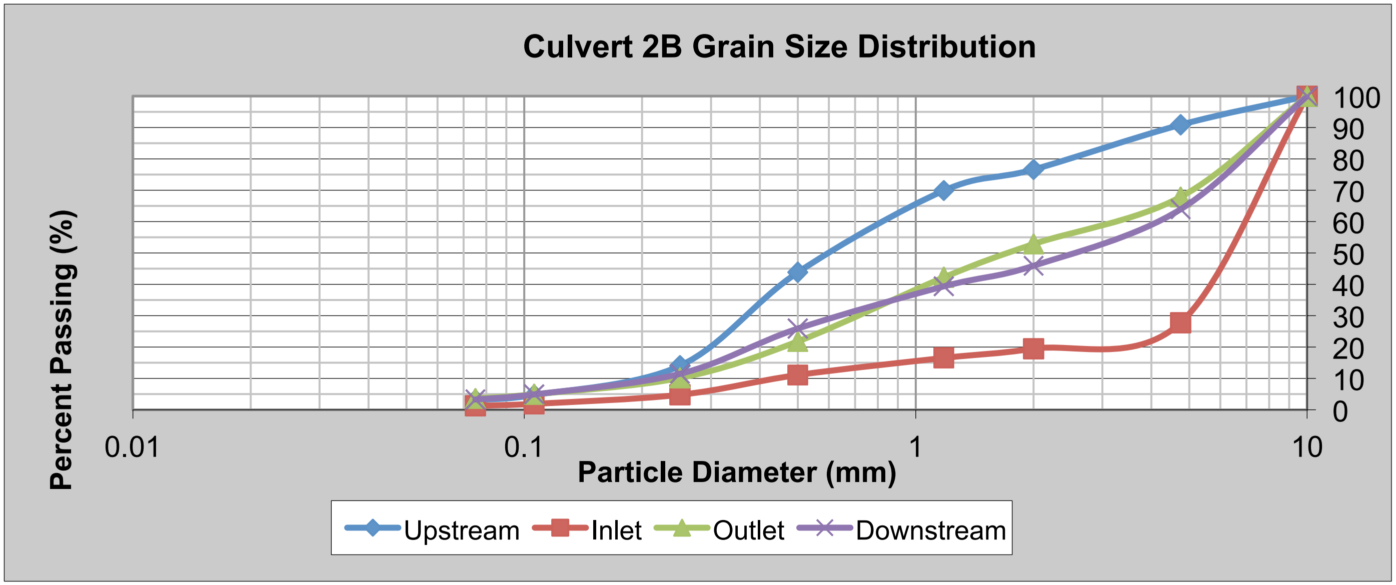
Culvert 1D Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

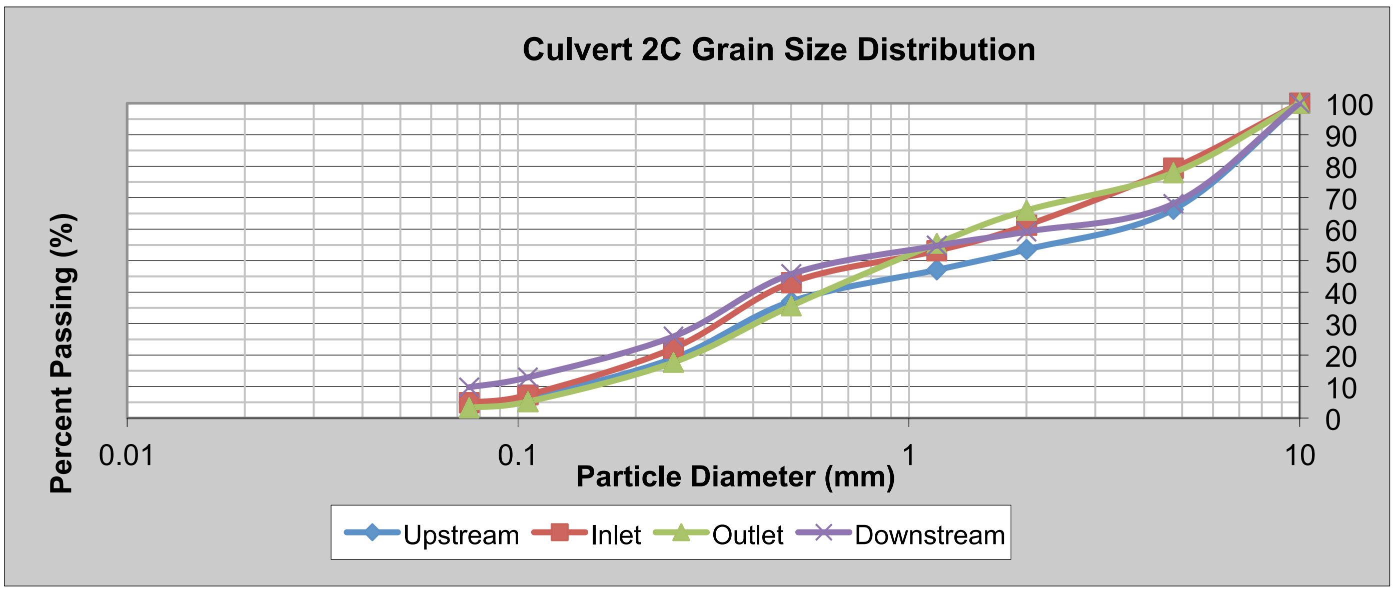


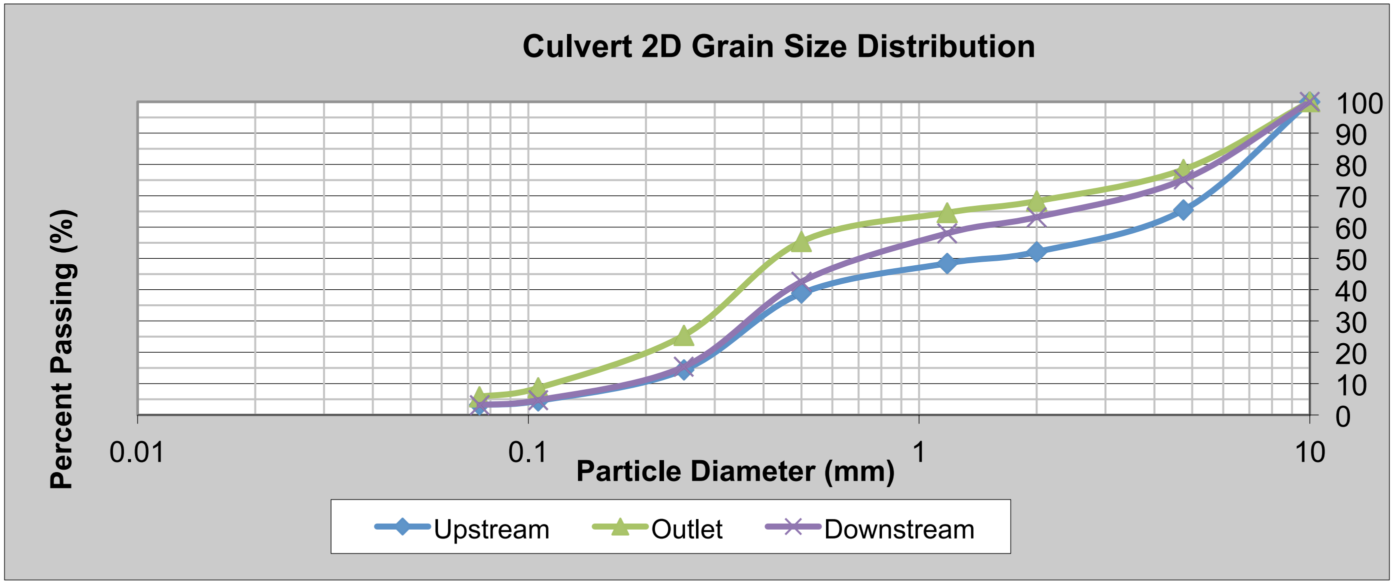
Culvert 1E Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert



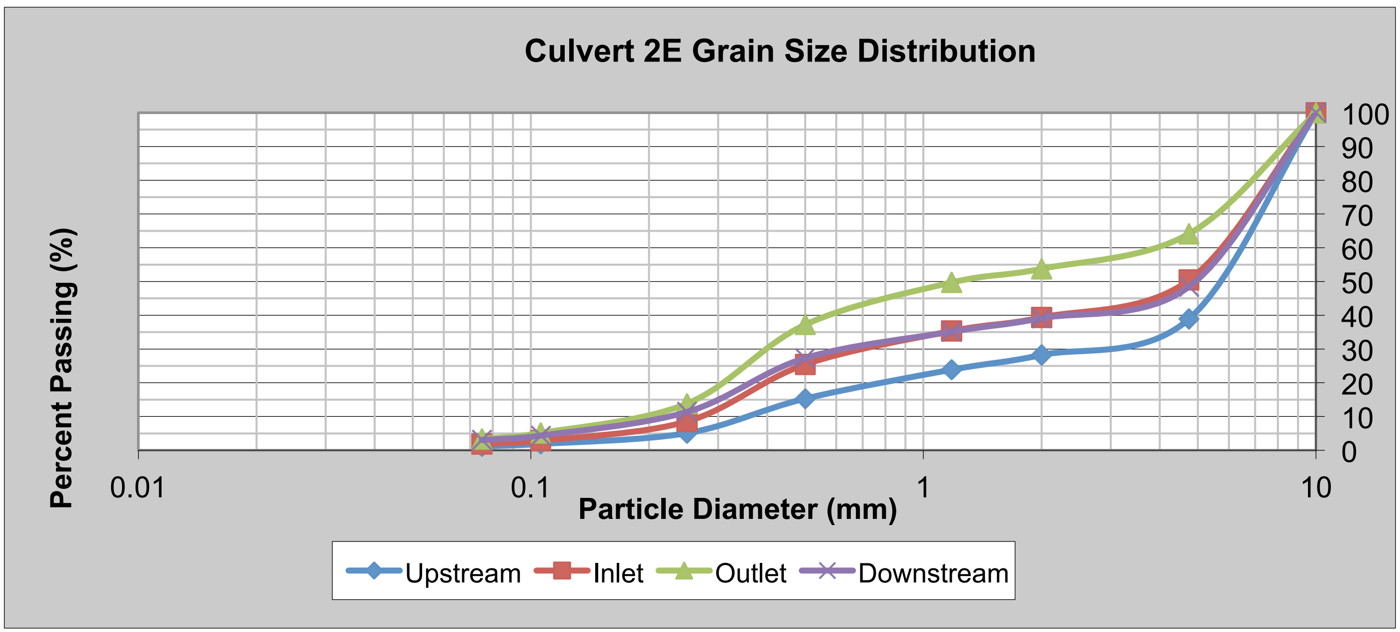
Culvert 2A Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream


Culvert 2B Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream

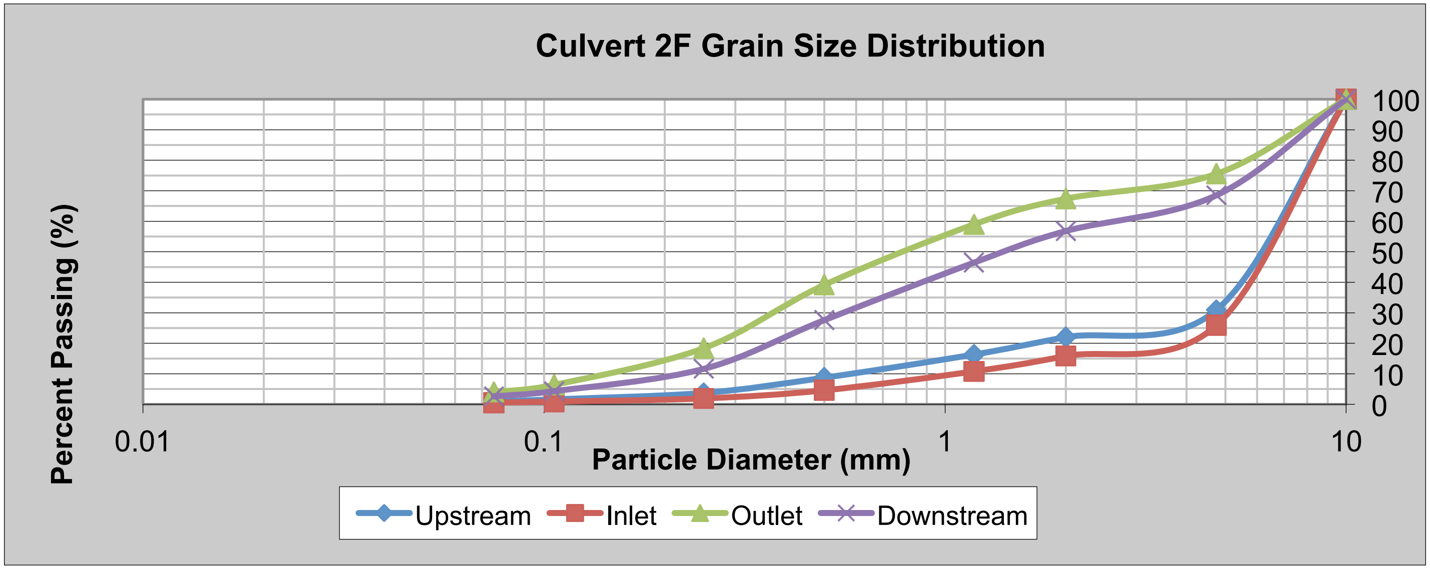

Culvert 2C Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream

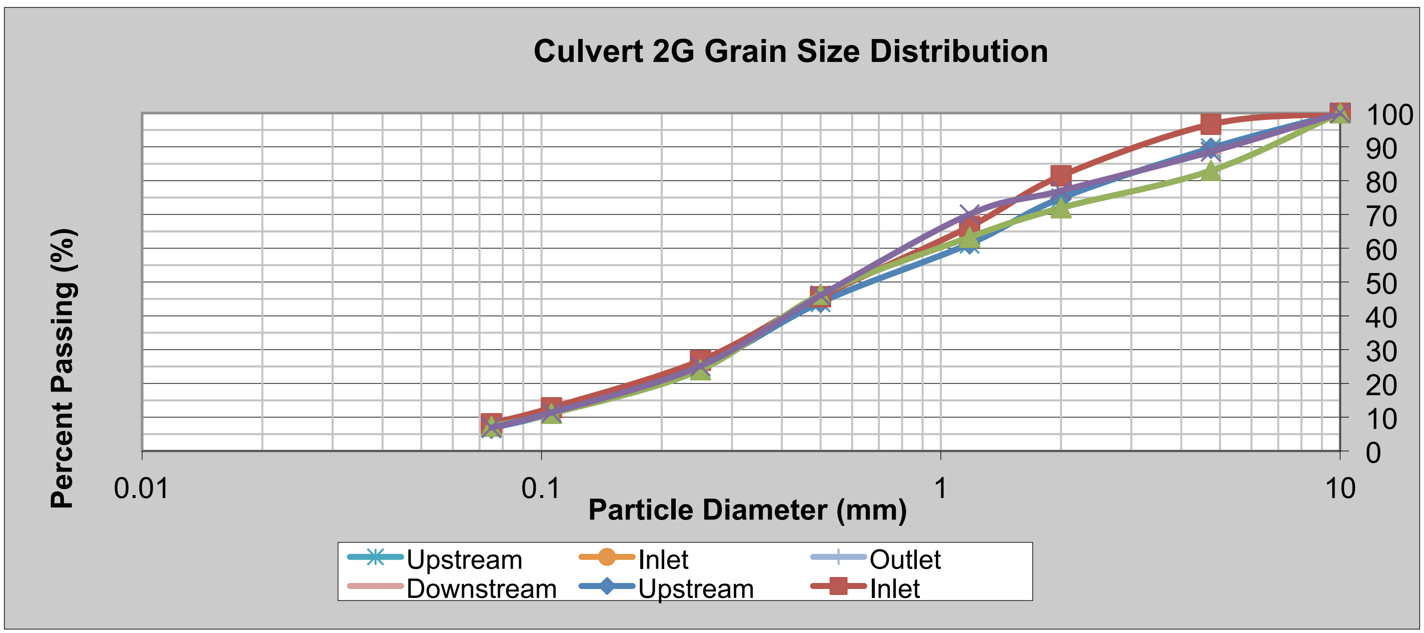


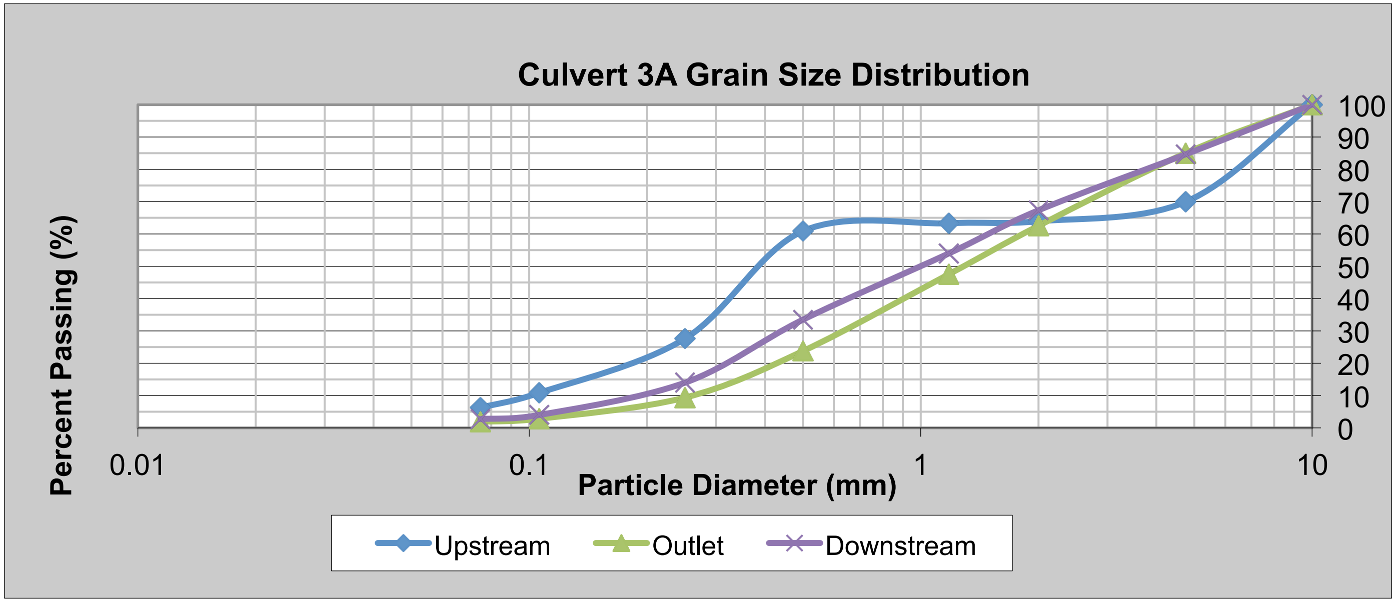
Culvert 2D Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Outlet
Downstream

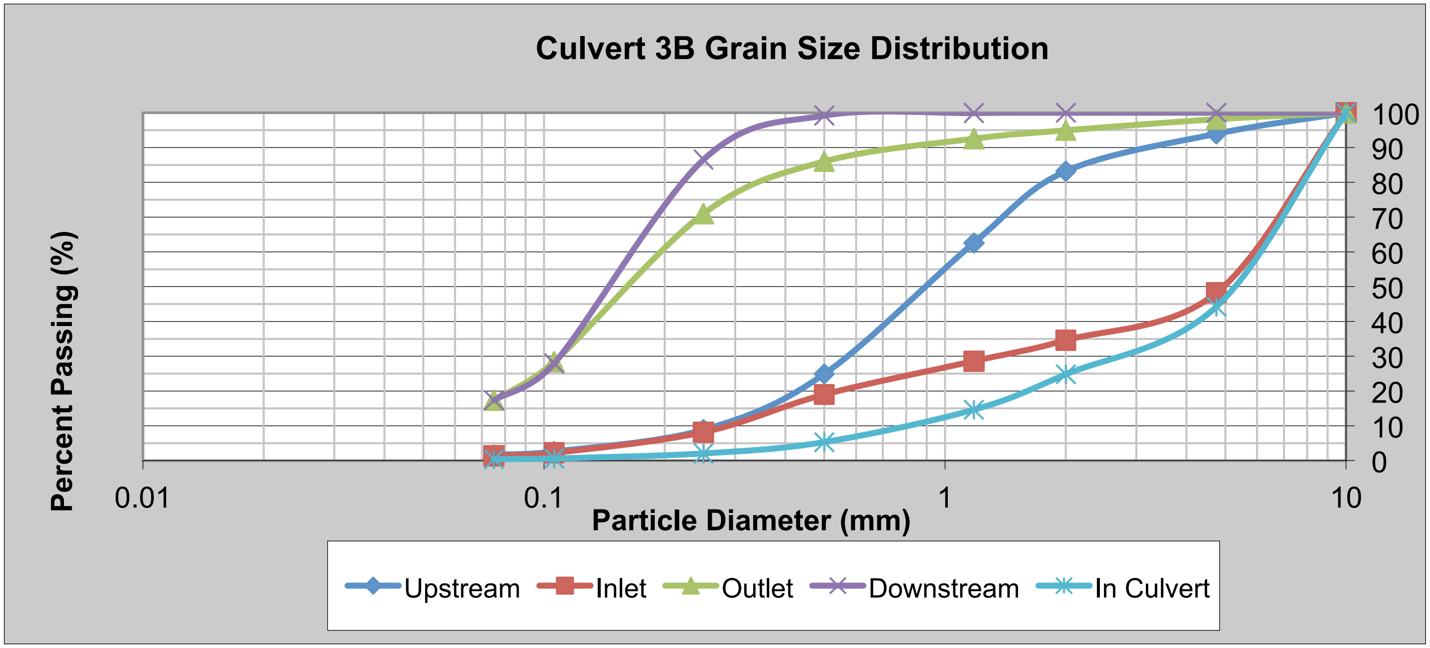


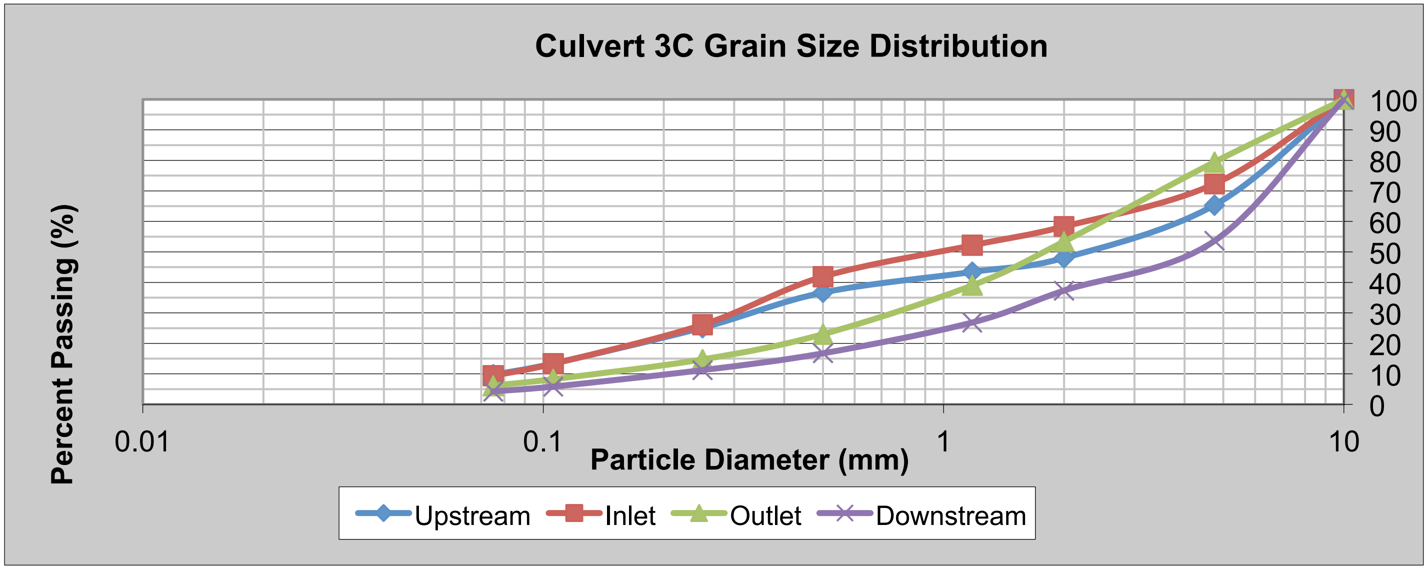
Culvert 2E Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream

