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MEASURING THE ENVIRONMENTAL IMPACT OF EMBEDDED/BANKFULL CULVERTS

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JOSEPH A. PAVLICK

ABSTRACT

Streams are dynamic systems constantly changing over time. The health of a stream system is tied to the amount of sedimentation occurring in a stream. The addition of roadway culverts into a stream has been shown to cause erosion and sedimentation problems if the culvert does not meet stream characteristics of slope, bankfull/width, and channel orientation. This has led to the design of embedded/bankfull culverts. In the State of Ohio, the Ohio Environmental Protection Agency and the United States Army Corps of Engineers now require the Ohio Department of Transportation to install embedded/bankfull culverts at all stream locations during new roadway construction. A 2008 preliminary study at Cleveland State University, showed an embedded/bankfull culvert can cost an additional 31.5% higher over traditional culvert installations. Though this design has been accepted by regulatory agencies, there has been little research to determine if embedded/bankfull culverts minimize the change in sedimentation patterns, or if embedded/bankful culverts minimize disruption to environment surrounding the culvert.

This study developed a decision tree approach to determine which existing testing methods are applicable to studying culverts, and then applied this decision tree to select tests for studying embedded/bankful culverts in the state of Ohio. 63 culverts were visited and surveyed. Sediment and water samples were collected and analyzed. Data was collected on particle-size distribution, total organic carbon, total suspended solids, and turbidity.

It was discovered through the field studies that many of the culverts surveyed in Ohio are not operating as embedded/bankfull culverts.The change is sedimentation patterns were compared to length, slope, diameter, and shear stress in the culvert. Some correlations were found between the change in sedimentation patterns and the physical characteristics of the culvert. All of the correlations found were in functioning culverts.More habitat data is needed to determine the effects on the habitat.

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CHAPTER I

INTRODUCTION

Generally, when the flow of water intersects the path of a roadway, either a culvert or bridge is constructed under the road to allow to the water to pass. Culverts are primarily used for storm drainage or stream flow (USEPA, 2005). Culverts offer a lower cost solution to bridges for allowing the flow water to pass under a highway. This study focuses on the impact of a roadway culvert on the stream environment.

Traditionally, culverts are designed to convey a specific design storm flow effectively. Because the culvert is primarily designed for storm flow, the design does not account for potential changes to the stream hydraulics or to sedimentation patterns over standard flow regimes (Tsihrintzis, 1995). Further, because culverts are designed to accommodate specific storm flows the stream is not concerned when selecting culvert sizes.

A stream is a dynamic system that is constantly changing over time (Banard, 2003). In a stream the energy of the flow, sediment load, and channel morphology are major factors in determining sedimentation patterns (Newton et al. 1997). The placement of a culvert in a stream can disrupt sedimentation patterns and the culvert does not adapt to natural changes in the stream. The interaction between a culvert and a stream is best described in the Washington Department of Fish and Wildlife Manual for Design of Road Culverts "A culvert is a rigid boundary set into a dynamic stream environment. As the natural stream channel changes, especially with changes in hydrology due to land use changes, culverts often are not able to accommodate those changes" (Bates, 2003). If a culvert is poorly designed, sediment may accumulate in the culvert thus reducing its capacity.

Culverts that do not match the characteristics (e.g. slope, orientation and bankful width) of the stream, can lead to excess sedimentation in and near the culvert due to the erosion of fill and bank material (ConnDOT, 2002). The bank-full width is defined as the width of the stream just before the stream over tops the channel bank and enters the flood stage (Sherwood & Huitger, 2005). Culverts that are designed to match the stream slope, orientation, and bank-full width are considered bank-full culverts. Of these parameters, the width and slope are most important for maintaining natural levels of sedimentation (Banard, 2003). In many cases, the culvert is sized larger than the bank-full width of the stream, and expansions and contractions are constructed to account for differences in width between the stream and the culvert. For example, a constriction at the inlet can result in culvert blowout that can release large volumes of sediment downstream (USEPA, 2005)(Banard, 2003).

In addition to blowouts, a constriction can accelerate water velocities through the culvert. As the jet of water exits the culvert, it can degrade and erode the stream bottom downstream of the culvert (Forest Service Stream Simulation Working Group, 2008).

The erosion of the downstream caused by a culvert is scouring. The continued scouring of a culvert can erode the stream to an elevation where the culvert invert is “perched” above the downstream tailwater. The perching of a culvert can obstruct the passage of aquatic organisms in a stream (Bouska &Paukert, 2009). Figure 1.1 shows a culvert installed in 1979 and in 1998 showing the result of scouring over a 19 year period.

Figure 1.1 Perching of a Culvert as a Result of Long-Term Scourring (Forest Service Stream Simulation Working Group, 2008)

a) Culvert installed in 1979   b) Culvert in 1998. Perching caused by scouring

Cui et al (2008) outlined several ways in which excess sediments, in particular fine sediments, affect stream health. As fine particles deposit, the voids in the streambed fill with fine particles creating an almost impenetrable bed. The filling of these small openings in the streambed causes both hydraulic and biological changes. For example, the reduction in the cross-sectional area of the stream as the bottom fills-in with sediments will change water depth and/or stream velocity. Further, the health of aquatic fauna, invertebrates and fish communities are dependent on the voids within the streambed. Without these voids, there is little room for benthic organisms to live and feed. Fish also rely on the voids for nesting as well. If there is a lack of benthic organisms for food, fish communities will decline due to lack of food resources (Artimage & Wood, 1997).