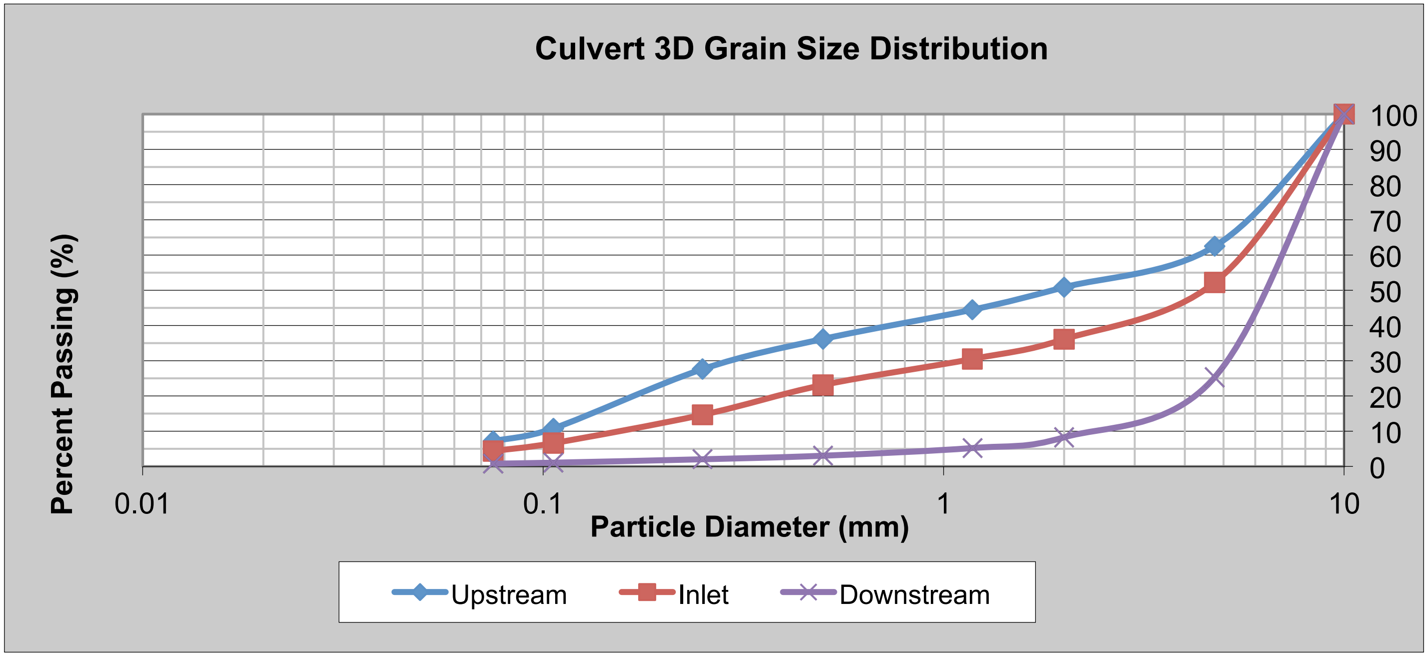

Culvert 2F Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream

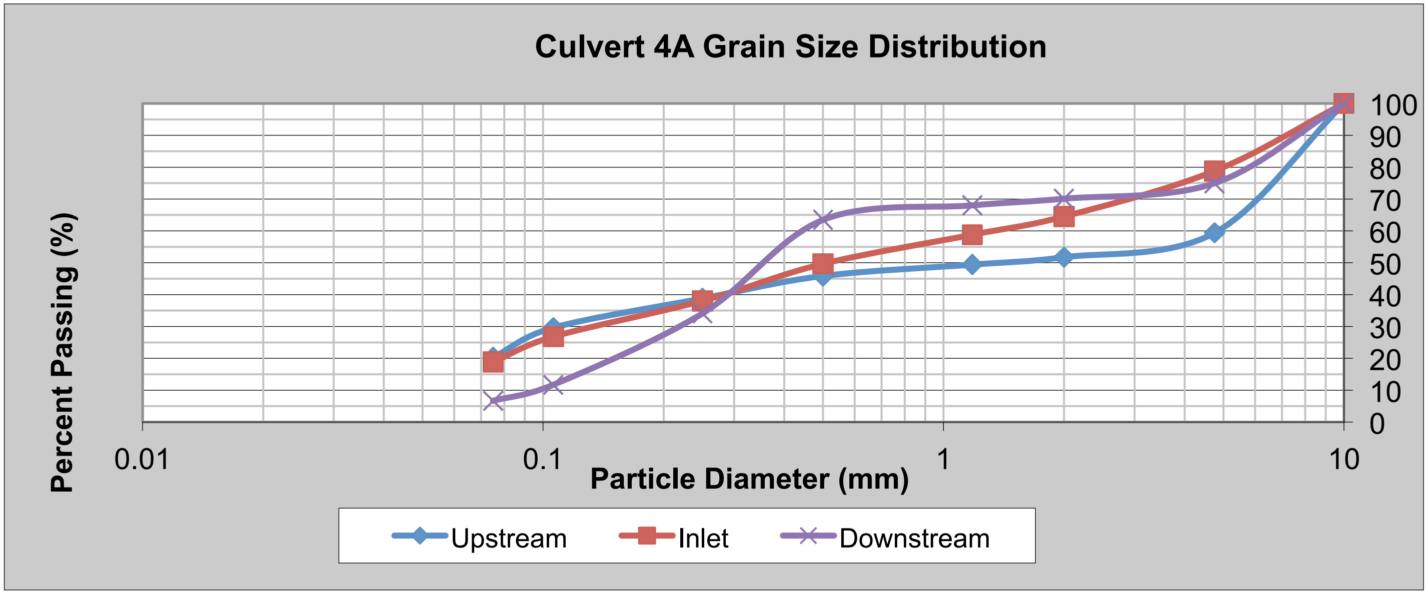

Culvert 2G Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
Upstream
Inlet

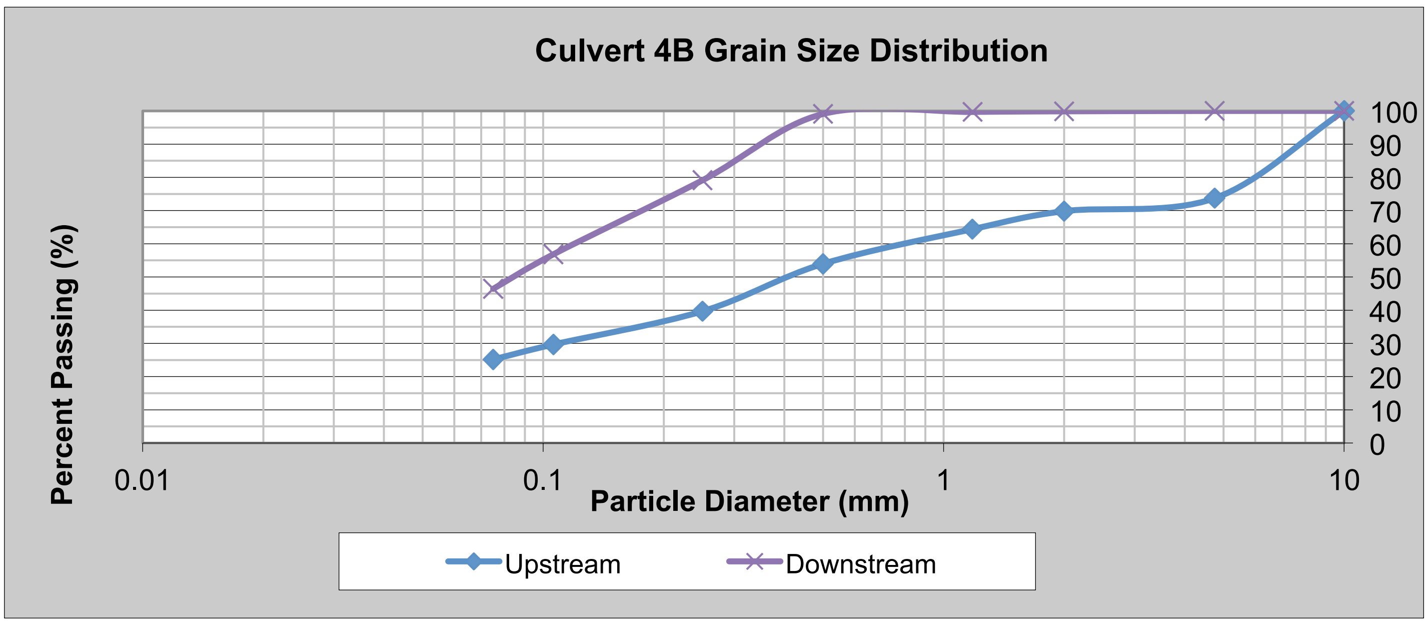

Culvert 3A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Outlet
Downstream

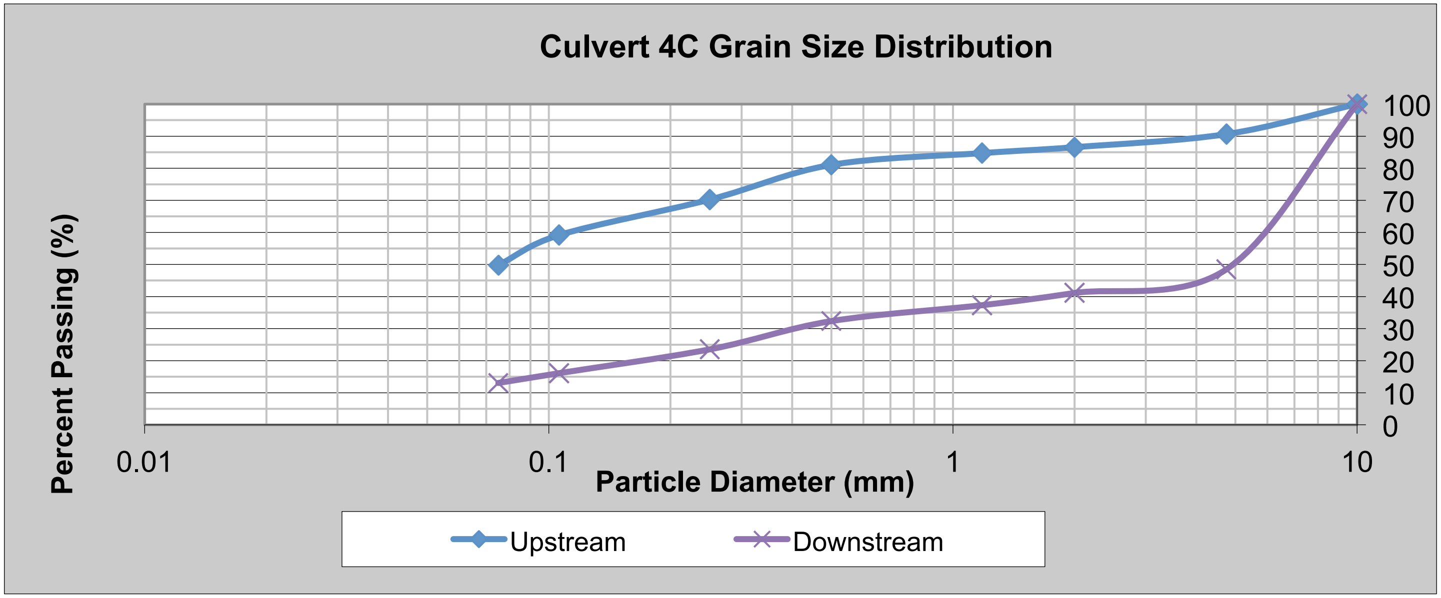

Culvert 3B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

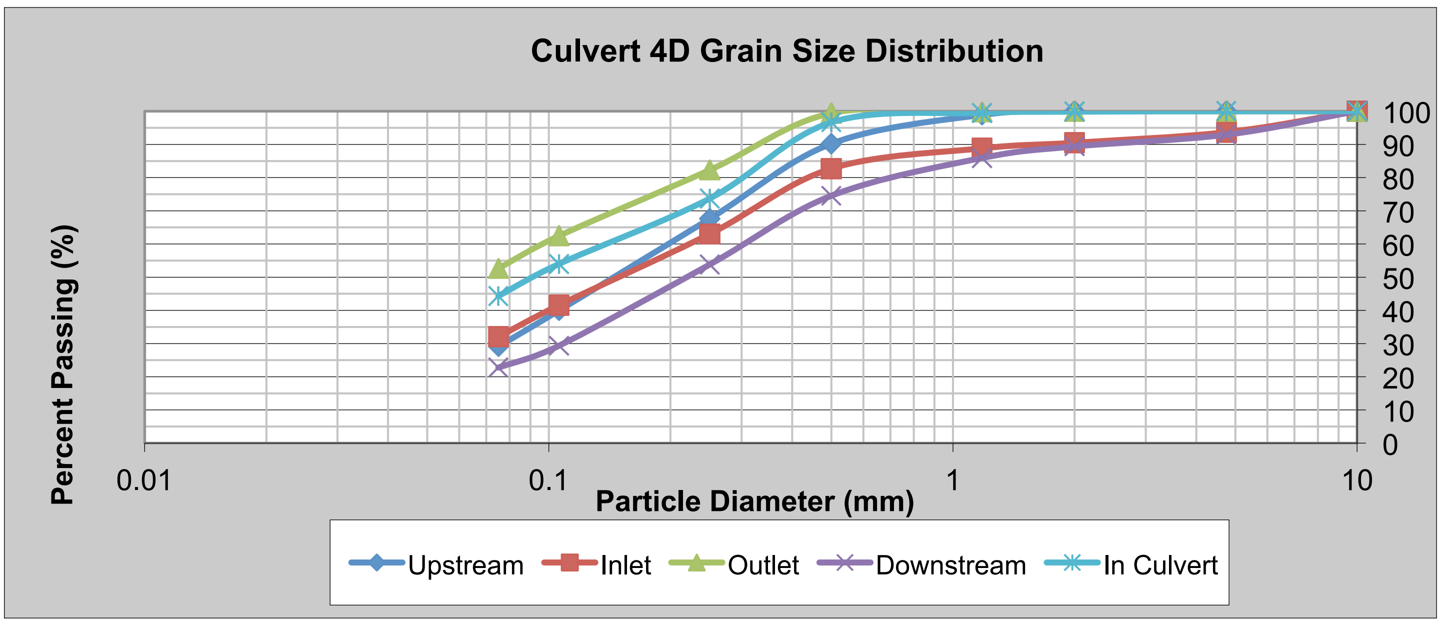

Culvert 3C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream

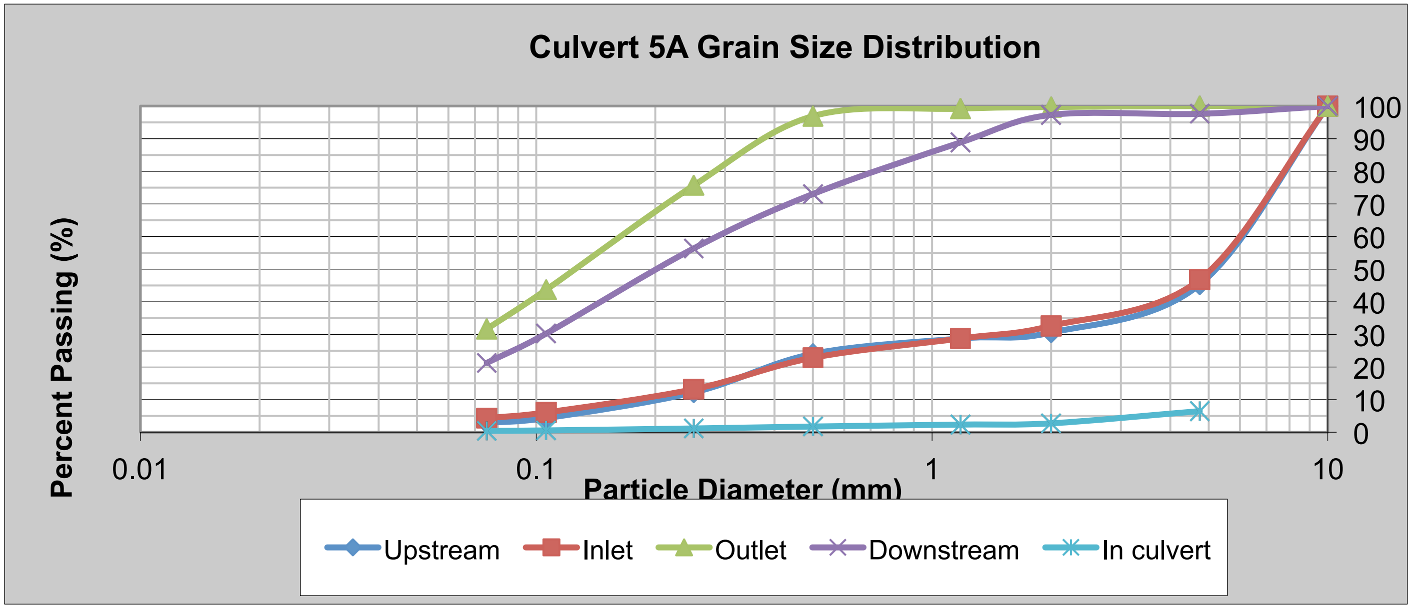

Culvert 3D Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Downstream

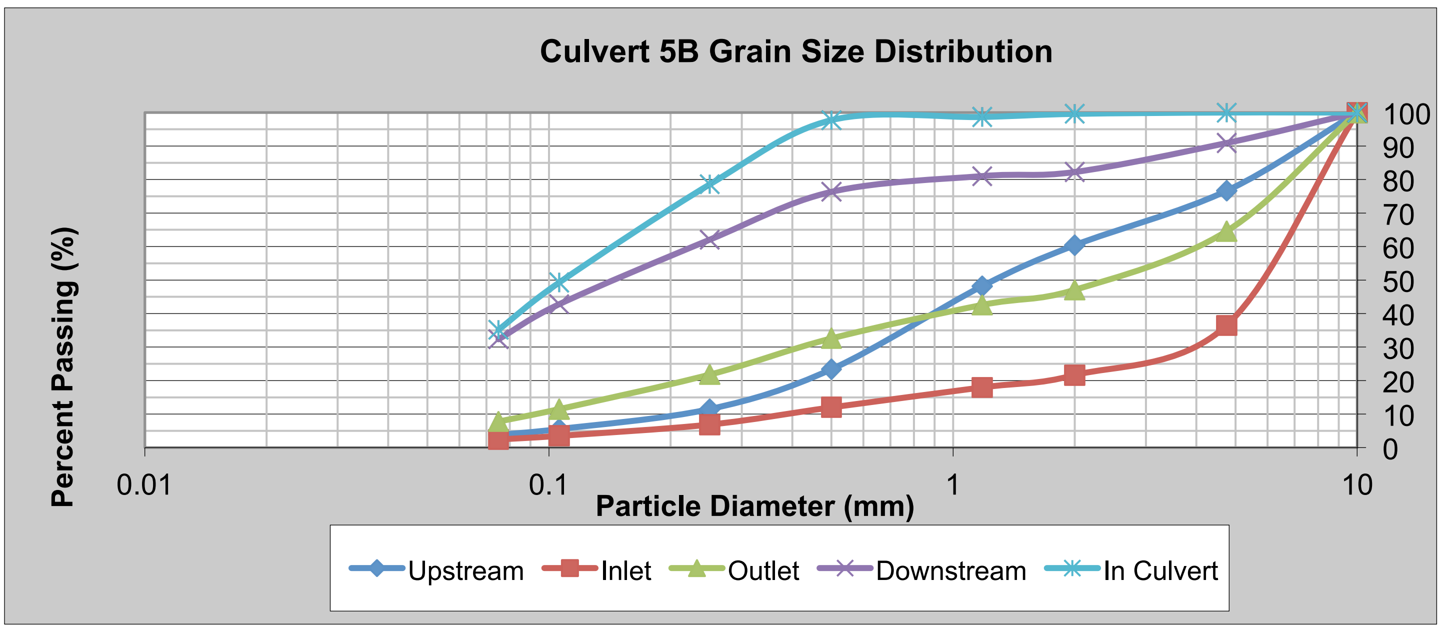

Culvert 4A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Downstream

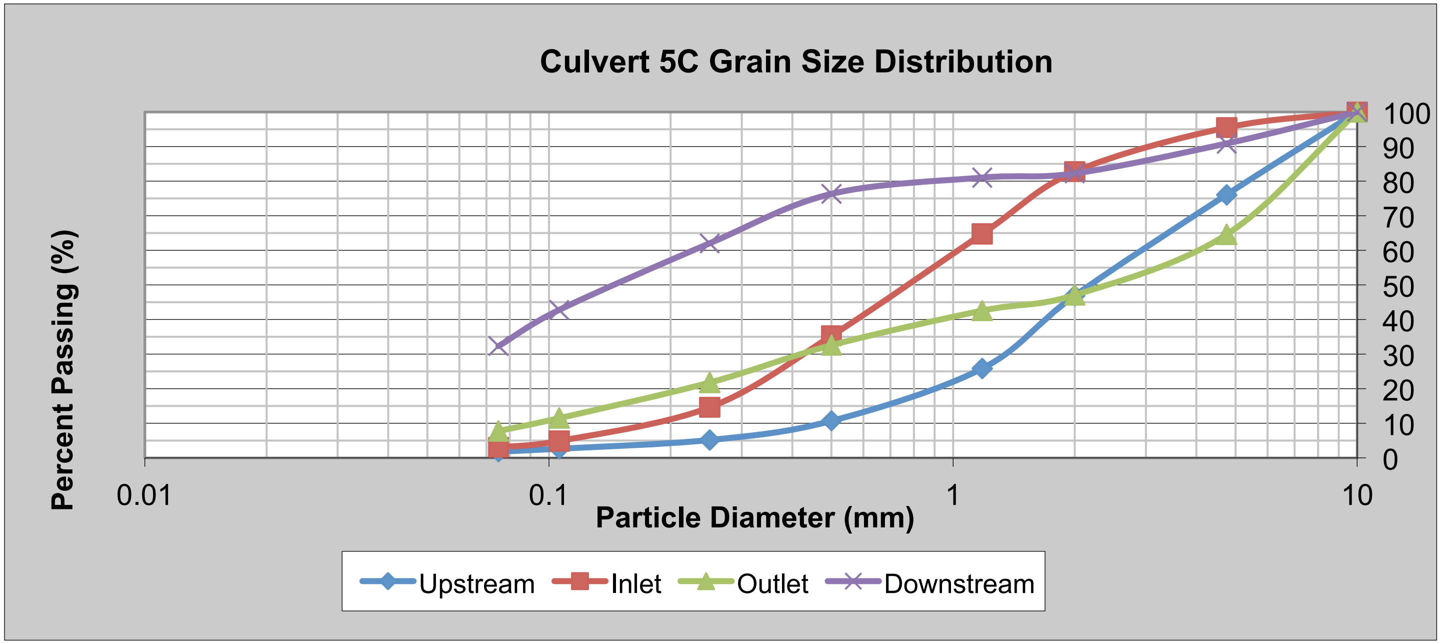

Culvert 4B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Downstream

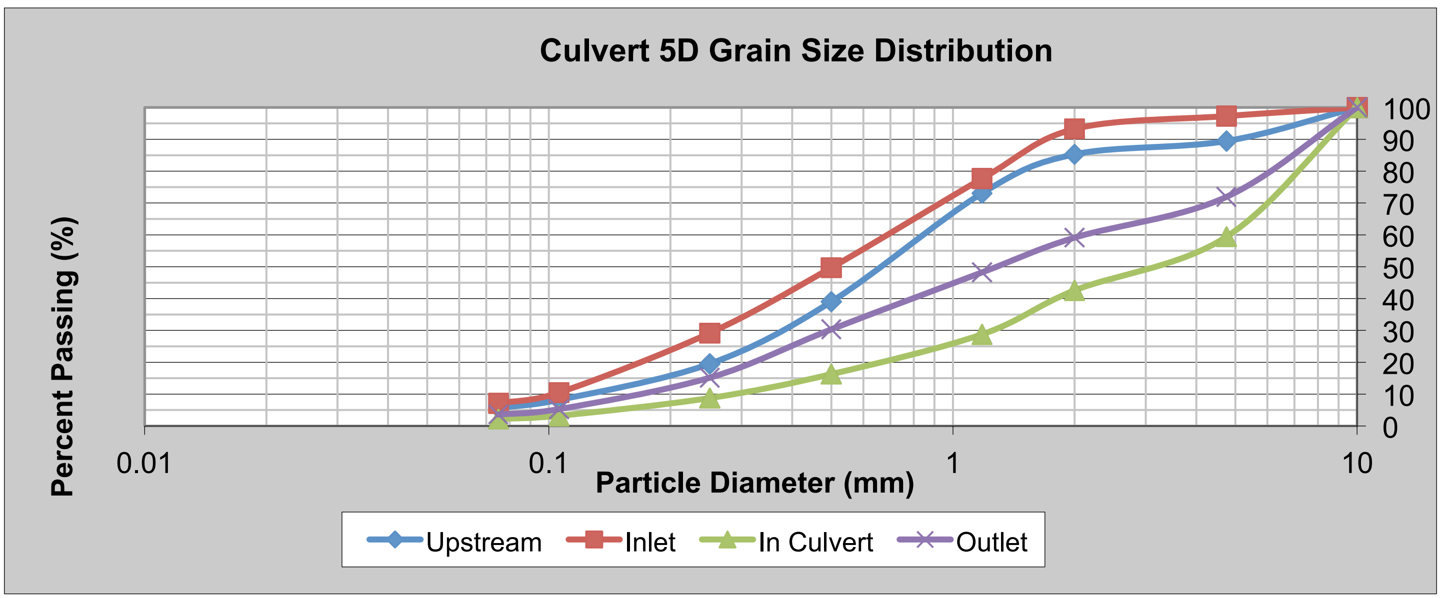

Culvert 4C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Downstream