In 2003, *Miltner et al*. showed that declining stream health in Ohio was attributed to excess run-off caused by poor land use planning and poor construction practices. Miltner also showed that highly specialized species of aquatic organisms or those on the brink of extinction were affected in a manner such that any further disturbances to the biologic community could result in an overall reduction in species diversity.

In response to the changes caused by culverts, states have begun advocating changes in design that will reduce the environmental impacts of new culverts. Culverts that best match a stream's natural characteristics have the most ability to transport sediments effectively (USDA, 1998).The design of culverts has evolved to an embedded/bank-full culvert design (EBC). EBCs also known as stream simulation culverts or countersunk culverts "is intended to take advantage of the cost savings of culverts yet allow many of the stream processes found in unconfined channels" (Banard, 2003). From the Ohio Drainage and Design Manual Volume Two, an EBC is defined as a culvert that is depressed at least 10% of the culvert diameter into the stream and the culvert diameter is sized to the bank-full width (ODOT, 2010). It is specified by the design manual a depressed culvert will naturally fill with sediment deposits over time. For this research study, a traditional culvert is defined as a culvert that is not depressed in the stream at least 10%, or the culvert is depressed below the stream bottom but has not become embedded with stream sediments after installation. Figure 1.2 illustrates the difference between an EBC and a non-embedded culvert.

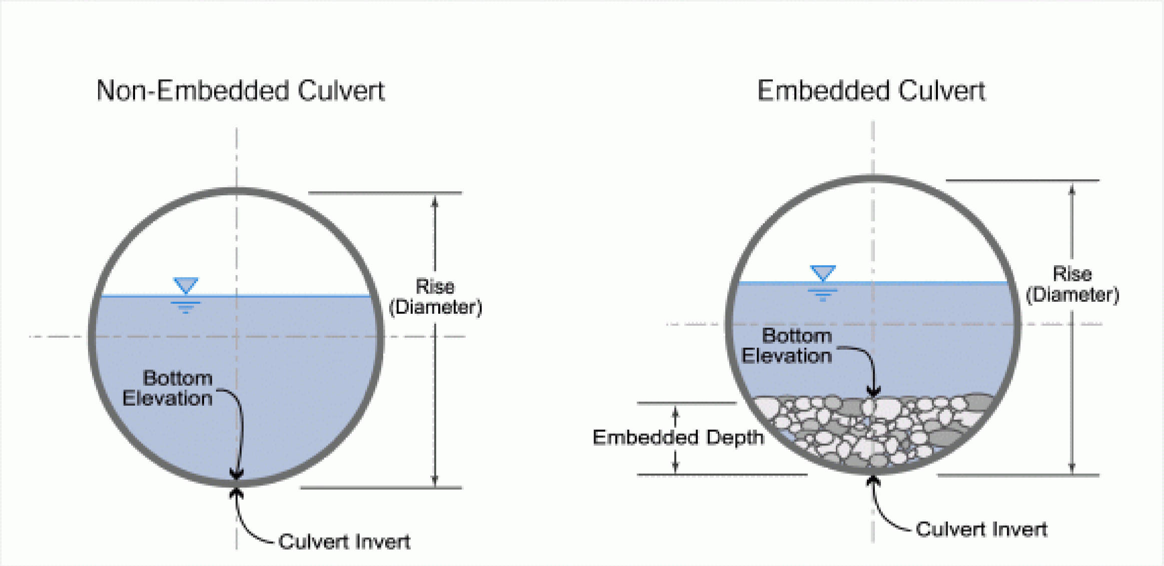

Figure 1.2 **Non-Embedded Culverts vs Embedded Culverts** (Corvallis, 2006)

This increased function of an EBC and purported reduction in impact has a price: the cost of installation of an EBC is more than a traditional culvert. In 2008, a preliminary study at Cleveland State University concluded that the increase in cost from an EBC compared to a traditional culvert is 31.5% higher (Cullen et al. 2008).

In Ohio, ODOT is now required by the Ohio Environmental Protection Agency (OhioEPA) to install EBCs as a requirement under the Clean Water Act 404 Nationwide Permit (NWP) program. Also, ODOT is required to install EBCsby the Army Corp of Engineer’s Nationwide Permit Number 14 (US Army Corp of Engineers, 2002).

At this point, there is currently little to no research that supports the effectiveness of the EBC design with respect to hydraulic function and biologic integrity. Due to the increased costs associated with EBCs and lack of scientific evidence, there is opposition from state DOT’s to the continued use of the EBC design. Currently, there is no universal set of testing methods for assessing the effectiveness of culverts. In addition, there is no published set of testing methods that specifically target EBCs. In order to evaluate if this EBC design is effective, a set of criteria for functionality must be established as well as the development of methods that will gather data related to the functionality criteria.

CHAPTER II

LITERATURE REVIEW

2.1 Stream Environment

Streams are complex and dynamic systems that change over time. Streams can have different properties and sizes as water flows down slope within a watershed. After a rain event, water starts flowing down slope through overland flow. As the flow progresses down slope water will start to become concentrated in shallow channels, this type of flow is classified as shallow concentrated flow. As more water continues to concentrate in these shallow channels, the flow becomes a first order stream. Downstream when two first order streams meet and combine, the resulting stream is classified as second order stream. When two-second order streams combine, the resulting stream is a third order stream, and the order of a stream will continue to increase as streams combine until the water discharges the watershed (Hughes, Kaufmann, & Weber, 2010).

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 in regards to change in sedimentation patterns (Newton et al. 1997). As stated in the Federal Highway Administration manual "Every sediment particle which passes a particular cross-section of the stream must satisfy the following two conditions: (1) it must have been eroded somewhere in the watershed above the cross-section; (2) it must be transported by the flow from the place of erosion to the cross-section" (Federal Highway Administration, 2001). 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 particle deposition or further transportation downstream (Ponce, 1989).

2.1.1Sediment Impacts on Flora and Benthic Organisms: Increased sedimentation, in particular fine sediments, can have adverse effects on aquatic flora as well as fish and invertebrate communities. High amounts of suspended fine sediments can limit light penetration. When fine sediments settle, they can deposit between the larger bed particles, clogging the substrate (Cui et al., 2008). The process of streambed clogging is best described by Cui et al. in 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, and impede filter feeding (Connolly & Pearson, 2007).

2.1.2 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). These fisheries rely on the successful spawning and migration of young fish. 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).

2.2 Culvert Functionality

Culverts have traditionally have been designed to convey a specific volume of water resulting from a storm and to ensure the stability of the culvert structure during that flow. Also due to the increased deposition inside the culvert, there is 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).

Major contributing factors to the functionality of a culvert are slope, orientation, and the ability to match culvert diameter and stream bank-full width. It has been observed that culverts that best match the slope, orientation and the bank-full width are less likely to have sedimentation problems (ConnDOT, 2002). As shown in Figure 2.1,*bank-full* 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). Scour can occur at both the inlet and outlet if the culvert is sized smaller than the bank-full width, thus leading to increased sediment loads downstream (ConnDOT, 2002).

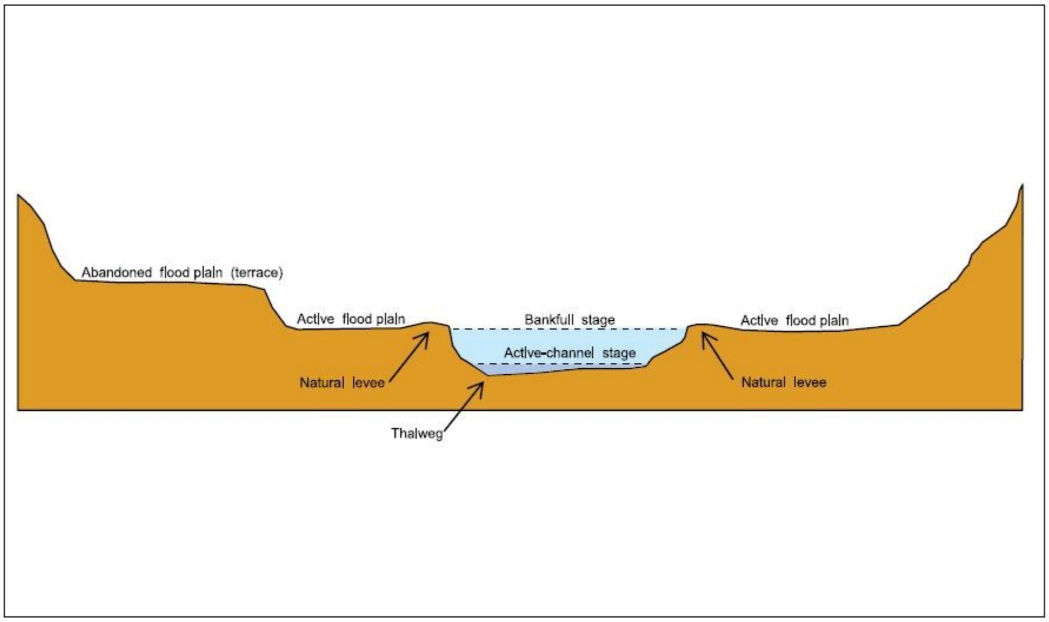

Figure 2.1 Illustration of Stream Bank-full Width (Sherwood & Huitger, 2005)

A change from the stream to the culvert can lead to sedimentation problems. Scour can occur at the inlet and outlet due to increased velocity of higher culvert slopes. Conversely, if the culvert 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 2.2 shows how the culvert can become blocked with debris at the inlet when the culvert is not aligned with the stream.