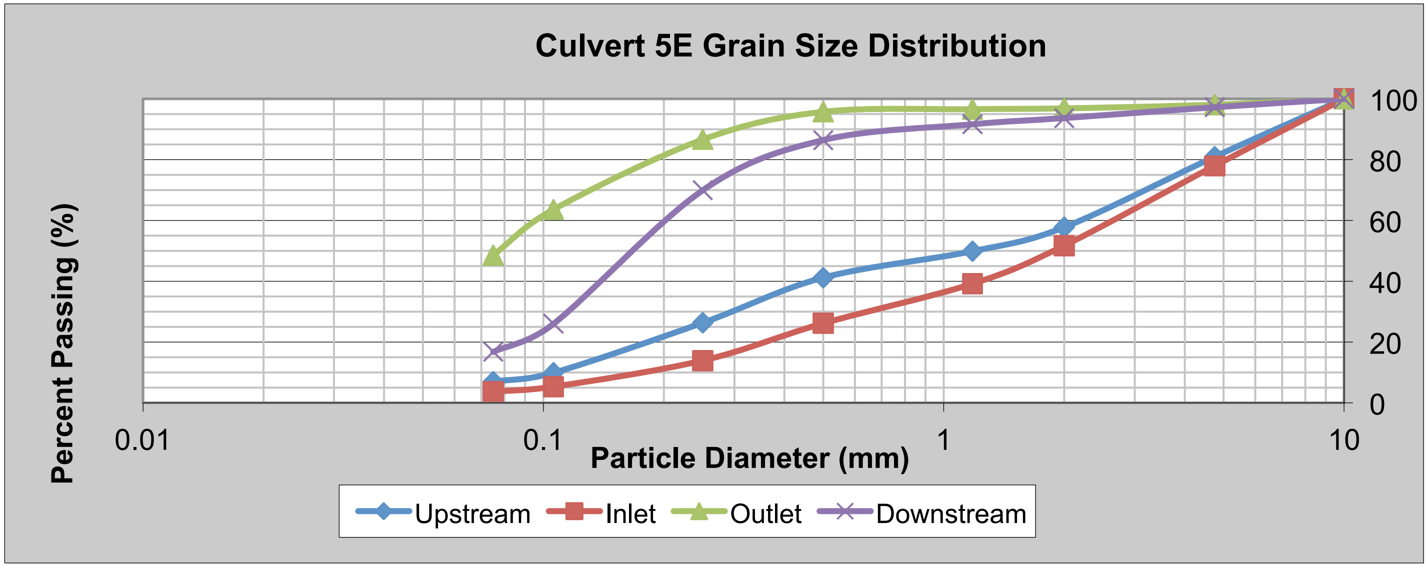

Culvert 4D Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

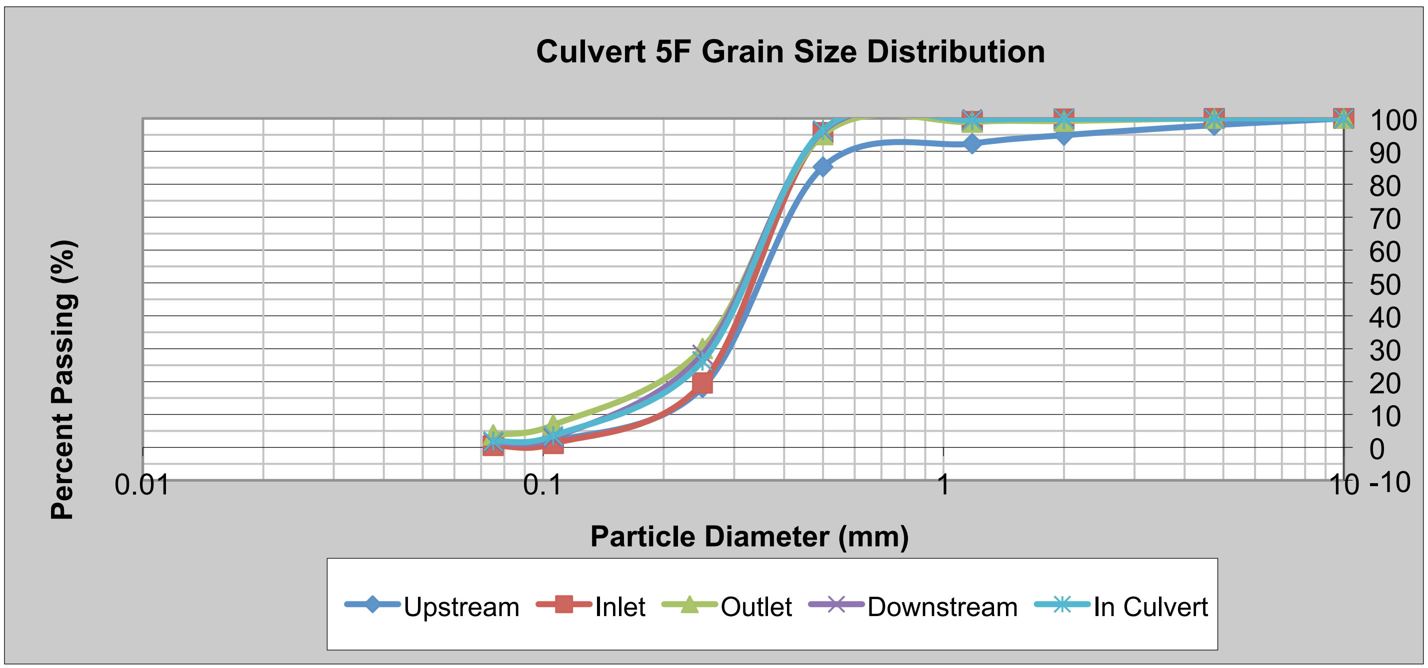

Culvert 5A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In culvert

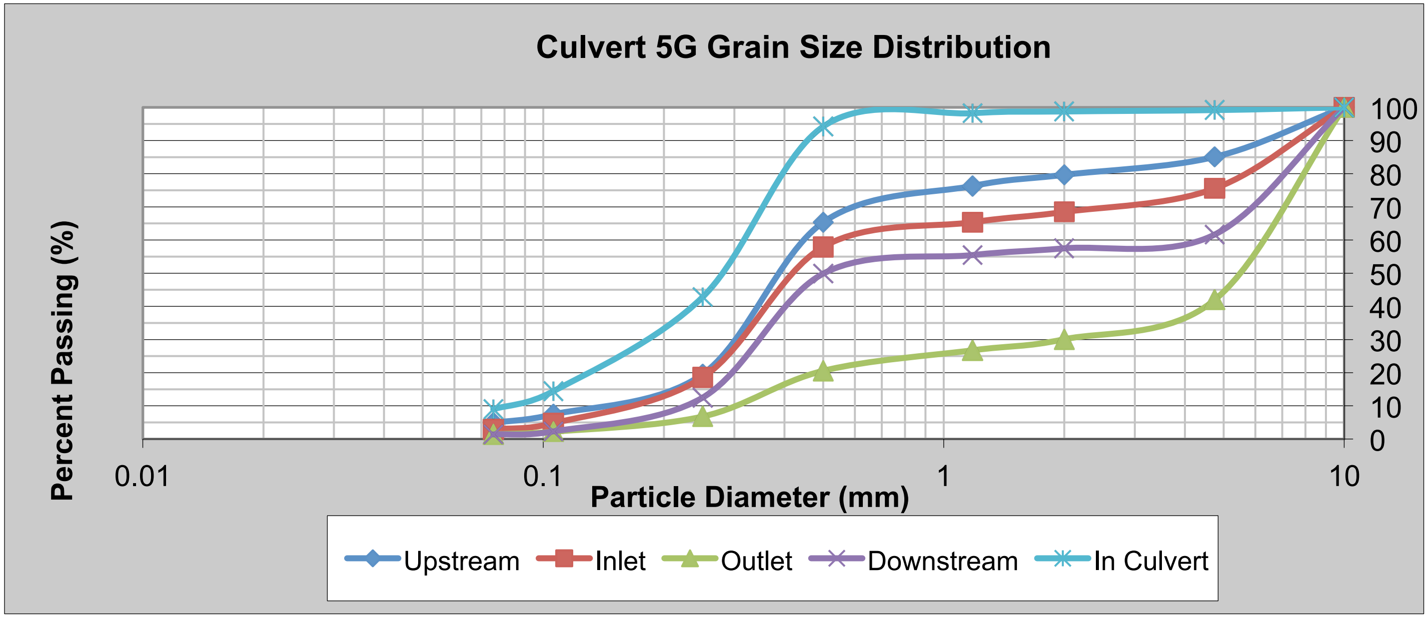

Culvert 5B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

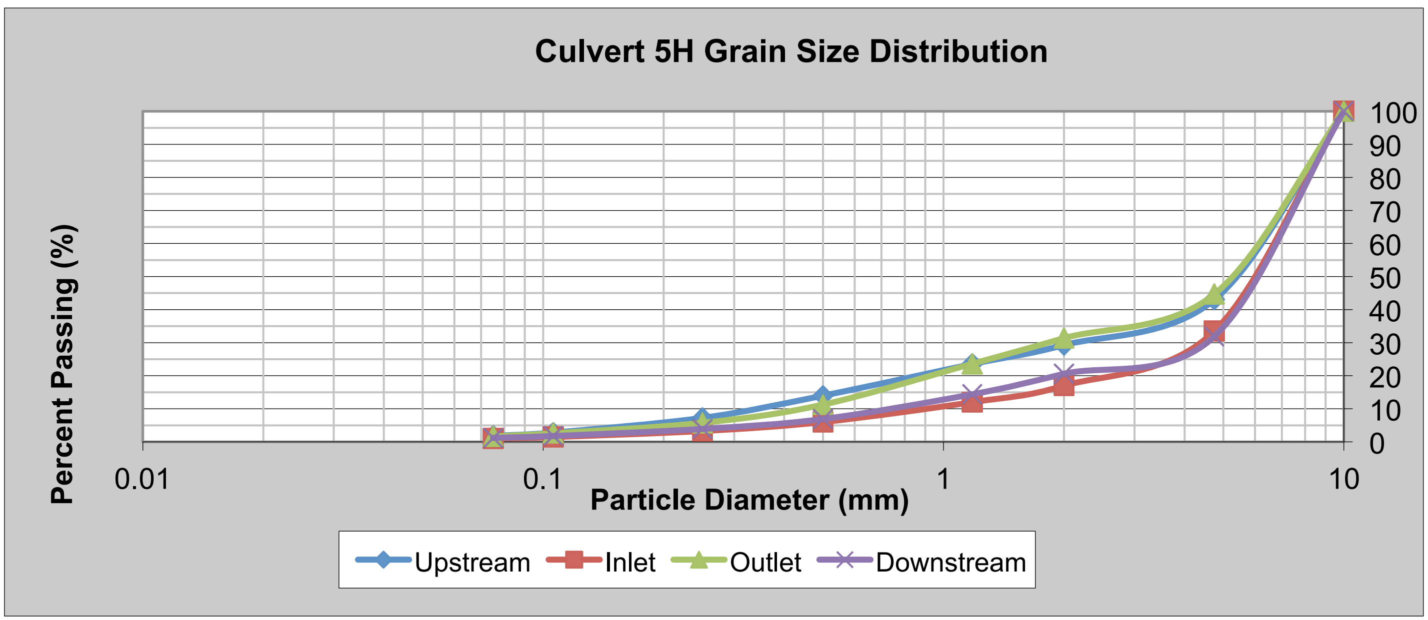

Culvert 5C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream

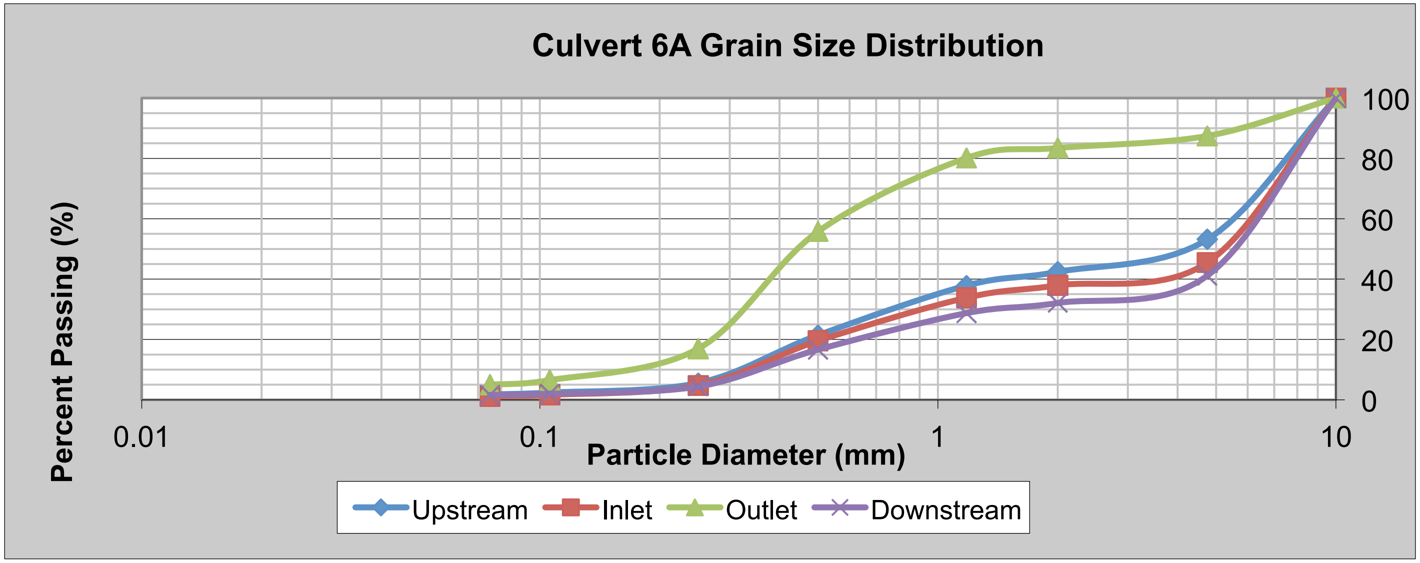

Culvert 5D Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
In Culvert
Outlet


Culvert 5E Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
20
40
60
80
100
Upstream
Inlet
Outlet
Downstream

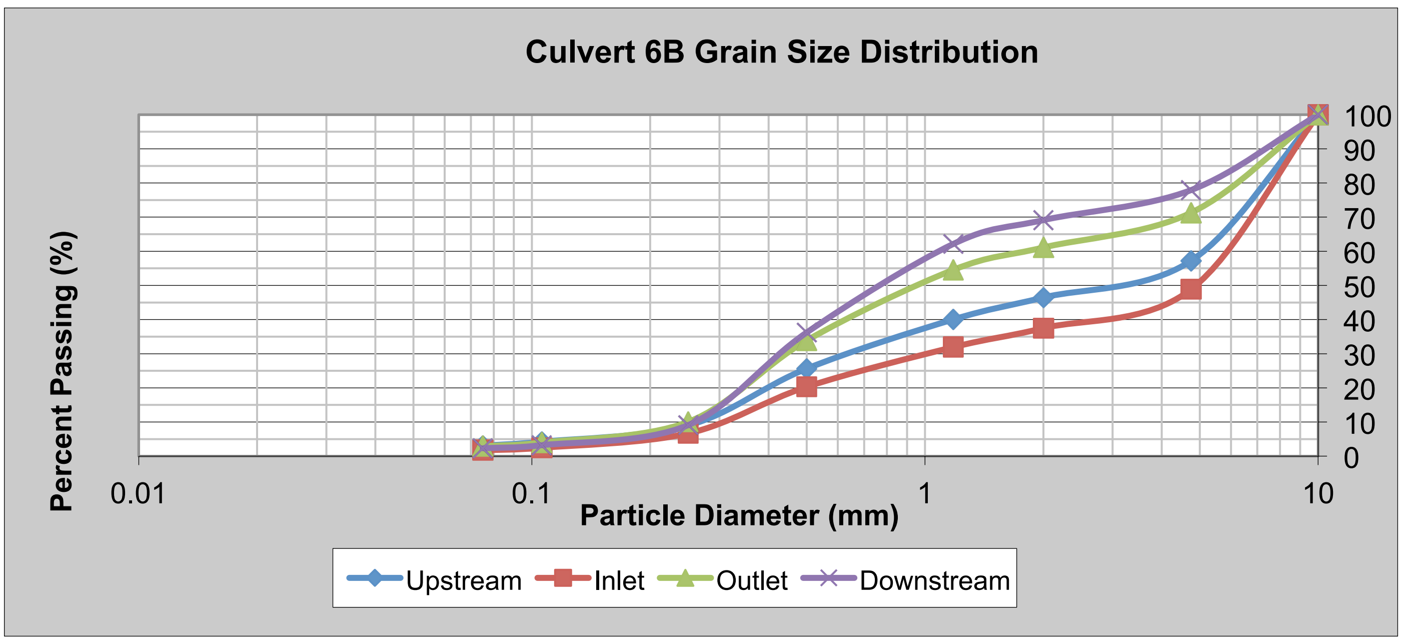

Culvert 5F Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
-10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert


Culvert 5G Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
100
90
80
70
60
50
40
30
20
10
0
Upstream
Inlet
Outlet
Downstream
In Culvert