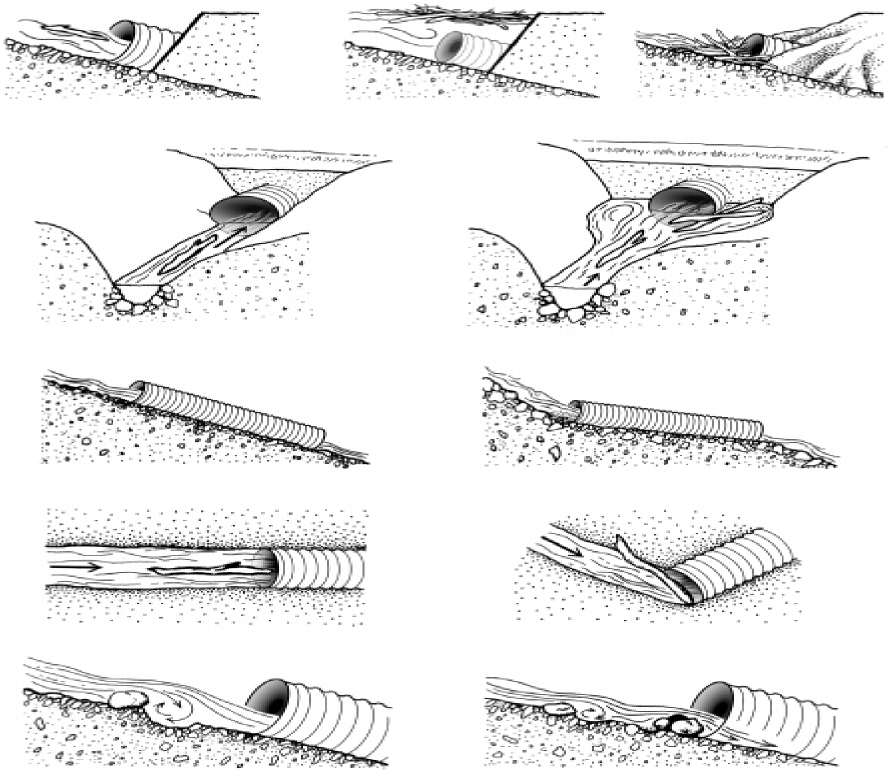

Figure 2.2 Illustrations Showing How Culvert Installation Can Affect Blockage at a Culvert Inlet (USDA, 1998)

Changes in land use from human activities change the ecology in streams. In 2001, Miltner et al. concluded that poor land use planning from new human development has an adverse effect on streams in Ohio. This study showed that due to the history of change through deforestation and other human activity, any further disturbances would result in an overall loss in diversity. Likewise, in 1997, Wood and Artimage showed that changes in land use and increased anthropogenic activities have increased the amount of fine sediments in stream environments. In some cases human activity have completely changed channel ecology and morphology (Artimage & Wood, 1997). Because improperly designed and installed culverts can lead to increased sediment loadings in a stream, it is important to minimize the amount of additional sediment loading introduced because of the culvert, and effectively allow for the continuity of sedimentation patterns through a culvert.

In addition to the change in sedimentation, traditional culverts can obstruct fish passage because of perched outlets (Bouska & Paukert, 2009), high water velocity in the culvert, and/or shallow water depth in the culvert (Poplar-Jeffers, Ira O. et al, 2009). Fish can become exhausted due to the energy expended to overcome greater culvert slopes or higher current velocities, and ultimately the fish may not be able to pass the culvert. If the fish does pass, the fish may not be able to travel nearly as far upstream (Bouska, Paukert, & Keane, 2010). Culverts not only impede the progress of the fish, but also can change the characteristics of the stream and thus change the fish habitat. An installed culvert replaces the natural meandering of a stream with a straight stretch in which there is little cover to build a nest or hide from predators (Bates, 2003).

In 2003, the Washington Department of Fish and Wildlife manual for design of road culverts detailed design procedures to match properties of the culvert with the characteristics of the stream for fish passage (Bates, 2003). Under this design, the culvert must meet the existing stream properties of slope, orientation and bankfull width. Because higher slopes increase velocity, matching the natural slope can reduce interior culvert velocities. Likewise, a culvert that matches the bank-full width can decrease culvert velocities as well as reduce the amount of sedimentation incurred. The State of Washington also requires culverts to be embedded 20 percent for culverts where fish passage is a design parameter.

As well as matching the physical characteristics of the stream, embedment of the culvert aids in reducing sedimentation increase as well as providing a natural bottom for fish to travel. It is stated in the Washington culvert design manual that embedding the culvert follows a stream simulation design and in “principle that, if fish can migrate through the natural channel, they can also migrate through a man-made channel that simulates the stream channel”(Bates, 2003).

2.3 Embedded/bank-full Culverts and Current Research

Current literature indicates that culverts that match slope, bank-full width, and orientation of the stream (bankfull culverts) experienced fewer blockage problems and fewer sedimentation problems (ConnDOT, 2002). As stated in Chapter I, culverts that are designed to match the stream slope, orientation, and bankfull width are considered bank-full culverts. Bankfull culverts that are embedded into the streambed are embedded/bankful culverts (EBC). Previous research has focused on studying the effects of existing traditional culverts on changes in sedimentation levels in the stream, and changes in fish passage. However, limited research has been done to examine the impact of EBCs to changes in sedimentation patterns or to the larger issue of how EBCs impact the surrounding environment(Tullis, Anderson, & Robinson, 2008).

Because there is little current research available about the environmental impact of a culvert, methods must first be developed to determine impact of a culvert. A culvert has the ability to change sedimentation patterns in stream (ConnDOT, 2002) and excess sedimentation has been shown to affect benthic populations (Cui et al., 2008).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. Though it has been observed that culverts that best match stream properties reduce excess sedimentation and erosion, actual sedimentation patterns through culverts are poorly understood (Singley & Hotchkiss, 2010). In addition to a lack of knowledge regarding sedimentation through culverts, there has been little research regarding hydraulics through EBCs. An example of the lack of understanding sedimentation patterns through a culvert is the balance between matching the design properties of an EBC to yield the desired result of little change in sedimentation patterns. 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).

There has also been little research conducted analyzing how a culvert effects the stream habitat (Bouska, Paukert, & Keane, 2010). Research is available detailing how an improperly placed culvert affects sedimentation, and how excess sedimentation affects stream ecology. As shown in the research, culverts that do not match stream characteristics can cause increased sedimentation problems. Increased sedimentation, in particular fine sediments, can clog the streambed and which is adversely effects aquatic species. Though the effects of increased sedimentation have been well documented, little research has been done to directly evaluate how the presence of a culvert affects the overall health of the stream environment. To evaluate the environmental impact of a culvert, a stream assessment is performed where previous assessments were made prior to the installation of a culvert. The change in score from the initial assessment to a new assessment allow for comparison of the impact of the culvert as well as the natural change of the stream over time (Bouska, Paukert, & Keane, 2010). The OhioEPA has developed a number of habitat assessment methods (Rankin, 2010) which have applicability to the culverts in this study. There are both qualitative and quantitative methods available for determining the health of a habitat. Quantitative measures include indices of the biotic and the invertebrate habitats. Qualitative assessments are available to evaluate the overall health of stream habitat in a relatively short period of time. Habitat assessment methods are further described in Chapter 3.

2.4 Scope of Work

The primary objective of this project is to determine if bankfull culverts installed in Ohio have caused quantitative environmental changes or cumulative impacts and are these changes, if any, related to stream size or culvert diameter, slope and/or length. Culvert diameter, slope, and length are all dimensions that are designed by an engineer. Because length, slope, and diameter are design variables, it is important to determine to what effect these parameters have on the effectiveness of a culvert. In order to address the overall objective specific research questions were developed. The research questions that this study attempted to answer are:

- How is the effectiveness of a bankfull culvert affected by culvert diameter, slope and length?
- Does the size of the stream in which the culvert is placed affect culvert effectiveness?
- How have bankfull culverts affected the overall habitat surrounding a culvert?
- What, if any, impacts do bankfull culverts have on flood attenuation?

In order to answer these research questions the first step was to develop a methodology to select a series of techniques that will properly evaluate the performance of EBCs. A search of the literature shows there is no published set of testing methods to evaluate the effectiveness of a culvert. The effectiveness of an EBC will be evaluated based on the ability of the culvert to minimize the change in environmental characteristics of the stream between upstream and downstream of the culvert. Using testing methods presently available to test stream quality, a decision tree was developed to aid researchers select testing methods for evaluating the impact of culverts. The decision tree was developed with a focus to allow researchers address a specific research objective but select tests that can gather relevant data on a limited budget.

The second step was to apply the decision tree to select the tests needed for culvert evaluation in Ohio. Currently there are 60 EBCs as designated by ODOT. Since there is little existing data on these culverts, the data in this study was used to compare EBCs to traditional culverts as well as provide baseline data for possible future studies on these culverts.

CHAPTER III

DEVELOPMENT OF DECISION TREE FOR TESTING CULVERTS

There is no established set of criteria to evaluate EBCs available in the scientific literature. In order to evaluate EBCs, a general methodology must first be developed for all scenarios in which an EBC exists. This chapter will first outline the most common and available methods for testing the environmental impact of EBCs. A decision tree methodology was developed to aid in the selection of tests applicable to the goals and resources of a specific study. This decision tree methodology was then applied to a specific study of EBC's in Ohio.

3.1 Available Testing Methods

3.1.1 Sediment Load Particle Sizes: As stated in Chapter 2, a culvert that does not match the stream characteristics may cause sedimentation patterns to change in a stream. A sediment particle can be transported in a stream in either one of two ways. One mode of transport is along the top of the bedload. The bedload consists of deposited sediment particles on the channel bottom. Movement of a sediment particle occurs when the shear stress of the stream becomes larger than the critical shear stress of a particle. A particle may travel along the bed load, rolling across deposited material where through the arrangement of the sediment particles, allow the stream to determine its own cross-sectional area(Ponce, 1989). In addition, present in the bedload is the wash load. The wash load consists of fine sediment particles and fine particles are easily transported through a stream. The transport of the wash load is limited by availability of fine particles in a watershed and not the hydraulics of the stream (Federal Highway Administration, 2001).

The second mode of sediment transportation is through the suspended load. A sediment particle can become suspended in the flow of the stream and its deposition is based on "the effects of sediment inertia, lift force, gravitational force, concentration gradient, fluid turbulence intensity gradient, and/or sediment-sediment collisions" (Wang et al., 2008). It is important to note that depending on the shear stress of the stream, a particle may be transported through the bed load or the suspended load. A bedload particle may become suspended if the shear stress increases, and vice versa if the shear stress decreases (Federal Highway Administration, 2001). The increase in shear stress at a constriction at a culvert inlet can cause erosion and scouring of the channel bed and stream banks disrupting the natural sedimentation patterns in a stream.

To evaluate if and how a culvert changes the characteristics of the bed load sediments in a stream, a particle grain-size distribution can be used. A sample of the bed load sediments shows the sedimentation at a given location over time. This distribution is the cumulative result of all deposition and erosion that has historically occurred (Stutter et al., 2009). The distribution data on sediments can be collected by sieve analysis

(ASTM, test #6913-04, 2009). The particle grain-size distribution should be measured for sediment samples upstream, downstream, and through the reach of the culvert. In this way, the sedimentation patterns can be compared and a determination made as to the culvert's functionality with respect to sediment transport. As mentioned above in Section 2.1-1, the percentage of fine particulates present in the bed load is of particular importance in terms of biotic integrity of a stream (Connolly & Pearson, 2007). Therefore, a change of fine particulates may be correlated to changes in the surrounding environment.

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).