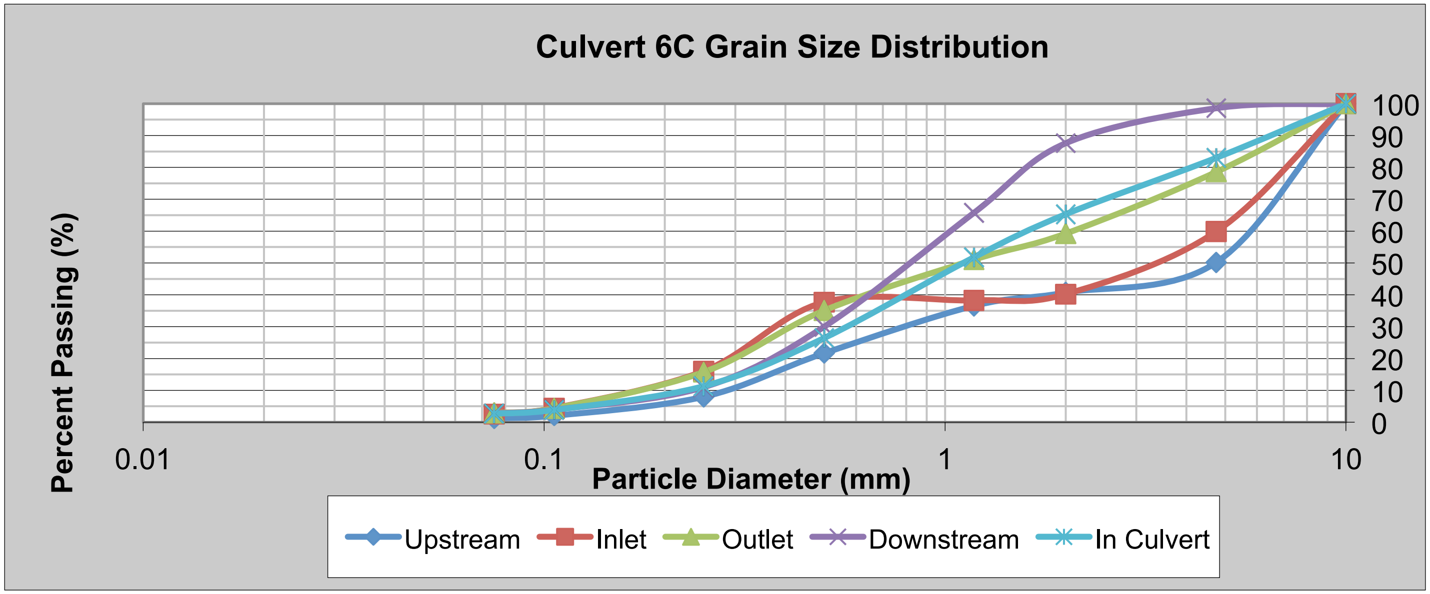

Culvert 5H Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
100
90
80
70
60
50
40
30
20
10
0
Upstream
Inlet
Outlet
Downstream

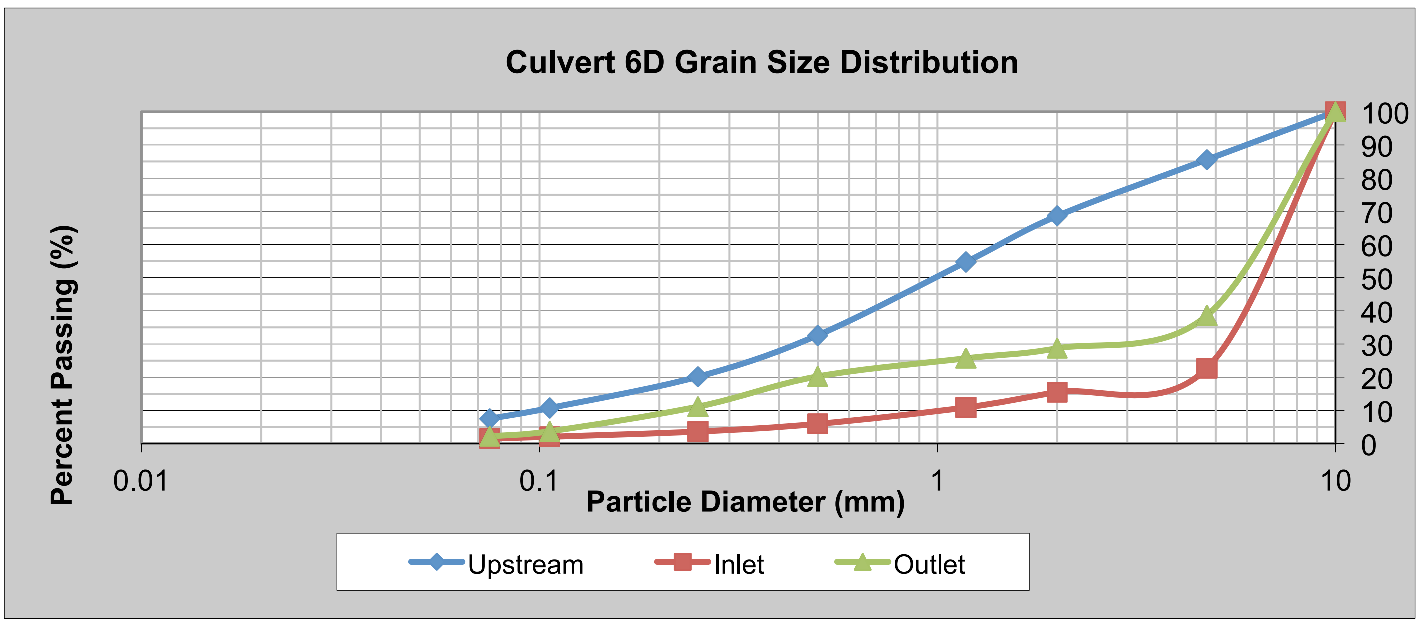


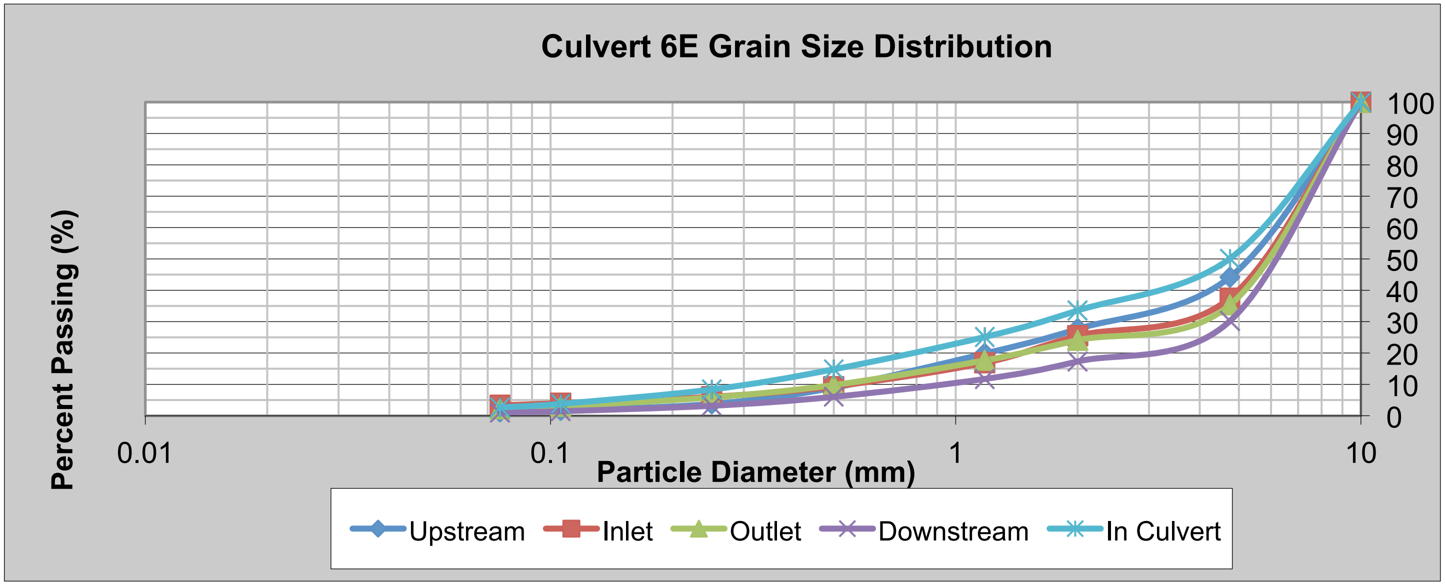
Culvert 6A Grain Size Distribution
Percent Passing (%)
100
80
60
40
20
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream



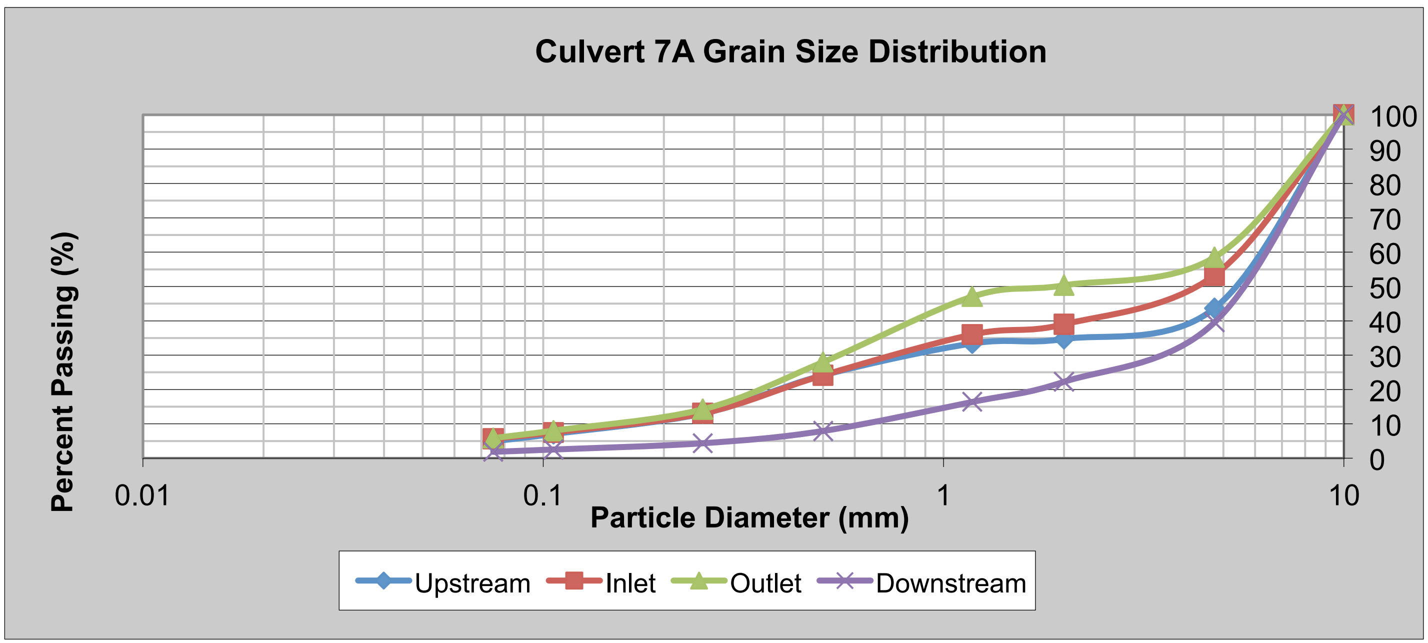
Culvert 6B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream


Culvert 6C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

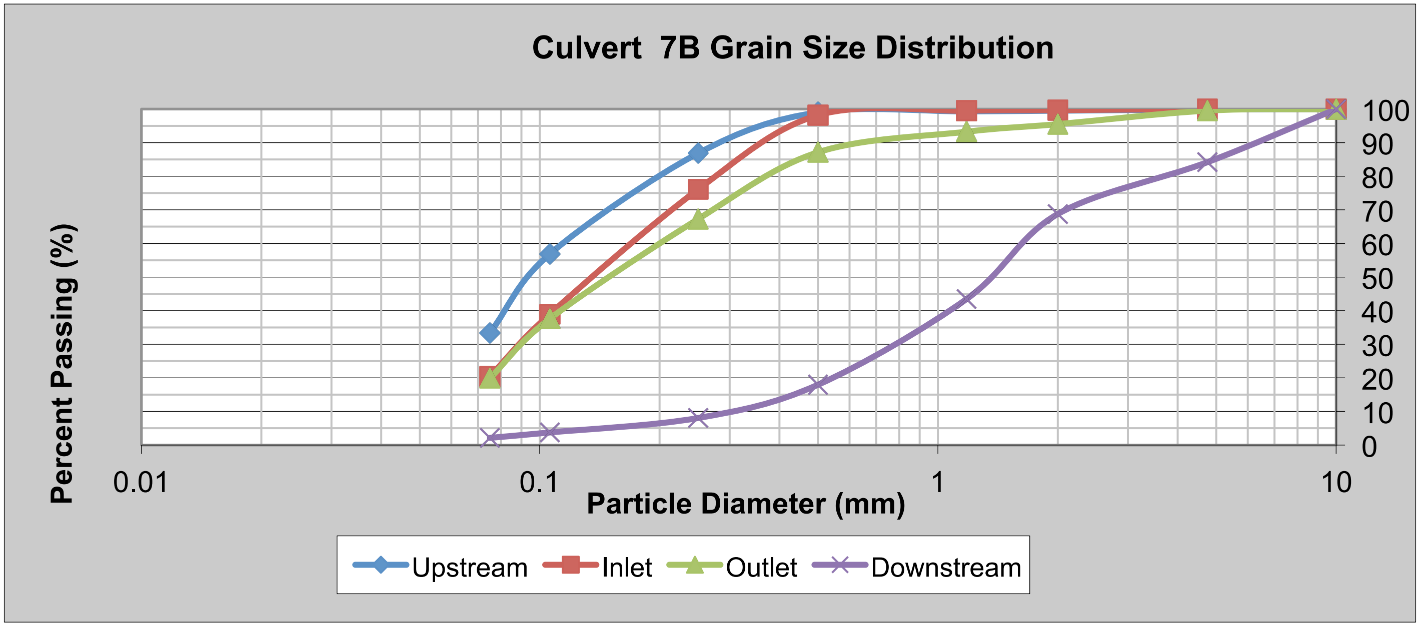

Culvert 6D Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet

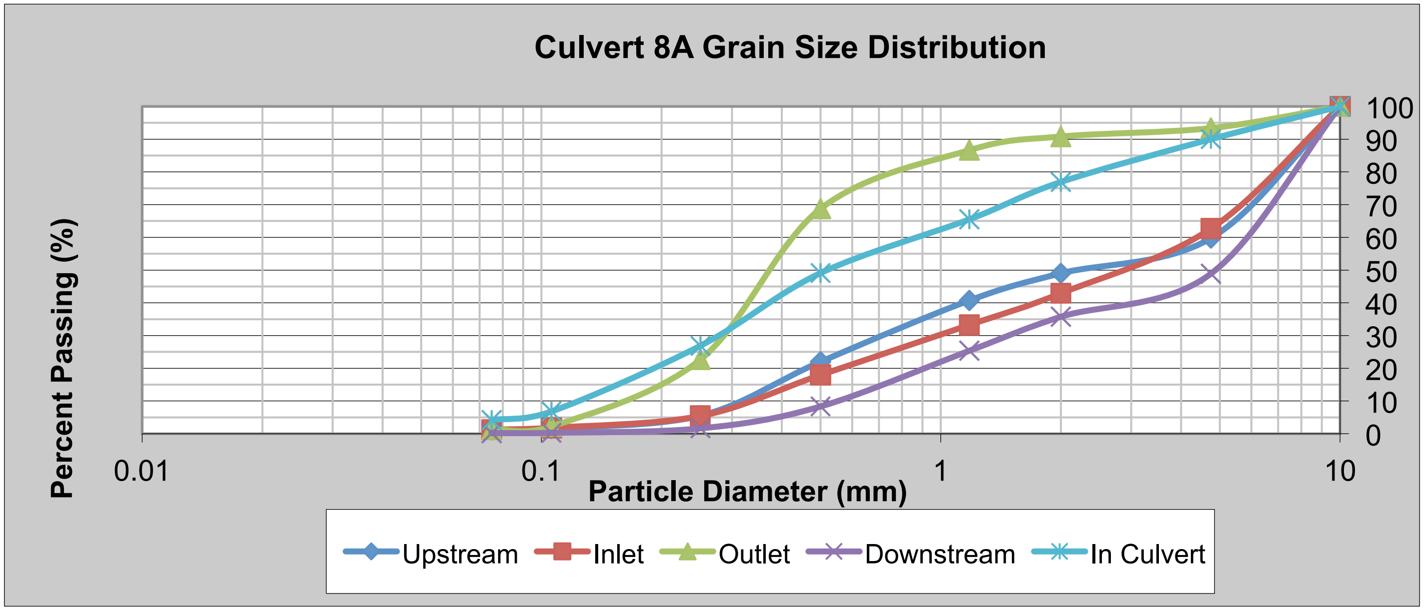


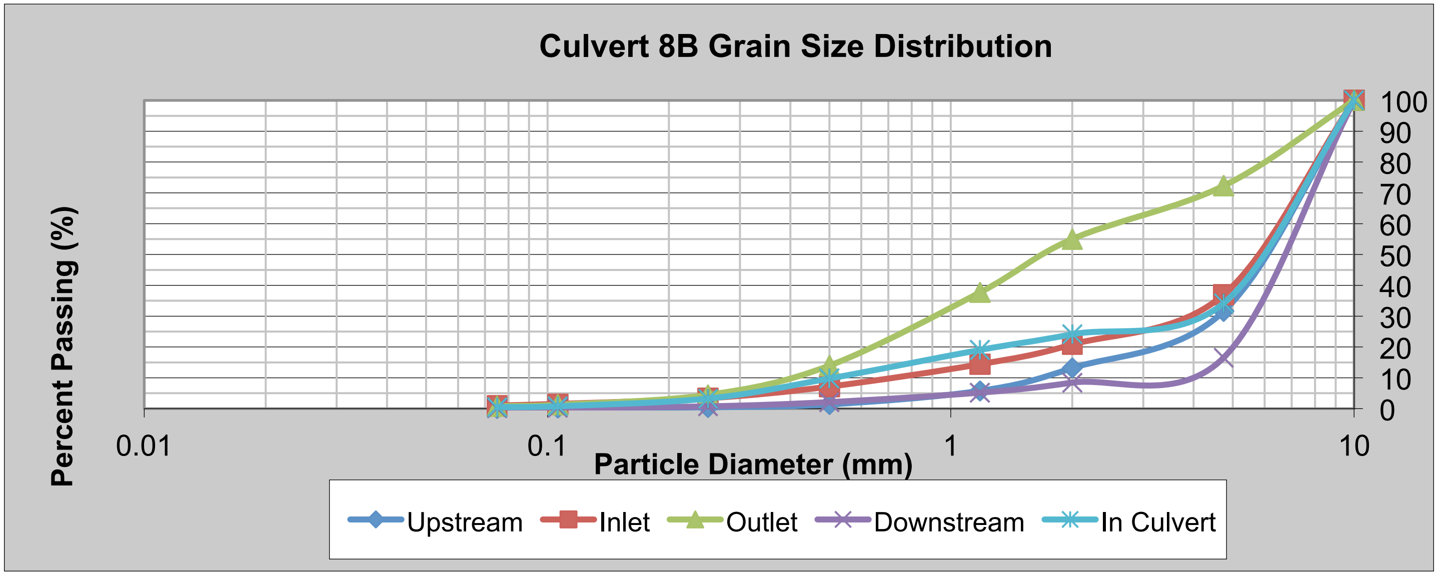
Culvert 6E Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert



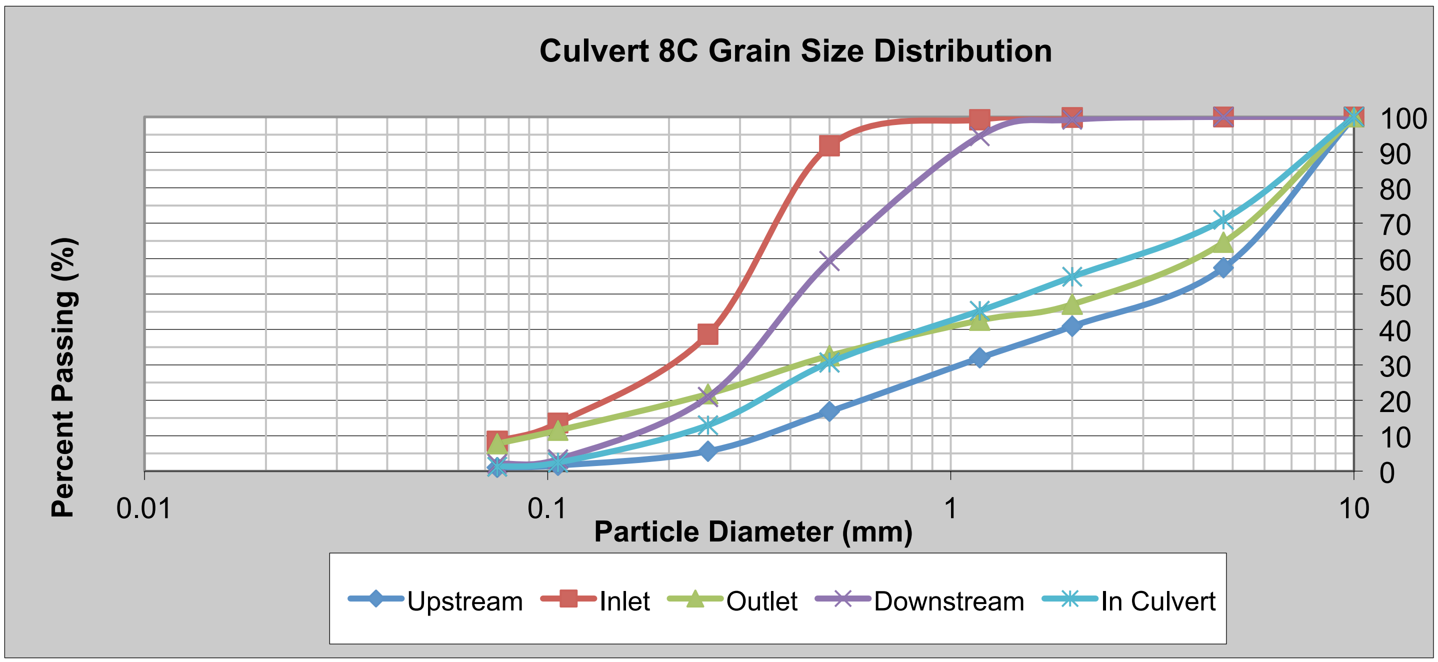
Culvert 7A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream


Culvert 7B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream

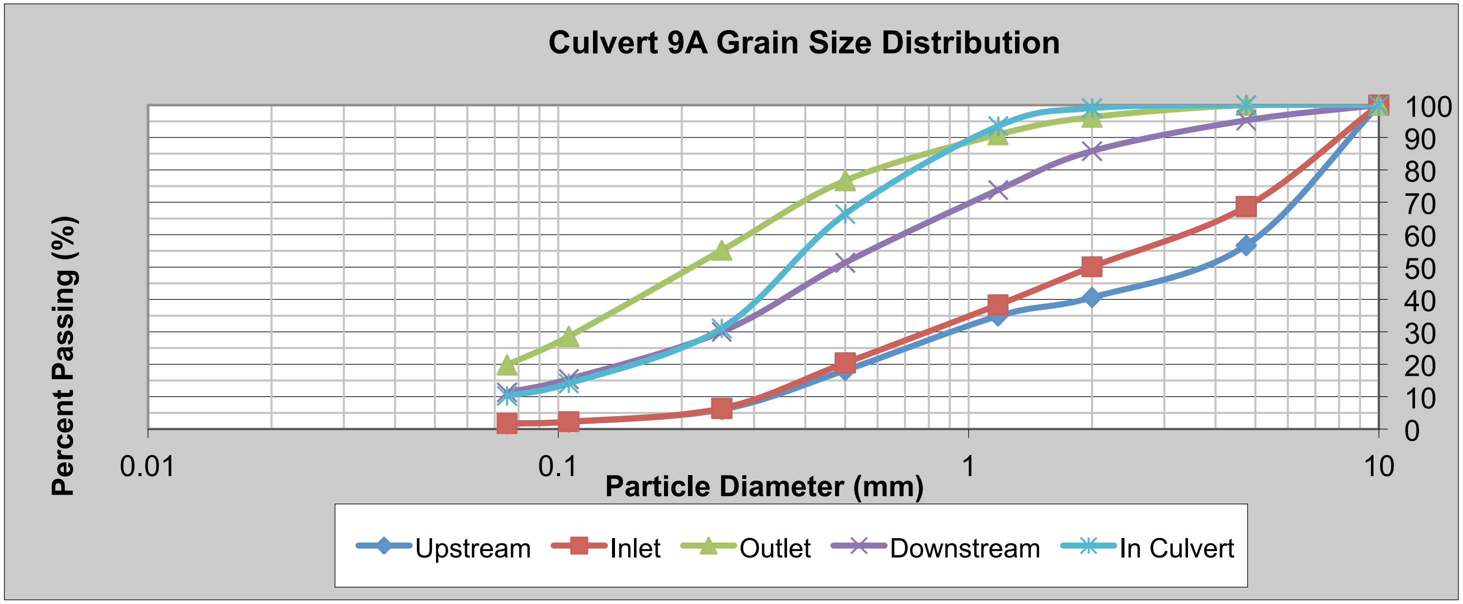

Culvert 8A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

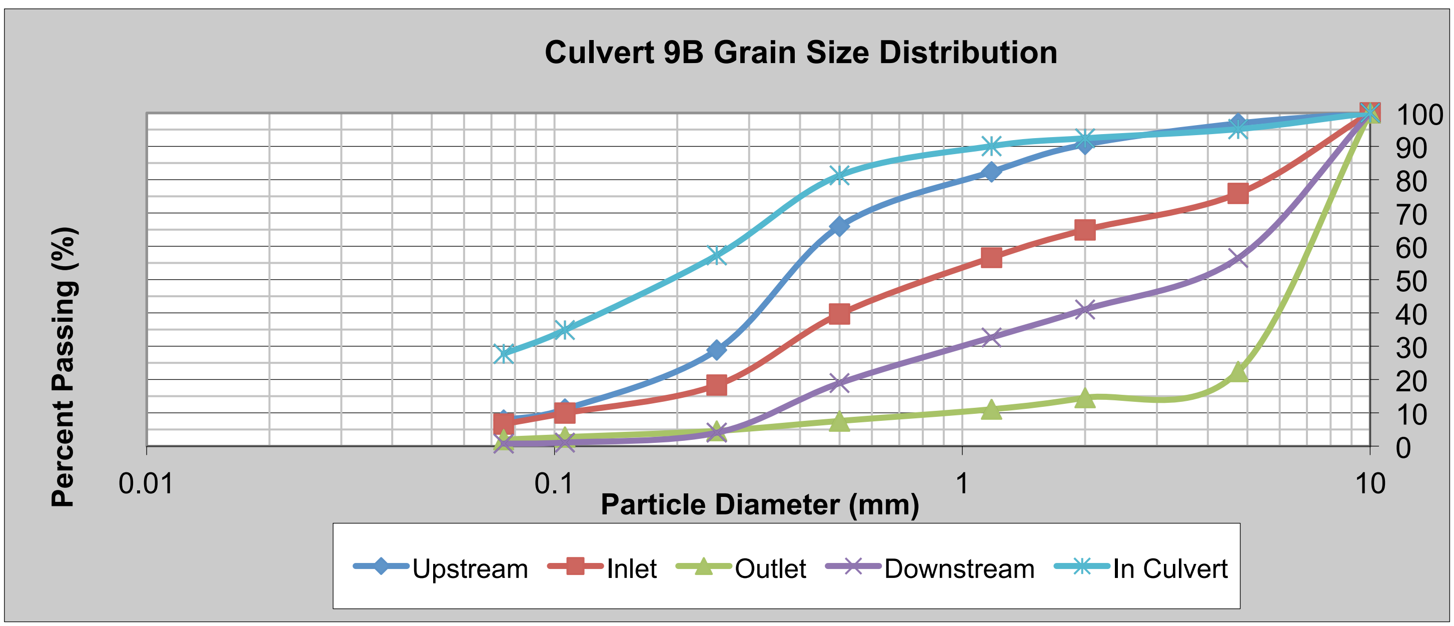


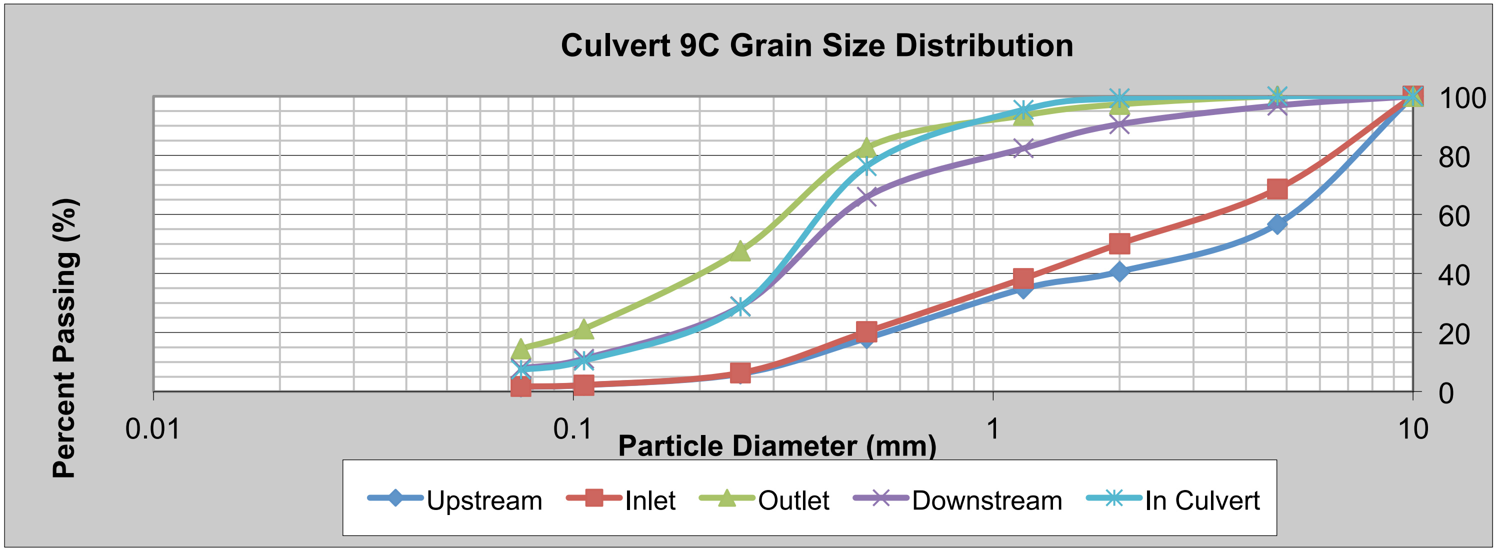
Culvert 8B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

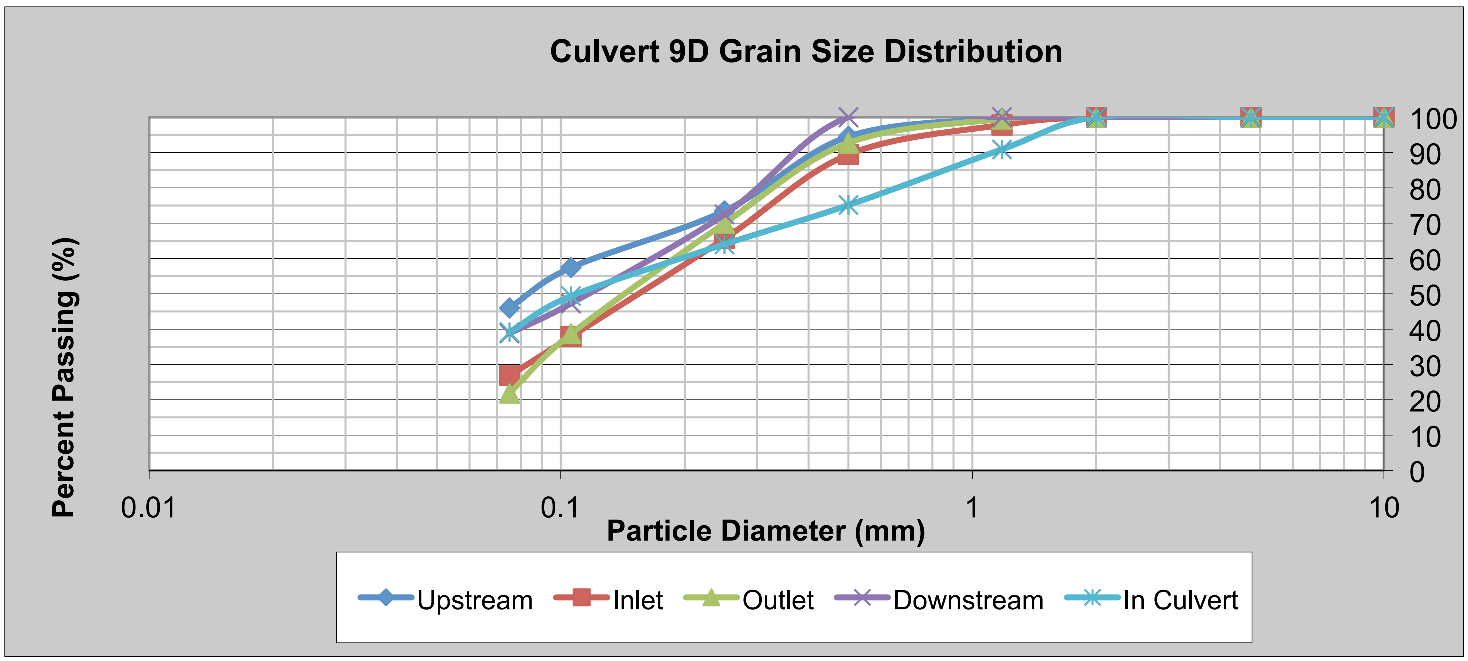


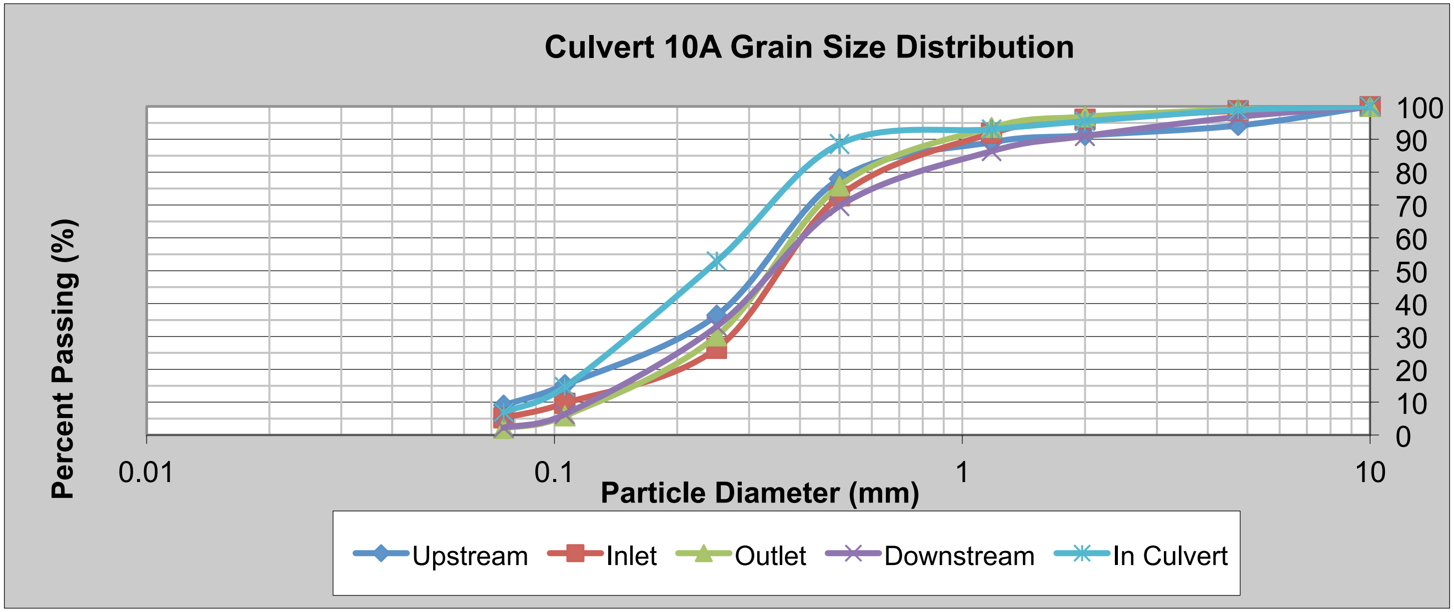
Culvert 8C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

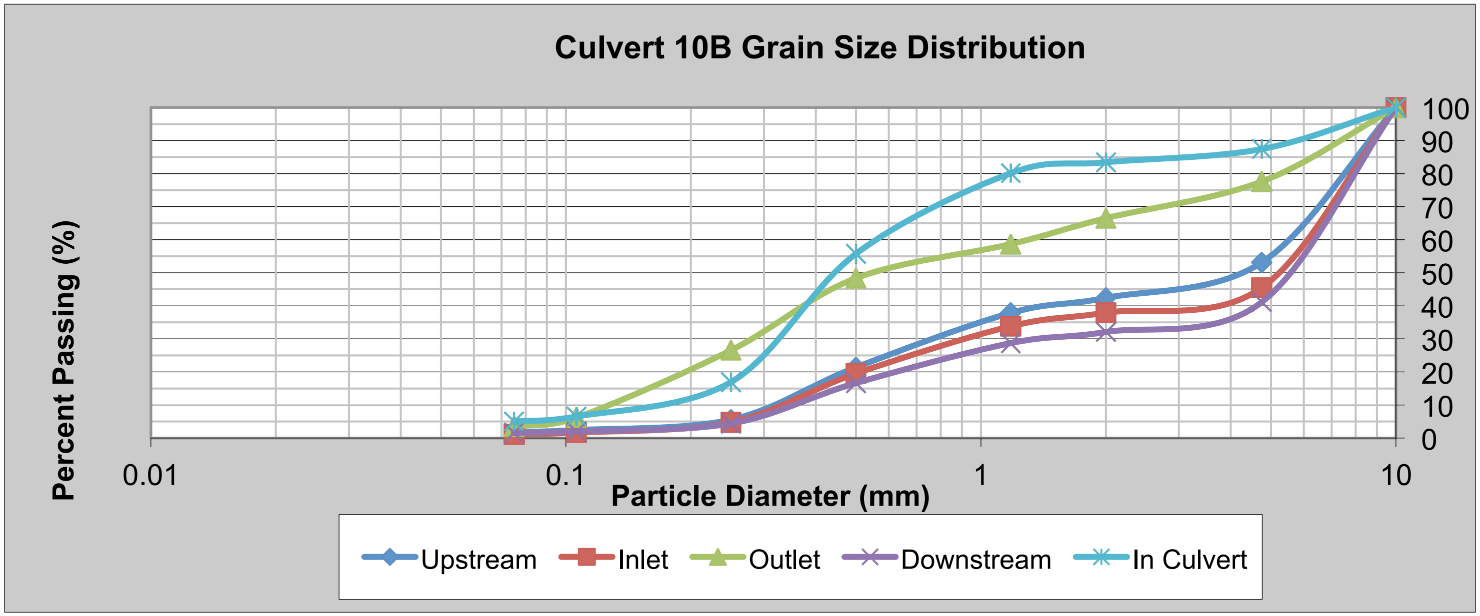

Culvert 9A Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert

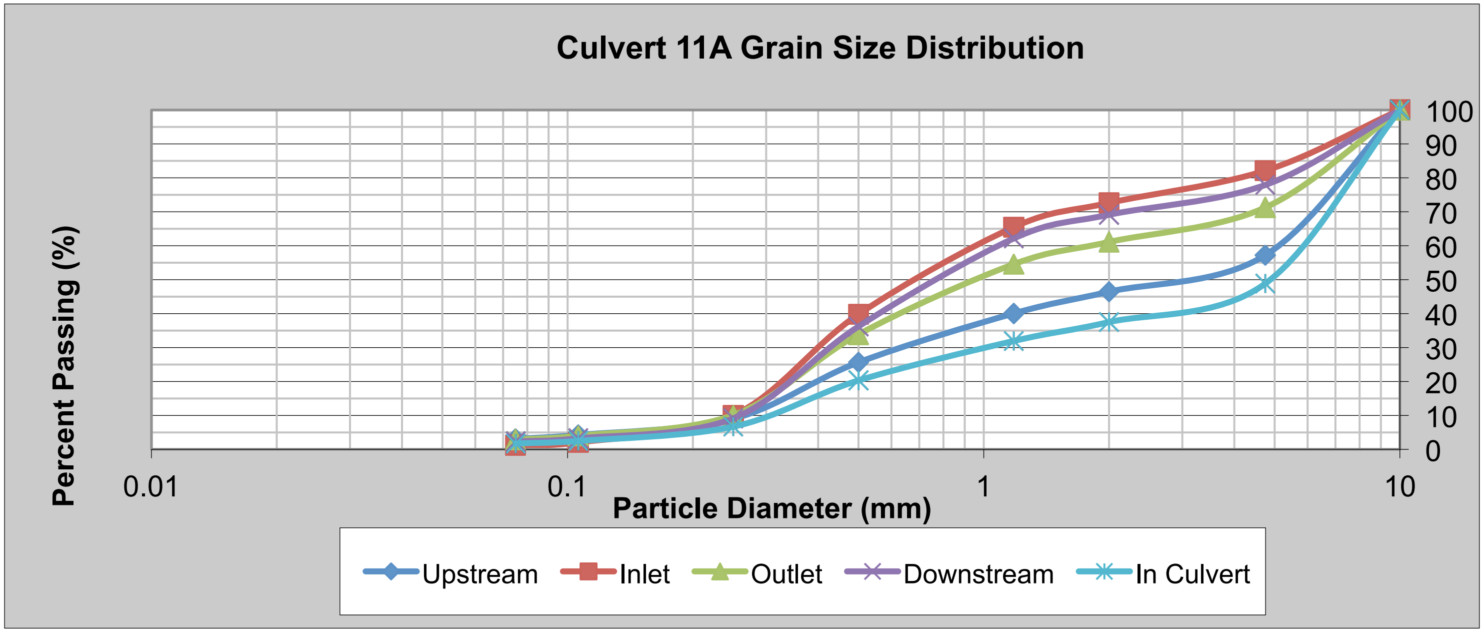

Culvert 9B Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert

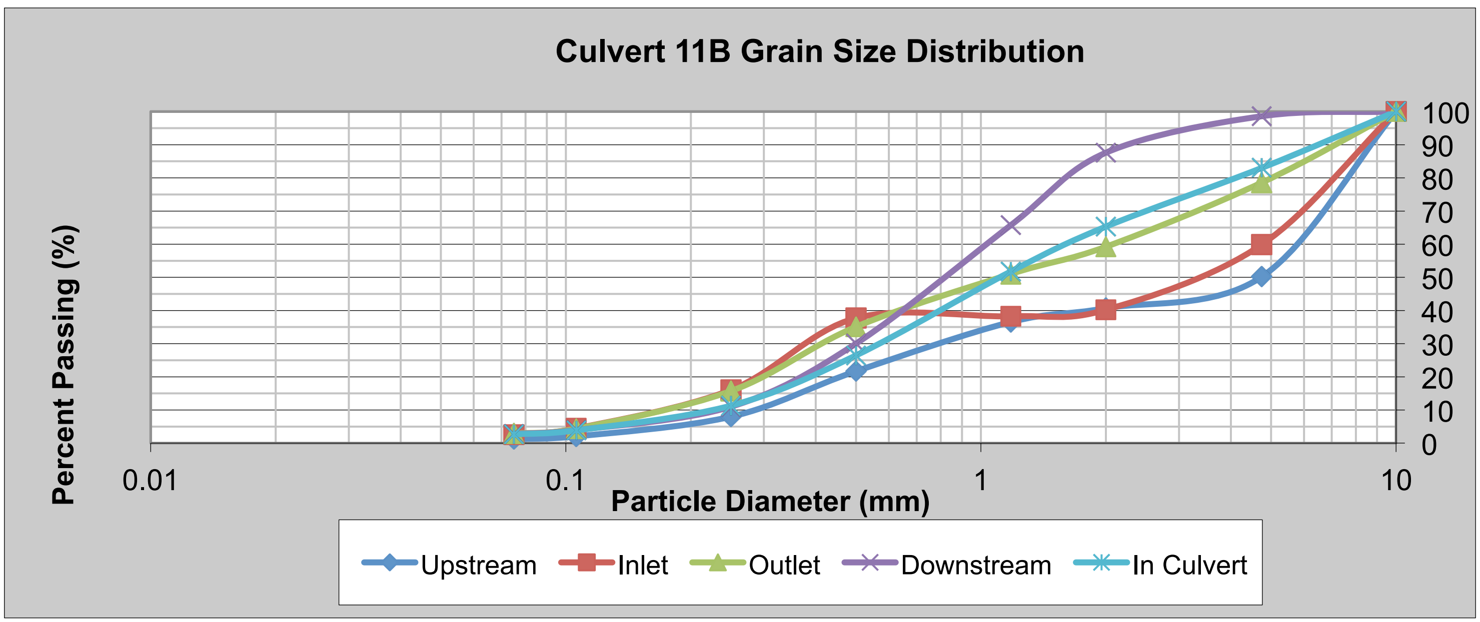

Culvert 9C Grain Size Distribution
Percent Passing (%)
0
20
40
60
80
100
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

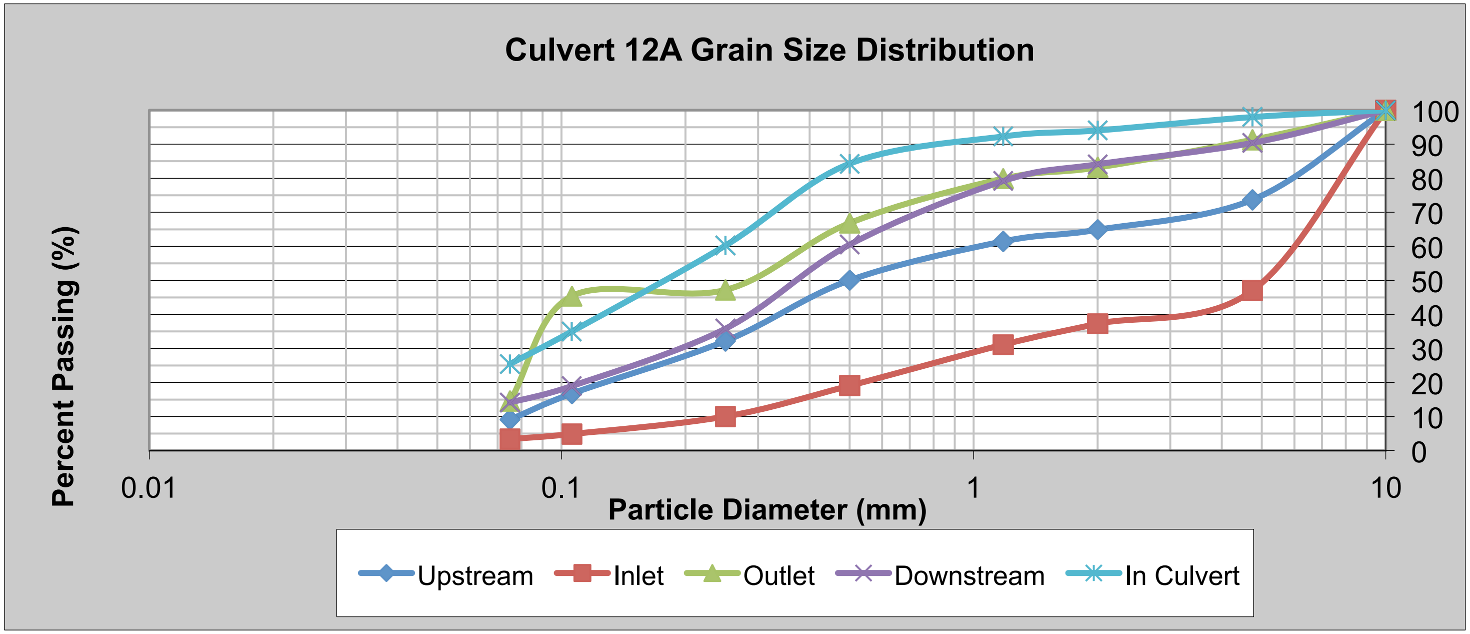

Culvert 9D Grain Size Distribution
Percent Passing (%)
0
10
20
30
40
50
60
70
80
90
100
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

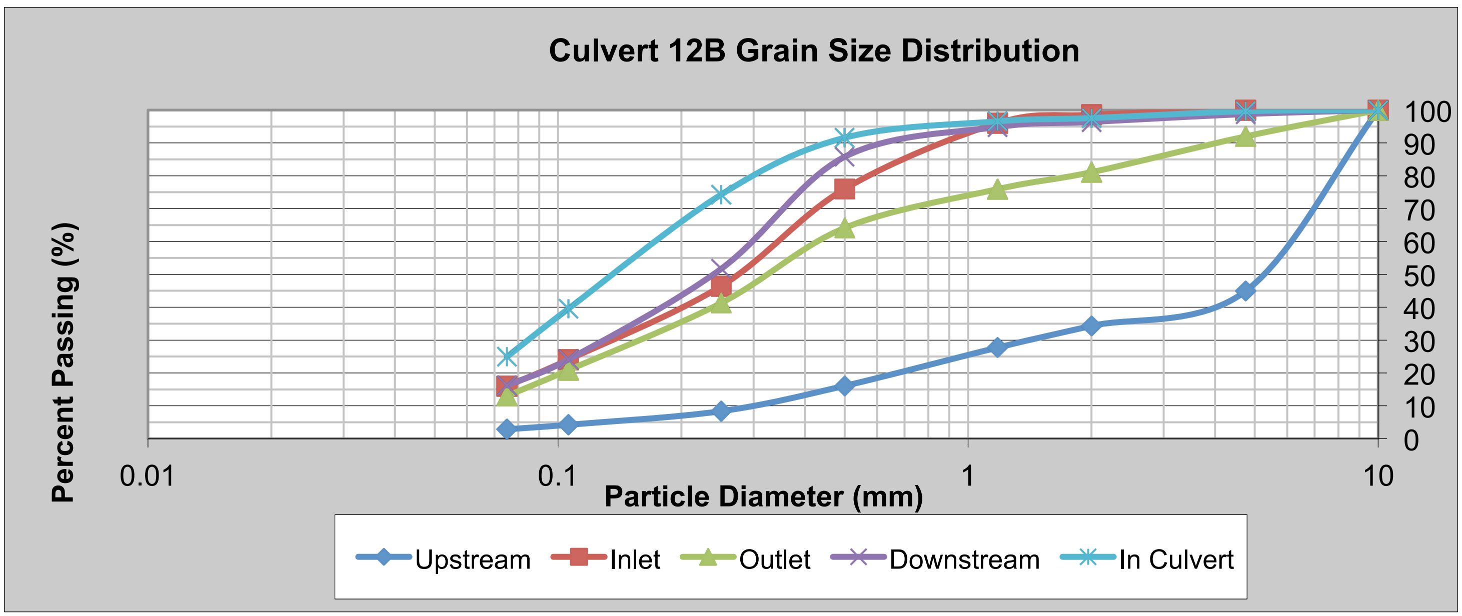

Culvert 10A Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert

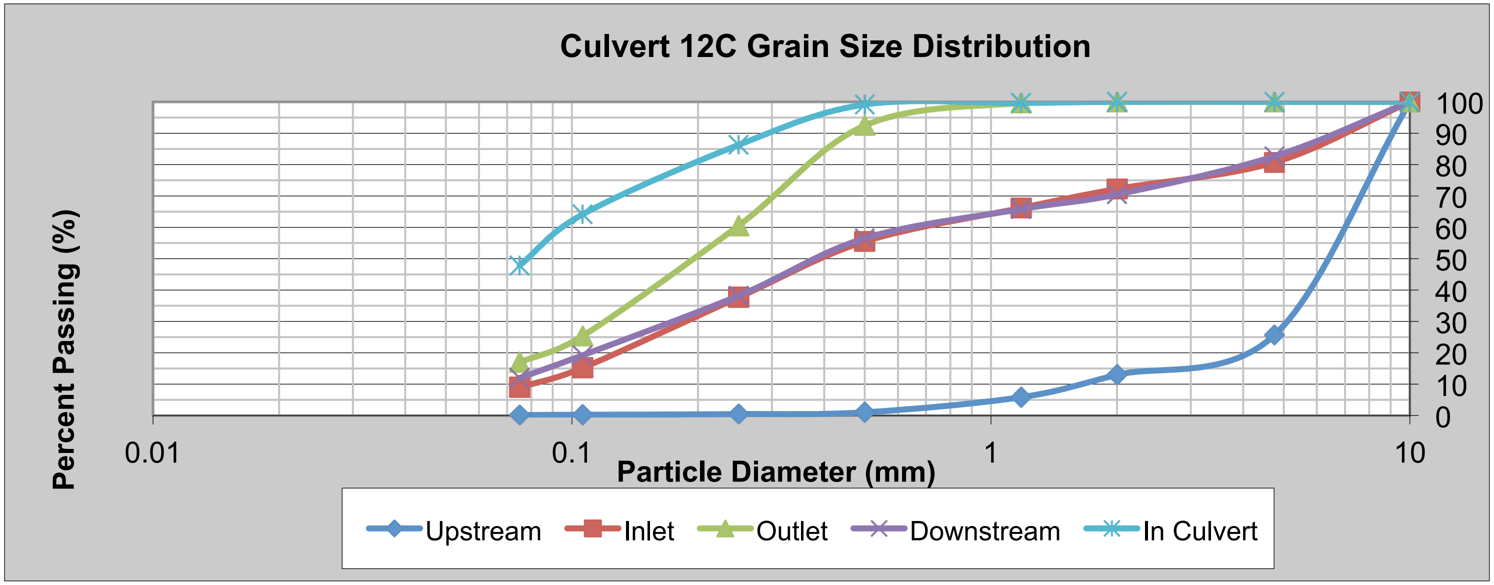

Culvert 10B Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert

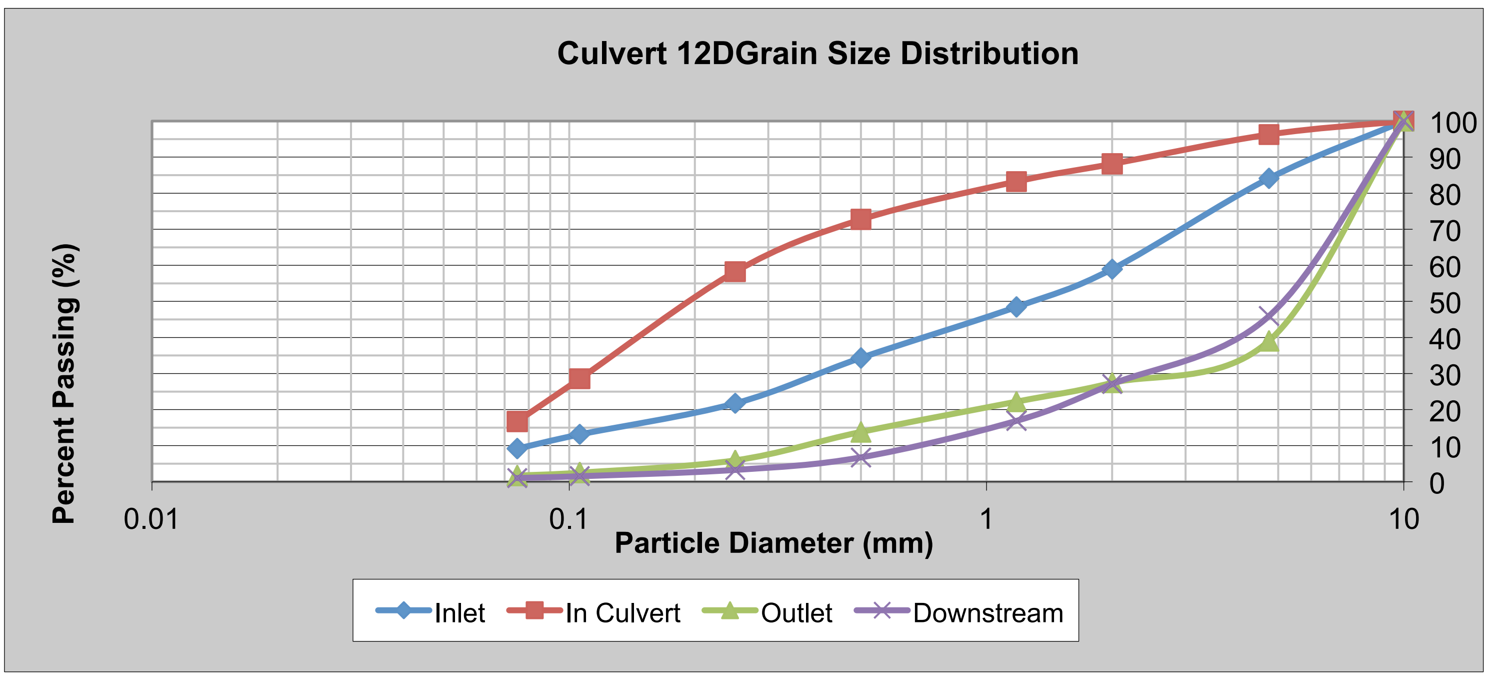

Culvert 11A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

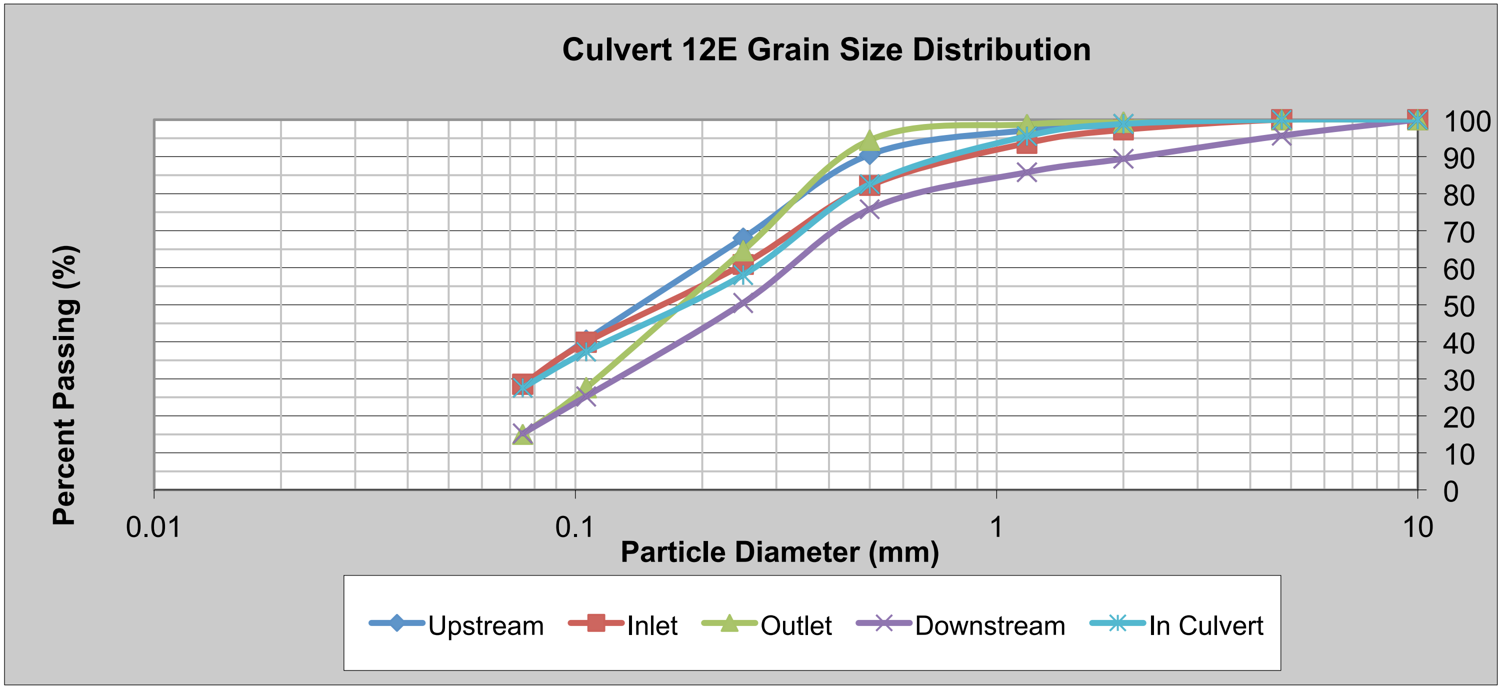

Culvert 11B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert


Culvert 12A Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert

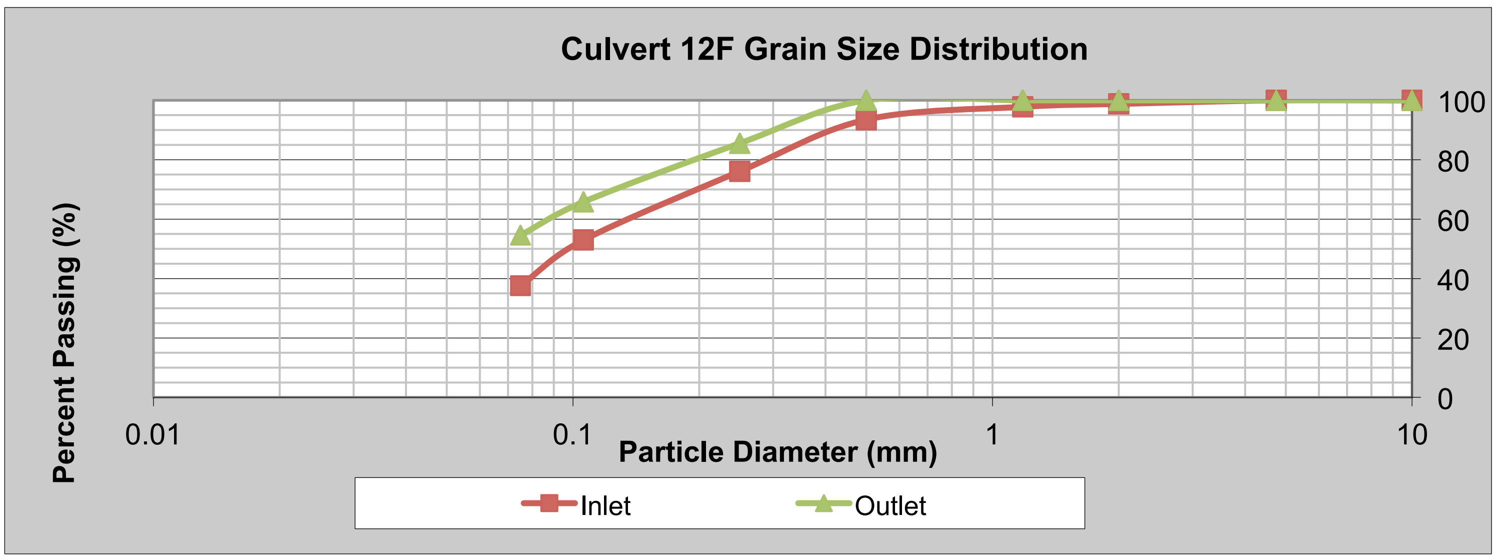

Culvert 12B Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert


Culvert 12C Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream
In Culvert

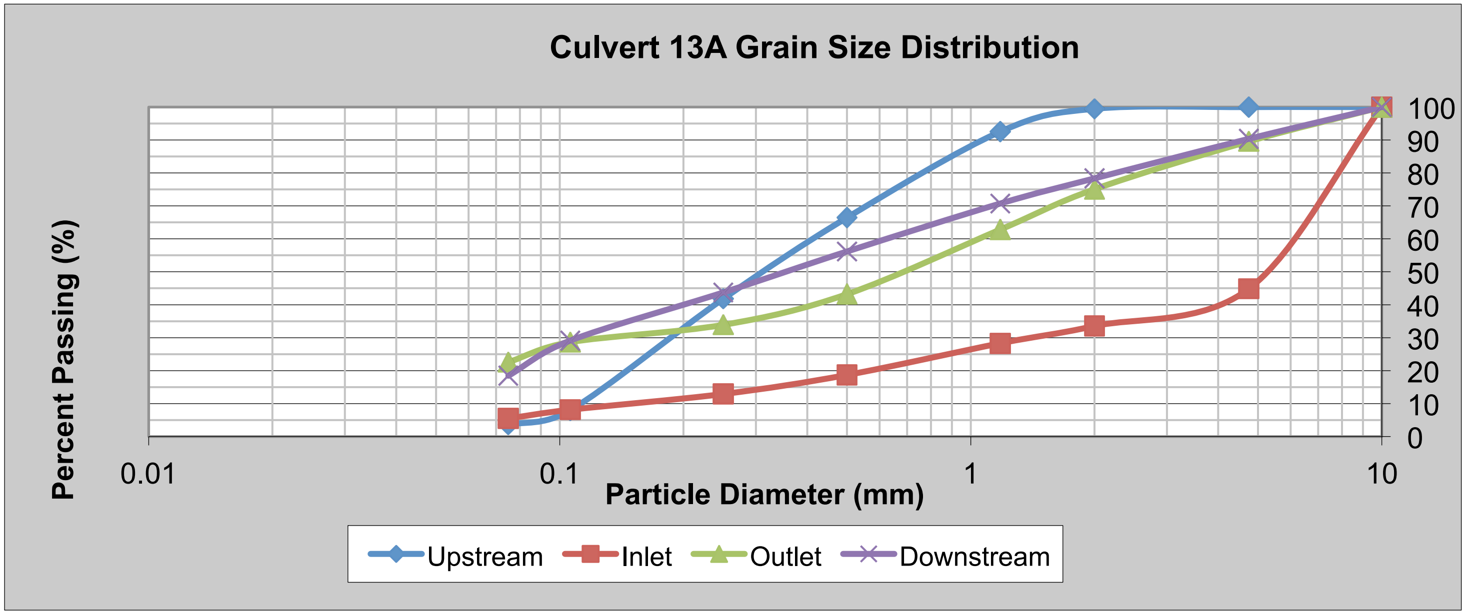

Culvert 12DGrain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Inlet
In Culvert
Outlet
Downstream