In addition to collecting data related to the long-term sedimentation patterns at a site, it may be useful to gather data on instantaneous sedimentation occurring during specific flows. Sediments can be transported along the top of the bed load by the energy of the flow as well as becoming suspended and traveling through the water. Collecting data on the amount of suspended sediment in the water at a moment in time may give insight to the instantaneous sedimentation occurring during specific flows. This can be accomplished by measuring the Total Suspended Solids (TSS) (Washington State Department of Ecology, 2010) in the water as it passes a specific point along the reach of the culvert. Using the methods outlined by ASTM D5907-09, the amount of total suspended solids can be measured by passing a sample of water through a filter. After drying the filter and cooling in a desiccator, the weight of material present on the filter can be used to determine the concentration of suspended solids in the water (Sawyer, McCarty, & Parkin, 2003).

The amount of suspended sediment can also be indirectly measured by determining the turbidity of the water at a specific point (Sawyer, McCarty, & Parkin, 2003). Turbidity is the measure of the dispersion of light through water. The higher the turbidity the more light is dispersed and the 'cloudier' the water appears. Light is dispersed by suspended colloids and solids in the water. The more suspended and colloidal material present, the higher the turbidity of the water. Thus by measuring the change in turbidity along the reach of the culvert, the change in suspended sediment in the water along the reach of the culvert can be estimated. Turbidity can be measured easily with a turbidimeter ASTM D7315. The meter measures the amount of light that passes through the sample and thus a measure of turbidity is obtained (Sawyer, McCarty, & Parkin, 2003).

3.1.2 Determining Stream Hydraulics: A culvert changes the hydraulics of a stream, which is important not only for sedimentation but for the movement of macro-invertebrates and fish passage as well. Streams naturally meander through a terrain and sinuosity creates energy losses and points for sedimentation (Bates, 2003). These energy "breaks" provide a place for aquatic migratory animals to rest while traveling upstream.

However, culverts are straight and have little to no sinuosity. Because of this, there is little opportunity within a culvert for the flow to lose energy. If there are no energy breaks within a culvert except for pipe friction loss, this can become a barrier for upstream movement of macro-invertebrates and fish (Bates, 2003). In addition, if the culvert changes the cross sectional area as compared to the natural stream the culvert may lower or raise the water depth. If the depth within a culvert becomes less than the minimum depth for the passing fish, it becomes a barrier (Bouska & Paukert, 2009). If the passage aquatic macro-invertebrates of fish or other specific through a culvert is being measured, hydraulic measurements and detailed velocity profiles must be taken at each site for modeling.

The presence of a culvert has the potential to create ponding upstream of the culvert during storm events. Ponding at culvert locations is important for transportation agencies where flooding can overtop the roadway or inundate land upstream of the culvert (DeGroot, 2010). Hydrologic modeling tools are available to model the flow caused by the design storm. Such models can be used to predict the height of ponding behind upstream of the culvert. This tool may be useful to compare the height of ponding for different percentages of culvert embedment. To model the flow data must be collected on hydrologic soil type, watershed area, land use, height of roadway above the culvert, storage-area relationship of the watershed, precipitation depth for design storm, and time of concentration (DeGroot, 2010).

3.1.3 Habitat Assessment: 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 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 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 fish. 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 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 much skill and experience. Reliable data is 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 an ICI. 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). In the QHEI, the primary focus of the evaluation is to determine the habitat quality for a fish community and identify sources of impairment (Rankin, 2010). As stated in its name, QHEI is a qualitative tool to assess a stream. The limitation of QHEI is that is not as comprehensive as an IBI or ICI study. Data gathered can be very general and does 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 determine a general condition of the local habitat quickly.

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 scores 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, the conditions that constitute a healthy stream differ from that of a higher order stream. For headwaters streams 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). Defined by the OhioEPA, the class of a primary headwater habitat (PHWH) is determined by the amount of annual flow present throughout the year, and the amount of aquatic life present in the stream. Streams can be classified as class I, class II, or class III PWHW. A class I stream is defined 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). 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 bank-full width and does not evaluate features important to fish habitat such as in-stream cover and quality of riffle or pool development (Tuckerman, 2002).

3.2 Decision Tree for Selection of Testing Methods for a Specific Study

By using the previous outlined tests and general methodology in this chapter for evaluating EBCs, a decision-tree approach can be developed to determine the appropriate tests required in a study of EBC. The selection of appropriate tests and collection methods for any study are determined by the research objectives and resources available. Table 3.1 lists a range of applicable tests along with the benefits and drawbacks for each test. Listed with the available tests is an approximation of the time and cost associated with performing each test. It is assumed in this table, that there no necessary equipment purchases and the main driver of cost is the cost of labor associated with the time required to perform each test. Therefore, the lower amount of time required, the lower the cost of performing the test. Table 3.1 lays out the criteria with which a decision tree can be developed. The decision tree is meant to aid a researcher in the selection of appropriate tests based on the specific scope and resource limitations of a specific research project relating to the evaluation of culverts. The decision tree is shown in Figure 3.1.