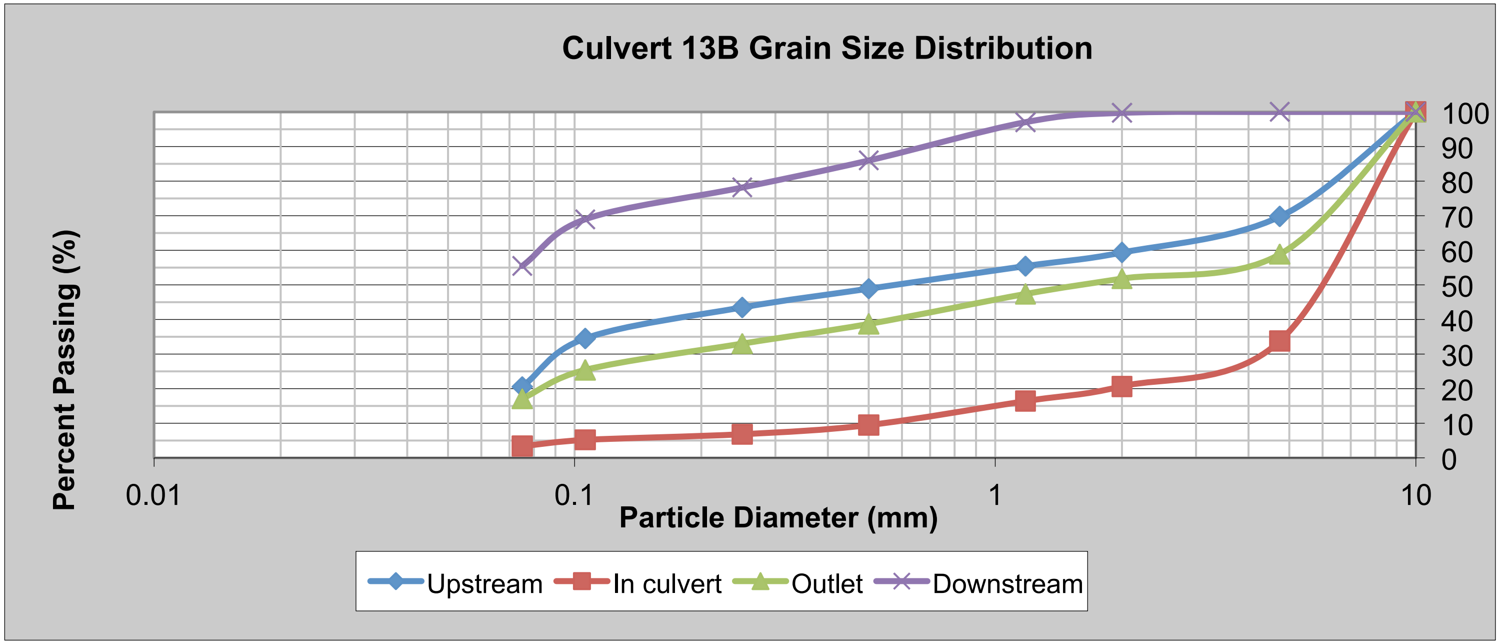


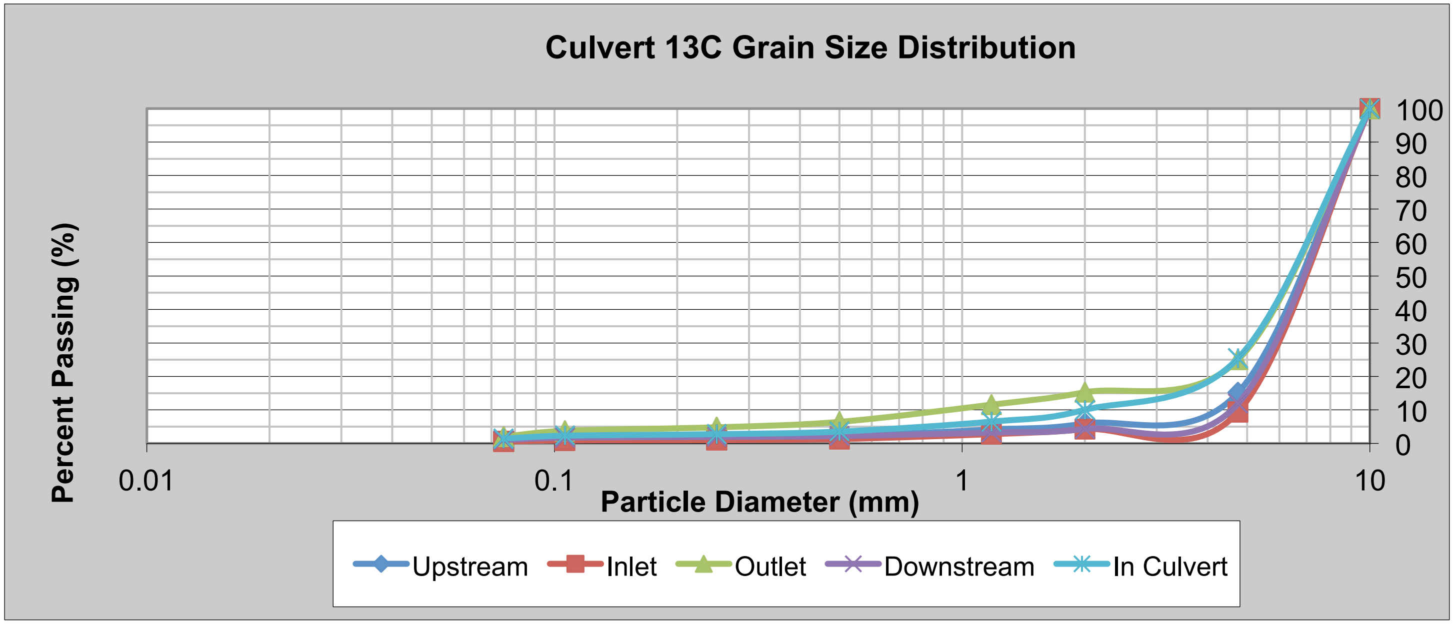
Culvert 12E Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

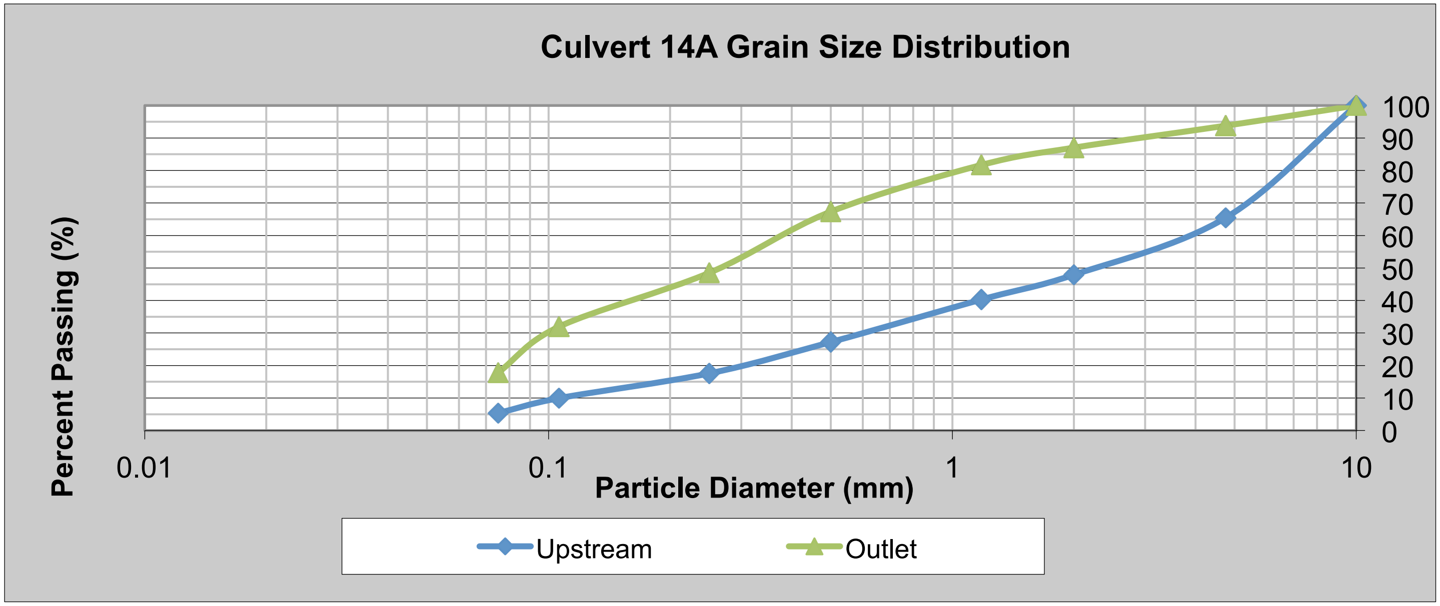


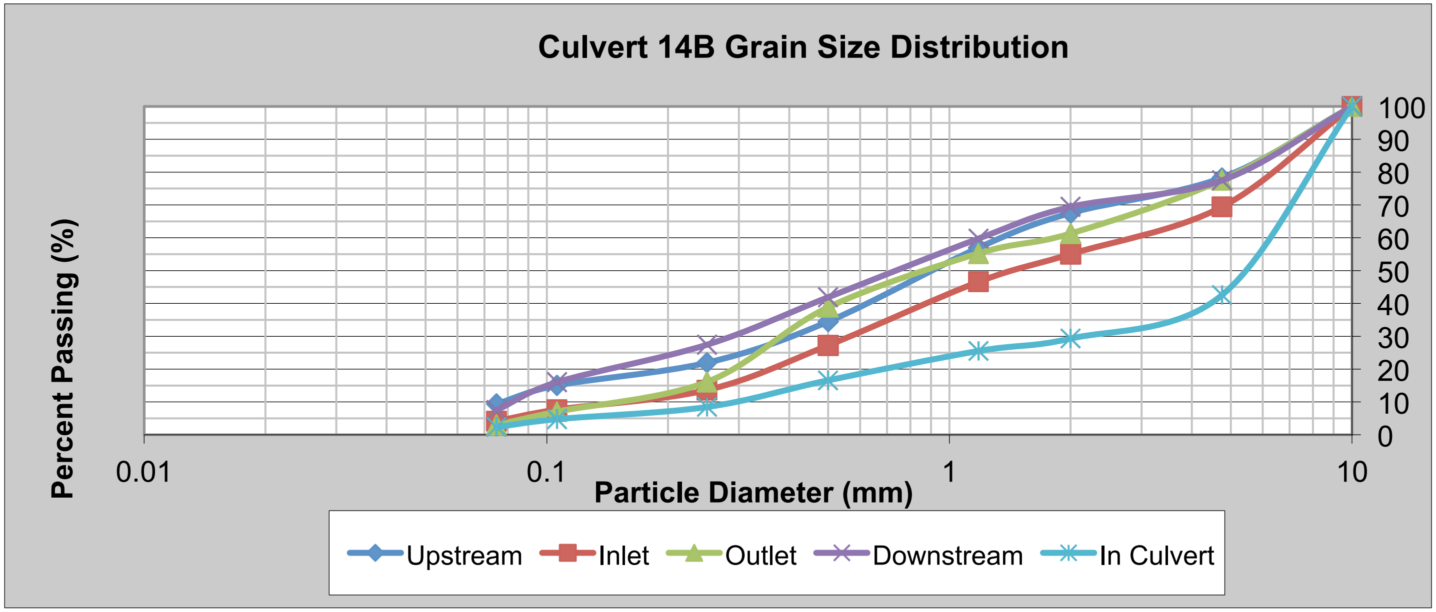
Culvert 12F Grain Size Distribution
Percent Passing (%)
100
80
60
40
20
0
0.01
0.1
1
10
Particle Diameter (mm)
Inlet
Outlet


Culvert 13A Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
Inlet
Outlet
Downstream

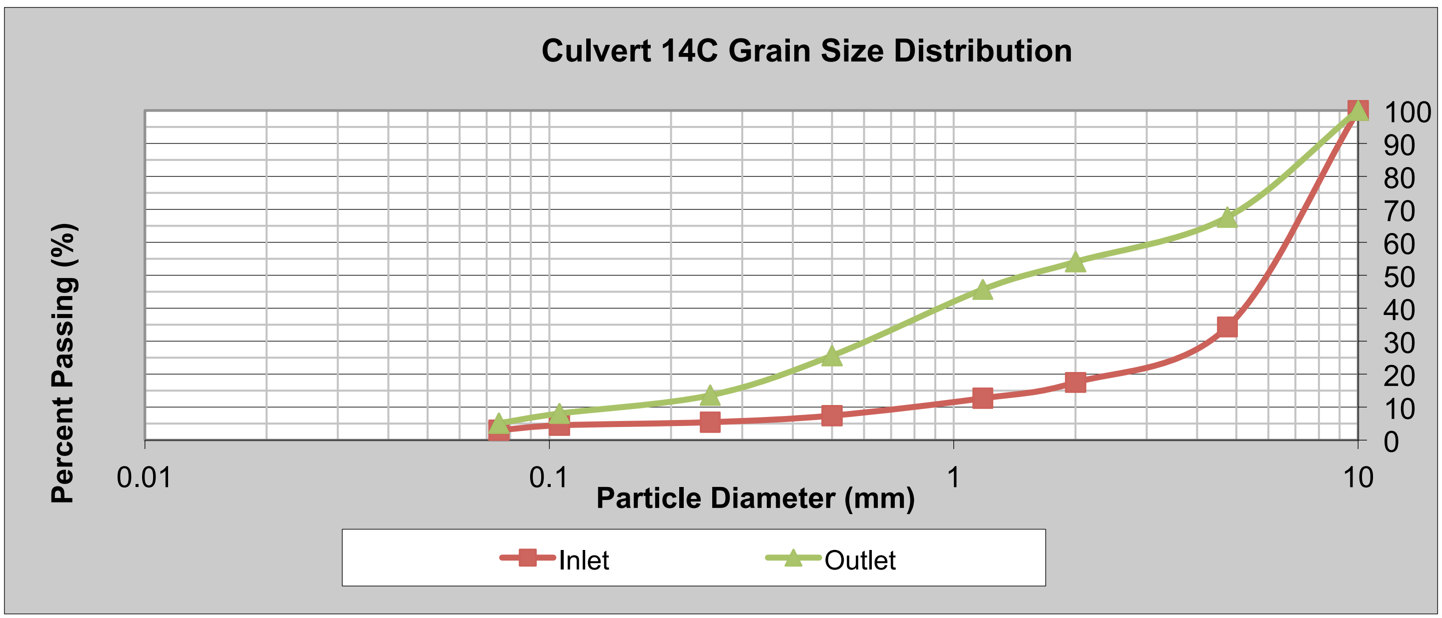

Culvert 13B Grain Size Distribution
Percent Passing (%)
Particle Diameter (mm)
0.01
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Upstream
In culvert
Outlet
Downstream


Culvert 13C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert

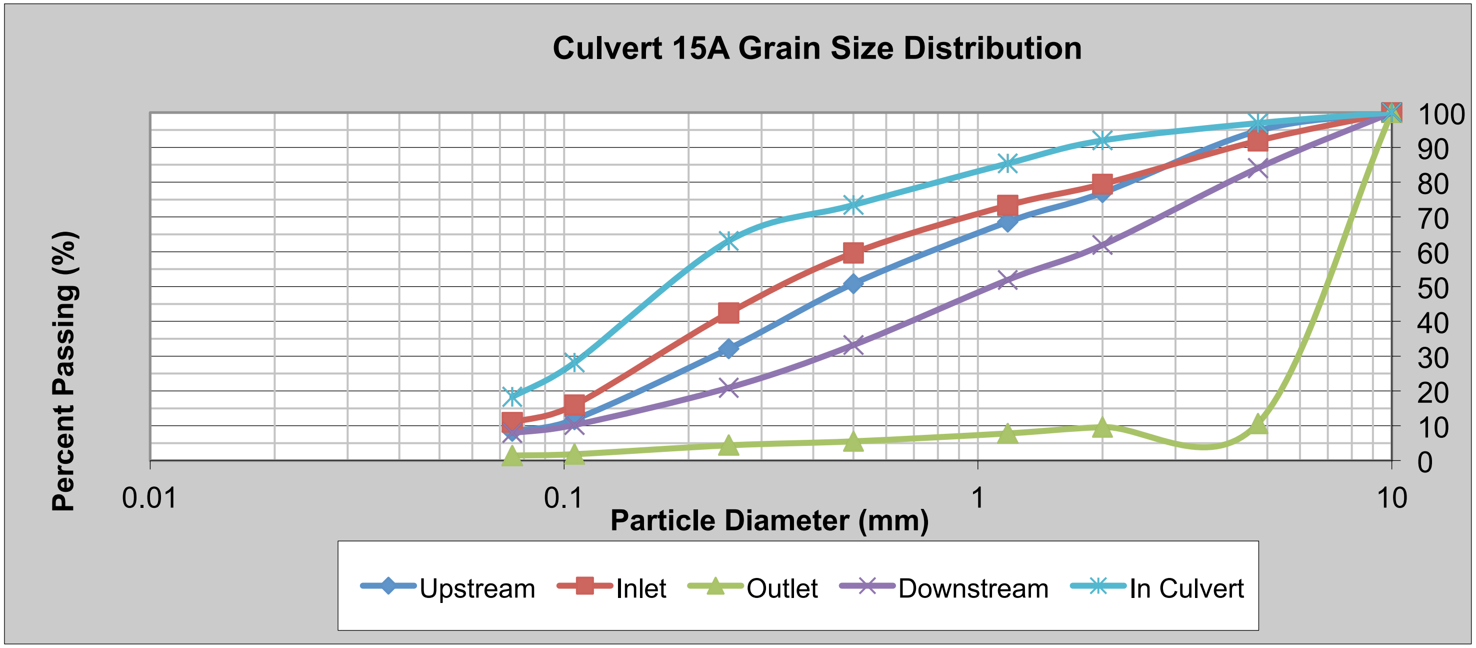

Culvert 14A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Outlet



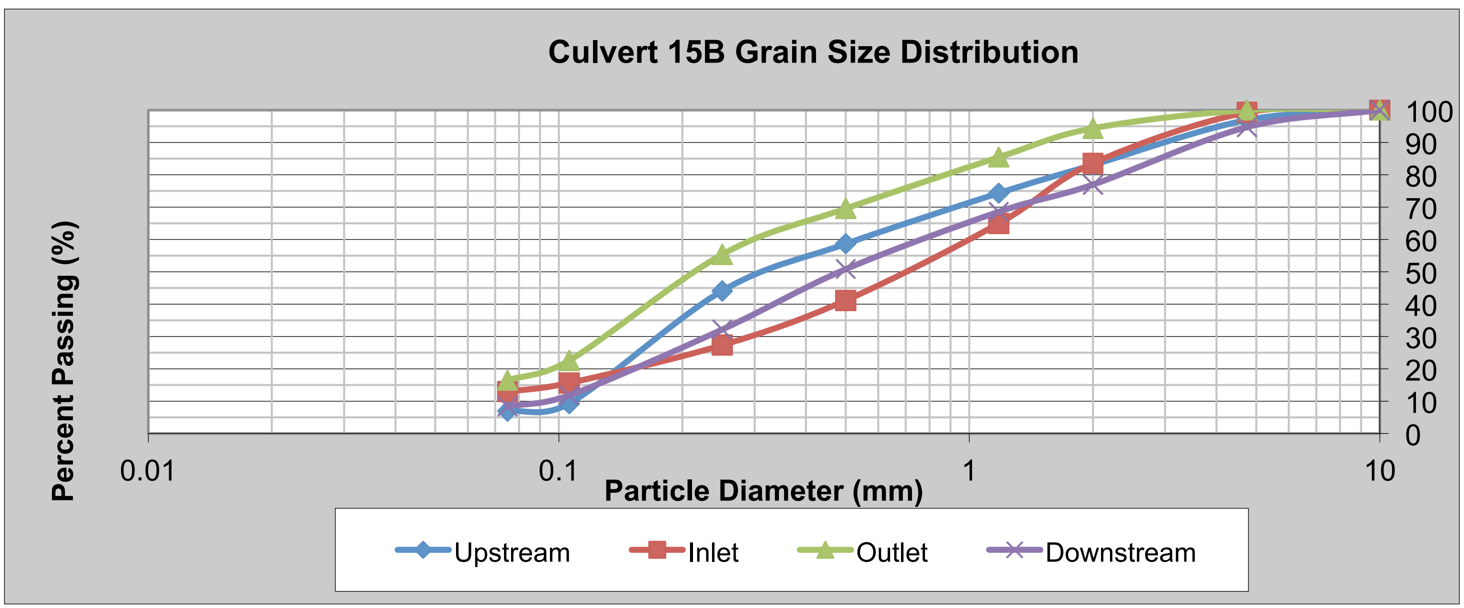
Culvert 14B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert



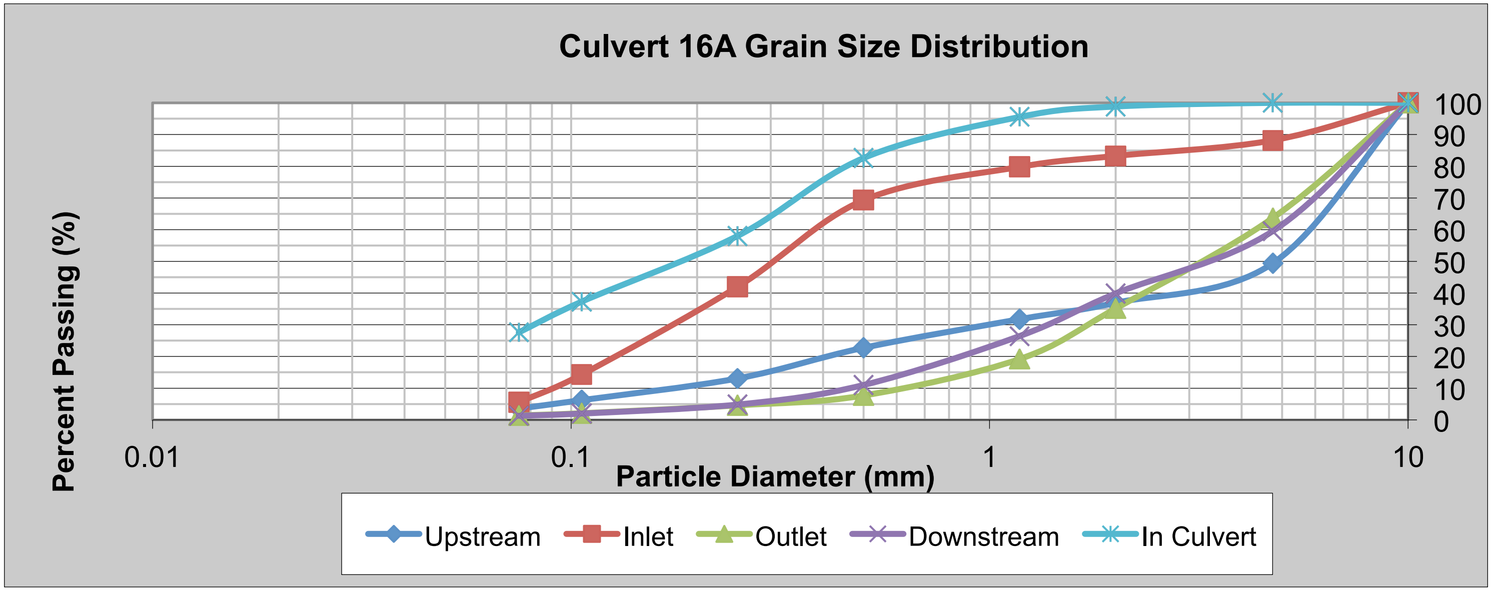
Culvert 14C Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Inlet
Outlet