Table 3.1 Available Tests for Determining Functionality of EBCs

Reason for Test	Parameter	Technique	Time and Cost[1]	Benefit	Drawback	Reference
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	(Washington Dep. Of Fish &Wildlife 2003) (House et al., 2005)
		Physical & Hydraulic Measurements	Hours	View of general physical and hydraulic conditions used for fish modeling	Fish passage is implied	(Washington Dep. Of Fish &Wildlife 2003) (House et al., 2005)
Changes in sedimentation may affect water quality and ability for stream to support invertebrates and salamanoids	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	(Wood &Armitage, 1997) (Lane & Sheridan, 2002)
		Turbidity	Hours	Detailed information on water quality and sediment transport through water	Information on water quality only, no information on habitat	(Wood &Armitage, 1997) (Lane & Sheridan, 2002)
		Particle Size Distribution	Weeks	General view of habitat quality through particle size distribution in sediment	Habitat quality in terms of sediment size only	(Miltner et al.,2003) (Wood &Armitage, 1997) (USDA Forest Service, 1998)
		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	(Cordone& Kelly 1961) (Shields et al., 2008)
Changes in continuity of the stream may be affect the overall habitat 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	(Ohio EPA, 1987a,1987b, 1989, Karr, 1981)
		Qualitative Habitat Evaluation Index (QHEI)	Hours	General view of habitat quality in a short time through	Habitat quality in terms of physical condition only	(Rankin, 2010)
		Invertebrate Community Index (ICI)	Months to a Year	Detailed view of habitat quality through diversity of macroinverbrae population	Habitat quality in terms of macroinvertebrate populations & pollution sensitive macroinvertebrates	(Ohio EPA, 1987a,1987b, 1989)

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

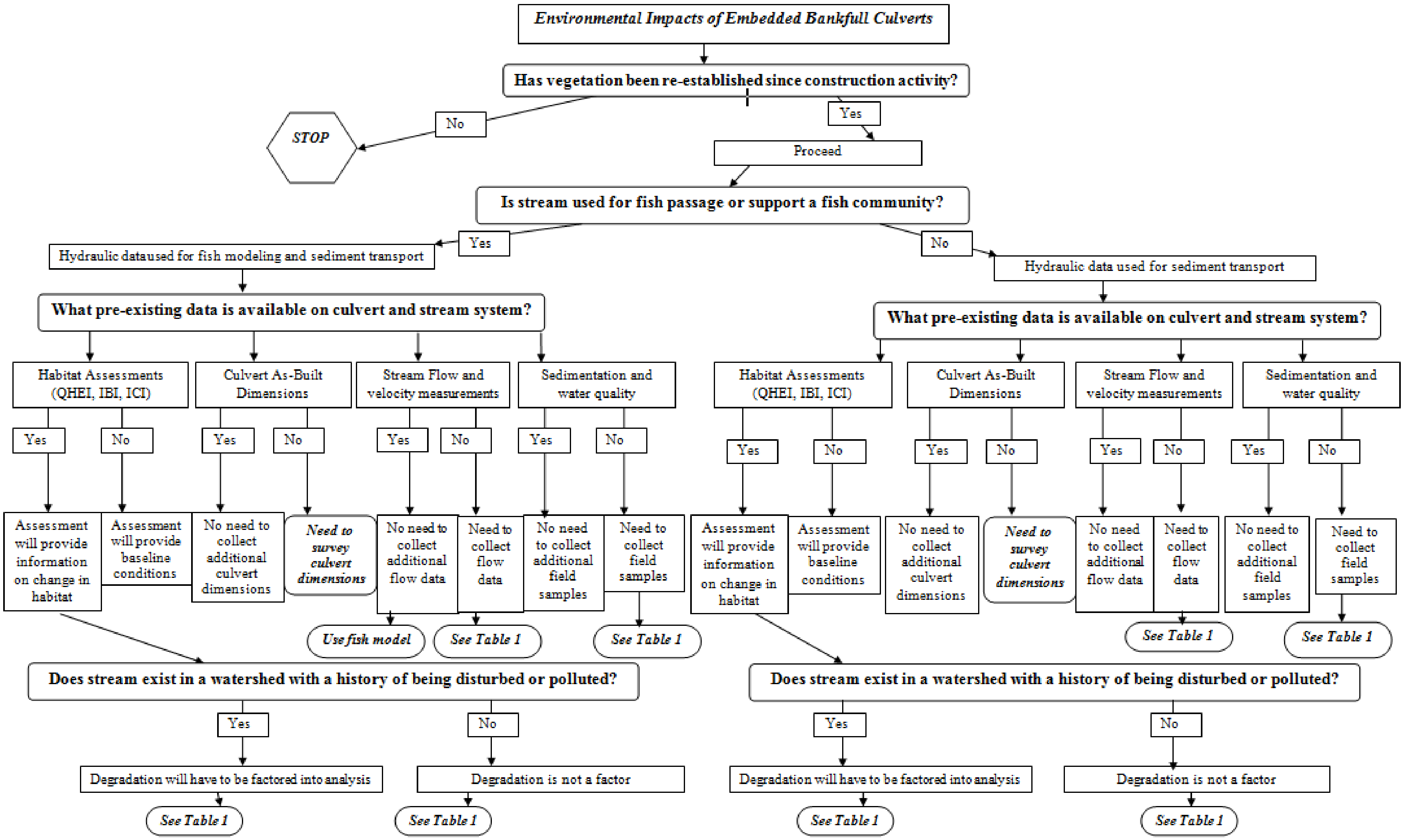

Figure 3.1 Decision Tree for Selecting Testing Methods

CHAPTER IV

OHIO FIELD STUDY

The decision tree was used for the selection of the tests for a study of EBCs in the State of Ohio. As stated in chapter 2 the research objectives of this study applied to this thesis are to determine:

- How is the effectiveness of a bankfull culvert affected by culvert diameter, slope and length?
- Does the size of the stream in which the culvert is placed affect culvert effectiveness?
- Have the bankfull culverts installed in Ohio caused quantitative environmental changesor cumulative impacts and are these changes, if any, related to stream size or culvert diameter, slope and/or length?
- What, if any, impactdobankfull culverts have on flood attenuation?