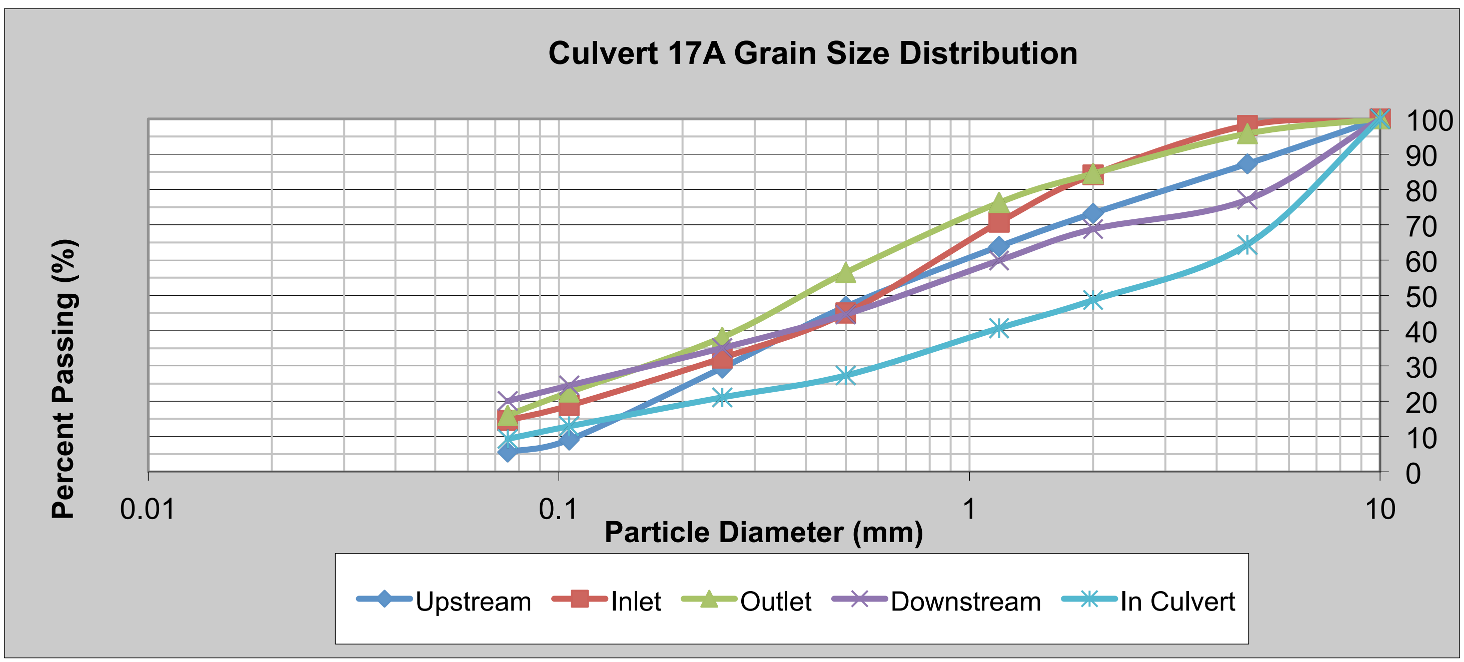


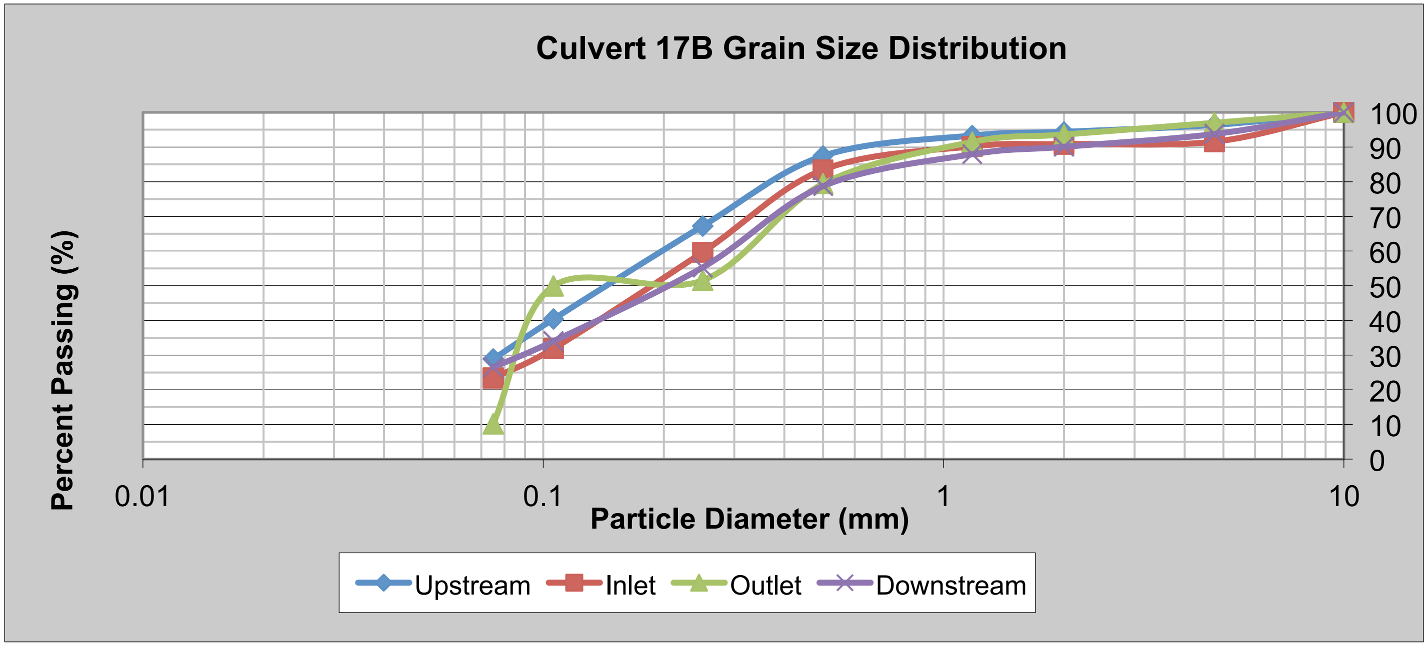
Culvert 15A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert



Culvert 15B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream


Culvert 16A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert


Culvert 17A Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream
In Culvert



Culvert 17B Grain Size Distribution
Percent Passing (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Particle Diameter (mm)
Upstream
Inlet
Outlet
Downstream

APPENDIX D
Summary of the Results for Total Suspended Solids

Of the **Draft** Final Report on

A Study of Bankfull Culvert Design Effectiveness

By: Mark A. Tumeo, Ph.D., J.D.
Joe Pavlick, MS Student

for the
Ohio Department of Transportation
Office of Research and Development

State Job Number 134465

May 16, 2011 (draft)

Summary of Total Suspended Solids Data Collected During Field Survey

	Upstream		Inlet		In Culvert		Outlet		Downstream	
	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev
1A	230.00	27.84	188.33	5.77	176.67	11.55	186.67	11.55	191.67	16.07
1B	343.33	89.63	230.00	17.32	183.33	20.82	210.00	0.00	210.00	17.32
1C	203.33	11.55	210.00	26.46	183.33	20.82	230.00	43.59	353.33	25.17
1D	50.00	95.39	36.67	11.55	23.33	10.00	730.00	11.55	343.33	89.63
1E	40.00	0.00	86.67	20.82	113.33	17.32	60.00	51.32	43.33	5.77
2A	16.67	5.77	10.00	0.00	10.00	10.00	13.33	5.77	16.67	5.77
2B	46.67	15.28	53.33	5.77	43.33	15.28	46.67	15.28	70.00	10.00
2C	140.00	20.00	113.33	30.55	100.00	20.00	146.67	41.63	193.33	30.55
2D	286.67	41.63	186.67	11.55	126.67	30.55	100.00	0.00	86.67	23.09
2E	213.33	11.55	160.00	20.00	133.33	23.09	133.33	75.72	153.33	64.29
2F	46.67	10.41	51.67	12.58	no sample	no sample	50.00	15.00	73.33	2.89
2G	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample	no sample
3A	73.33	30.55	126.67	46.19	126.67	30.55	173.33	41.63	106.67	11.55
3B	126.67	11.55	206.67	30.55	180.00	34.64	166.67	23.09	60.00	103.92
3C	120.00	34.64	66.67	23.09	220.00	20.00	113.33	11.55	166.67	23.09
3D	146.67	61.10	40.00	40.00	60.00	20.00	53.33	50.33	106.67	122.20
4A	136.67	45.09	116.67	15.28	133.33	45.09	80.00	20.00	83.33	15.28
4B	193.33	11.55	173.33	11.55	166.67	15.28	183.33	49.33	153.33	5.77
4C	153.33	23.09	140.00	17.32	146.67	5.77	150.00	10.00	150.00	26.46
4D	43.33	11.55	106.67	15.28	156.67	5.77	183.33	15.28	143.33	15.28
5A	380.00	111.36	393.33	122.20	200.00	52.92	113.33	11.55	66.67	11.55
5B	95.00	5.00	123.33	18.93	473.33	30.14	115.00	15.00	96.67	2.89
5C	76.67	18.93	181.67	10.41	251.67	81.29	206.67	7.64	255.00	22.91
5D	33.33	2.89	26.67	2.89	20.00	10.00	10.00	5.00	no sample	no sample
5E	150.00	35.00	150.00	8.66	188.33	5.77	181.67	2.89	196.67	5.77
5F	128.33	14.43	113.33	2.89	138.33	7.64	140.00	8.66	145.00	17.32
5G	400.00	39.69	101.67	7.64	98.33	7.64	83.33	7.64	95.00	13.23
5H	28.33	20.21	103.33	20.21	96.67	23.63	128.33	17.56	148.33	12.58
6A	111.67	10.41	75.00	13.23	51.67	5.77	30.00	13.23	15.00	5.00
6B	640.00	0.00	626.67	94.52	406.67	30.55	480.00	20.00	480.00	20.00
6C	46.67	15.28	51.67	2.89	56.67	17.56	75.00	13.23	78.33	7.64
6D	473.33	80.83	320.00	52.92	246.67	30.55	246.67	41.63	206.67	41.63
6E	60.00	13.23	50.00	5.00	76.67	2.89	53.33	2.89	73.33	7.64

Summary of Total Suspended Solids Data Collected During Field Survey

	Upstream		Inlet		In Culvert		Outlet		Downstream	
	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev	Avg (mg/l)	Std Dev
7A	560.00	45.83	376.67	34.03	341.67	5.77	143.33	2.89	185.00	57.66
7B	115.00	0.00	108.33	5.00	no sample	no sample	83.33	20.82	370.00	193.71
8A	136.67	5.77	146.67	2.89	128.33	17.56	111.67	12.58	128.33	15.28
8B	168.89	50.48	75.56	34.21	46.67	6.67	51.11	7.70	40.00	17.64
8C	145.00	25.98	133.33	2.89	105.00	18.03	90.00	10.00	76.67	11.55
9A	176.67	16.07	315.00	8.66	151.67	25.66	101.67	17.56	63.33	5.77
9B	15.00	22.91	175.00	8.66	150.00	10.00	145.00	7.64	131.67	2.89
9C	78.33	2.89	65.00	10.00	48.33	14.43	21.67	14.43	15.00	5.00
9D	96.67	5.77	98.33	7.64	130.00	5.00	213.33	30.55	126.67	10.41
10A	15.00	8.66	23.33	15.28	298.33	56.20	38.33	10.41	70.00	40.93
10B	100.00	26.46	160.00	10.00	270.00	17.32	43.33	11.55	56.67	20.82
11A	78.33	12.58	53.33	17.56	40.00	8.66	30.00	5.00	31.67	2.89
11B	23.33	16.07	33.33	20.82	55.00	10.00	23.33	7.64	33.33	5.77
12A	120.00	17.64	82.22	13.88	51.11	20.37	35.56	7.70	57.78	16.78
12B	168.89	40.73	184.44	19.25	177.78	13.88	191.11	3.85	148.89	19.25
12C	61.67	18.93	113.33	24.66	106.67	17.56	120.00	5.00	100.00	10.00
12D	no sample	no sample	266.67	50.33	246.67	11.55	120.00	0.00	246.67	50.33
12E	173.33	23.09	200.00	20.00	186.67	30.55	213.33	30.55	173.33	46.19
12F	no sample	no sample	380.00	69.28	no sample	no sample	200.00	20.00	no sample	no sample
13A	360.00	10.00	363.33	57.74	no sample	no sample	370.00	52.92	353.33	35.12
13B	191.67	30.55	188.33	15.28	230.00	28.87	176.67	20.82	186.67	15.28
13C	280.00	20.00	293.33	11.55	200.00	11.55	200.00	91.65	273.33	11.55
14A	46.67	30.55	6.67	11.55	53.33	30.55	46.67	11.55	193.33	23.09
14B	193.33	23.09	326.67	23.09	500.00	70.71	186.67	94.52	193.33	11.55
14C	no sample	no sample	53.33	30.55	no sample	no sample	no sample	no sample	no sample	no sample
15A	170.00	10.00	30.00	20.00	16.67	11.55	46.67	40.41	193.33	28.87
15B	213.33	5.77	233.33	49.33	426.67	45.09	176.67	23.09	170.00	10.00
16A	63.33	11.55	65.00	5.00	70.00	13.23	85.00	8.66	83.33	10.41
17A	33.33	15.28	36.67	15.28	43.33	11.55	13.33	15.28	43.33	41.63
17B	68.33	2.89	56.67	12.58	53.33	20.82	56.67	2.89	76.67	5.77

APPENDIX E
Culvert 2-year, 5-year and 10-year Flows and Shear Stresses

Of the **Draft** Final Report on

A Study of Bankfull Culvert Design Effectiveness

By: Mark A. Tumeo, Ph.D., J.D.
Joe Pavlick, MS Student

for the
Ohio Department of Transportation
Office of Research and Development

State Job Number 134465

May 16, 2011 (draft)

Site	2-Year Flow (cfs [m3/sec])	5-Year Flow (cfs [m3/sec])	10-Year Flow (cfs [m3/sec])	Shear from 2-year flow (lb/ft^2 [Pa])	Shear from 5-year flow (lb/ft^2 [Pa])	Shear from 10-year flow (lb/ft^2 [Pa])
1A	140 [4.0]	218 [6.2]	267 [7.6]	0.05 [2.5]	0.06 [3.0]	0.07 [3.2]
1B	140 [4.0]	218 [6.2]	267 [7.6]	0.21 [10.1]	0.26 [12.6]	0.29 [13.8]
1C	182 [5.2]	276 [7.8]	335 [9.5]	0.34 [16.2]	0.42 [20.3]	0.47 [22.4]
1D	140 [4.0]	218 [6.2]	267 [7.6]	0.19 [8.9]	0.23 [11.0]	0.25 [12.1]
1E	140 [4.0]	218 [6.2]	267 [7.6]	0.38 [18.1]	0.48 [22.8]	0.53 [25.3]
2A	63.8 [1.8]	121 [3.4]	165 [4.7]	0.81 [39.0]	1.02 [48.7]	1.14 [54.7]
2B	33 [0.9]	65.5 [1.9]	91 [2.6]	1.47 [70.4]	1.78 [85.4]	2.00 [96.0]
2C	13.7 [0.4]	28.6 [0.8]	40.5 [1.1]	2.19 [104.8]	2.24 [107.1]	2.33 [111.7]
2D	22.5 [0.6]	45.5 [1.3]	63.8 [1.8]	0.98 [47.1]	1.15 [55.2]	1.26 [60.5]
2E	25.9 [0.7]	52.7 [1.5]	74.2 [2.1]	1.46 [69.8]	1.75 [84.0]	1.95 [93.1]
2F	19.1 [0.5]	39.8 [1.1]	56.6 [1.6]	1.21 [58.1]	1.29 [61.9]	1.37 [65.7]
2G	*no flow available*				[]	[]
3A	26.4 [0.7]	52.8 [1.5]	73.5 [2.1]	1.86 [89.0]	2.08 [99.6]	2.26 [108.1]
3B	180 [5.1]	326 [9.2]	436 [12.3]	0.82 [39.1]	0.97 [46.4]	1.07 [51.3]
3C	25.5 [0.7]	50.4 [1.4]	69.8 [2.0]	1.50 [71.6]	1.79 [85.5]	2.01 [96.5]
3D	28.5 [0.8]	56.9 [1.6]	79.4 [2.2]	2.75 [131.5]	3.10 [148.4]	3.35 [160.2]
4A	226 [6.4]	417 [11.8]	563 [15.9]	1.74 [83.5]	2.05 [97.9]	2.25 [108.0]
4B	24 [0.7]	50.3 [1.4]	71.8 [2.0]	0.81 [38.7]	0.99 [47.4]	1.12 [53.7]
4C	20.4 [0.6]	42 [1.2]	59.3 [1.7]	0.92 [44.0]	1.09 [52.1]	1.22 [58.5]
4D	42.8 [1.2]	80.4 [2.3]	109 [3.1]	0.29 [13.8]	0.41 [19.6]	0.48 [23.2]
5A	98.4 [2.8]	176 [5.0]	233 [6.6]	1.84 [88.2]	2.27 [108.5]	2.52 [120.6]
5B	23.8 [0.7]	48.2 [1.4]	67.5 [1.9]	1.78 [85.3]	1.87 [89.3]	1.89 [90.7]
5C	22.3 [0.6]	45.6 [1.3]	64.2 [1.8]	1.69 [81.1]	1.76 [84.2]	1.86 [88.9]
5D	90.5 [2.6]	174 [4.9]	238 [6.7]	1.75 [83.8]	1.97 [94.3]	2.13 [101.9]
5E	90.9 [2.6]	171 [4.8]	233 [6.6]	0.54 [26.1]	0.57 [27.3]	0.59 [28.1]
5F	25.9 [0.7]	51.5 [1.5]	71.5 [2.0]	0.74 [35.3]	0.75 [36.0]	0.77 [36.7]
5G	66.9 [1.9]	127 [3.6]	173 [4.9]	0.17 [8.2]	0.18 [8.6]	0.18 [8.8]

Site	2-Year Flow (cfs [m3/sec])	5-Year Flow (cfs [m3/sec])	10-Year Flow (cfs [m3/sec])	Shear from 2-year flow (lb/ft^2 [Pa])	Shear from 5-year flow (lb/ft^2 [Pa])	Shear from 10-year flow (lb/ft^2 [Pa])
6A	15.1 [0.4]	30.3 [0.9]	42.3 [1.2]	0.77 [36.9]	0.82 [39.1]	0.85 [40.5]
6B	14.6 [0.4]	29.3 [0.8]	40.9 [1.2]	1.14 [54.7]	1.22 [58.4]	1.27 [60.8]
6C	45.3 [1.3]	86.5 [2.4]	118 [3.3]	*Elliptical culvert - stress not calculated*		
6D	26 [0.7]	51.8 [1.5]	72 [2.0]	3.49 [167.1]	3.54 [169.4]	3.58 [171.6]
6E	47.1 [1.3]	84.7 [2.4]	113 [3.2]	*Elliptical culvert - stress not calculated*		
7A	16.9 [0.5]	34.5 [1.0]	48.4 [1.4]	1.27 [60.7]	1.46 [70.1]	1.59 [76.1]
7B	205 [5.8]	352 [10.0]	459 [13.0]	0.70 [33.4]	0.75 [35.9]	0.79 [37.7]
8A	202 [5.7]	357 [10.1]	474 [13.4]	0.20 [9.6]	0.26 [12.7]	0.30 [14.5]
8B	183 [5.2]	320 [9.1]	420 [11.9]	1.03 [49.5]	1.16 [55.7]	1.25 [59.9]
8C	54.2 [1.5]	101 [2.9]	136 [3.9]	0.61 [29.2]	0.74 [35.4]	0.83 [39.5]
9A	350 [9.9]	611 [17.3]	806 [22.8]	0.55 [26.1]	0.72 [34.7]	0.83 [39.7]
9B	62.4 [1.8]	117 [3.3]	158 [4.5]	0.90 [42.9]	1.09 [52.1]	1.21 [57.9]
9C	62.4 [1.8]	117 [3.3]	158 [4.5]	0.50 [24.0]	0.63 [30.3]	0.70 [33.5]
9D	135 [3.8]	246 [7.0]	329 [9.3]	0.23 [11.1]	0.28 [13.6]	0.29 [14.0]
10A	13.8 [0.4]	28.1 [0.8]	39.4 [1.1]	2.03 [97.0]	2.20 [105.5]	2.35 [112.7]
10B	101 [2.9]	190 [5.4]	259 [7.3]	0.41 [19.4]	0.49 [23.4]	0.55 [26.2]
11A	289 [8.2]	490 [13.9]	637 [18.0]	0.17 [8.0]	0.22 [10.3]	0.24 [11.7]
11B	289 [8.2]	490 [13.9]	637 [18.0]	0.56 [27.0]	0.73 [35.2]	0.83 [40.0]
12A	12.6 [0.4]	23.3 [0.7]	31 [0.9]	0.04 [2.0]	0.06 [2.8]	0.07 [3.2]
12B	21.1 [0.6]	38.4 [1.1]	51 [1.4]	0.42 [20.2]	0.59 [28.1]	0.68 [32.6]
12C	86.8 [2.5]	153 [4.3]	202 [5.7]	0.07 [3.2]	0.07 [3.5]	0.08 [3.8]
12D	86.8 [2.5]	153 [4.3]	202 [5.7]	0.54 [25.8]	0.65 [31.3]	0.73 [34.8]
12E	100 [2.8]	173 [4.9]	225 [6.4]	0.17 [8.3]	0.21 [10.1]	0.23 [11.1]
13A	20.1 [0.6]	39.8 [1.1]	55.2 [1.6]	0.11 [5.3]	0.13 [6.0]	0.14 [6.7]
13B	13.5 [0.4]	26.6 [0.8]	36.7 [1.0]	1.12 [53.6]	1.30 [62.4]	1.43 [68.6]
13C	135 [3.8]	238 [6.7]	315 [8.9]	2.23 [106.8]	2.57 [123.2]	2.81 [134.4]

Site	2-Year Flow (cfs [m3/sec])	5-Year Flow (cfs [m3/sec])	10-Year Flow (cfs [m3/sec])	Shear from 2-year flow (lb/ft^2 [Pa])	Shear from 5-year flow (lb/ft^2 [Pa])	Shear from 10-year flow (lb/ft^2 [Pa])
14A	52.2 [1.5]	91.2 [2.6]	118 [3.3]	0.81 [38.8]	0.94 [45.0]	1.02 [49.0]
14B	52.2 [1.5]	91.2 [2.6]	118 [3.3]	*Elliptical culvert - stress not calculated*		
15A	46.7 [1.3]	80.5 [2.3]	104 [2.9]	0.13 [6.4]	0.16 [7.7]	0.18 [8.4]
15B	46.7 [1.3]	80.5 [2.3]	104 [2.9]	0.34 [16.2]	0.38 [18.3]	0.41 [19.9]
16A	76.9 [2.2]	130 [3.7]	166 [4.7]	1.69 [81.1]	1.78 [85.2]	1.83 [87.8]
17B	92.9 [2.6]	150 [4.2]	187 [5.3]	0.66 [31.6]	0.71 [34.2]	0.74 [35.6]