This project was funded at $20,000 by ODOT and the duration of the project was 16 months. Therefore, data had to be collected in a relatively short period of time and at a

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[1] "Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS, 1998).

minimal cost. For this study, fish passage was not of concern for stream health because there are few species of fish that migrate through streams in Ohio.

4.1 Application of Decision Tree

The decision tree developed in Chapter 3 shown in Figure3.1 can be used to determine what tests are required for a specific study. This tree was used to determine what tests were required in the study of EBCs in the ODOT study. Following the progression of the decision tree the following steps and reasons are listed below. Table 4.1 shows a summary of tests selected for the study of EBCs in the State of Ohio.

Question 1: Has vegetation been re-established since construction activity?

Answer: Yes, the vegetation was present at each site, so the stream habitat has been re-established after construction. The study examined a stream system at steady state.

Question 2: Is stream used for fish passage or support a fish community?

Answer: None of the culverts studied are located on streams where fish passage is an issue. The hydraulic data was used for sediment transport analysis.

Question 3: What pre-existing data is available on culvert and stream system?

Answer : There have been QHEI assessments performed on some of the streams being studied. A new QHEI assessment at these sites will provide data on how the habitat has responded with the addition of a culvert into the stream. There is little or no as-built, flow, or sedimentation data on any of the culverts being studied. Therefore, surveys were performed to collect data on the as-built dimensions, flow, and sedimentation patterns at each site. Grab samples and water samples were collected at each site. Particle-size

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[1] "Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS, 1998).

distributions were determined using sieve analysis, and TOC was determined using the burn on ignition methods proposed by Schumacher. TSS and Turbidity were determined using the methods listed previously in this chapter. Flow rates were also measured at each site during collection. The flow rates were used to determine instantaneous the shear stress at each culvert for TSS and Turbidity analysis. Because ODOT also requested the height of ponding during flood events, data was collected through available internet resources on the watershed and precipitation depth during the 100 year flood event.

Question 4: Does stream exist in a watershed with a history of being disturbed or polluted?

Answer: Very little Total Maximum Daily Load (TMDL) data is available for the watersheds in question. QHEIs were performed but the state of the watershed as a whole was not factored in analysis.

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[1] "Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS, 1998).

Table 4.1 Tests Selected for EBCs in Ohio

Aspect Being Measured	Data Collected	Laboratory Tests Performed	Reason for selection
Sedimentation Patterns	Grab samples collected at upstream, downstream , and through reach of culvert	Particle-Size Distribution using Sieve Analysis.TOC using burn on ignition method.	Data will provide information on sedimentation patterns upstream, downstream, and through reach of culvert. Little to no prior data collected
Water Quality	Water samples collected upstream, downstream , and through reach of culvert	Total Suspended Solids and Turbidity	Data will provide information on water quality upstream, downstream, and through reach of culvert. Little to no prior data collected
Hydraulic Data	Instantaneous Flow Rate	Field Collection	Data used to determine shear stress in culvert for TSS and Turbidity analysis
As-built dimensions	Survey of culvert length, slope, diameter, with upstream and downstream profiles	Field Collection	Data used to determine effect of length, slope, width, and shear stress on sedimentation patterns
Stream Habitat	New habitat assessments at sites where QHEIs were performed prior to installation	Qualitative Habitat Evaluation Index (QHEI)	Limited time and funds available for habitat assessments.Data used to determine response of habita after addition of stream.
Flood Attenuation	Hydrologic Soil Group, Watershed Area, Precipitation	Resources Available through internet databases	Determine ponding depth during flood events

4.2 Data Collection Methods

ODOT provided 60 sites where EBCs were installed. The culverts were installed in various regions of Ohio with different geology, topography, and land use. Specifics on the 60 culverts are provided in Section 4.3 below. The 60 culverts listed by ODOT included 45 circular culverts, 12 box and 3 elliptical culverts. For comparison of EBC to

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[1] "Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS, 1998).

traditional culverts, three traditional culverts were selected in the field to provide control data.

At each site, grab samples of sediment and water were collected. Samples were collected at five locations along the reach of the culvert. The locations are upstream of the culvert, at the inlet, inside the culvert, at the outlet, and downstream of the culvert. The samples were collected progressing from downstream culvert to upstream of the culvert. At some locations, a water or sediment sample could not be collected. Sediment samples could not be collected where there was no sediment present or the culvert was too small in diameter to collect sediment from the interior. Some water samples could not be collected either because the

- culvert was too small to enter to collect a sample
- the depth of the water was too deep to enter
- the stream had dried due to low summer flows
- the culvert was a control traditional culvert, and only selected data was collected

After the samples were collected, a field survey was done using a data collector, total station and prism. The surveyed locations were the top of culvert, edge of each headwall and the upstream and downstream stream profiles. In addition, dimensions were verified for the depth of the embedment and diameter of the culvert. Using the surveyed information, length and slope of the culvert were determined. Collected samples were analyzed in the lab to determine the particle size distribution using sieve analysis (ASTM

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[1] "Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS, 1998).

#6913-04), TOC of the sediments using the methods proposed by Schumacher, TSS using ASTM #D5907-09, and Turbidity using ASTM #D7315.

4.3 Culvert Location Details & Results of Field Study

The culverts studied are located in Athens, Crawford, Meigs, Fairfield, Paulding, Ross, and Wayne counties. The culverts are 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. Figure 4.1 shows the location of the culverts by county along with the number of culverts in each county, and Figure 4.2 shows the basic physiogeography of Ohio.

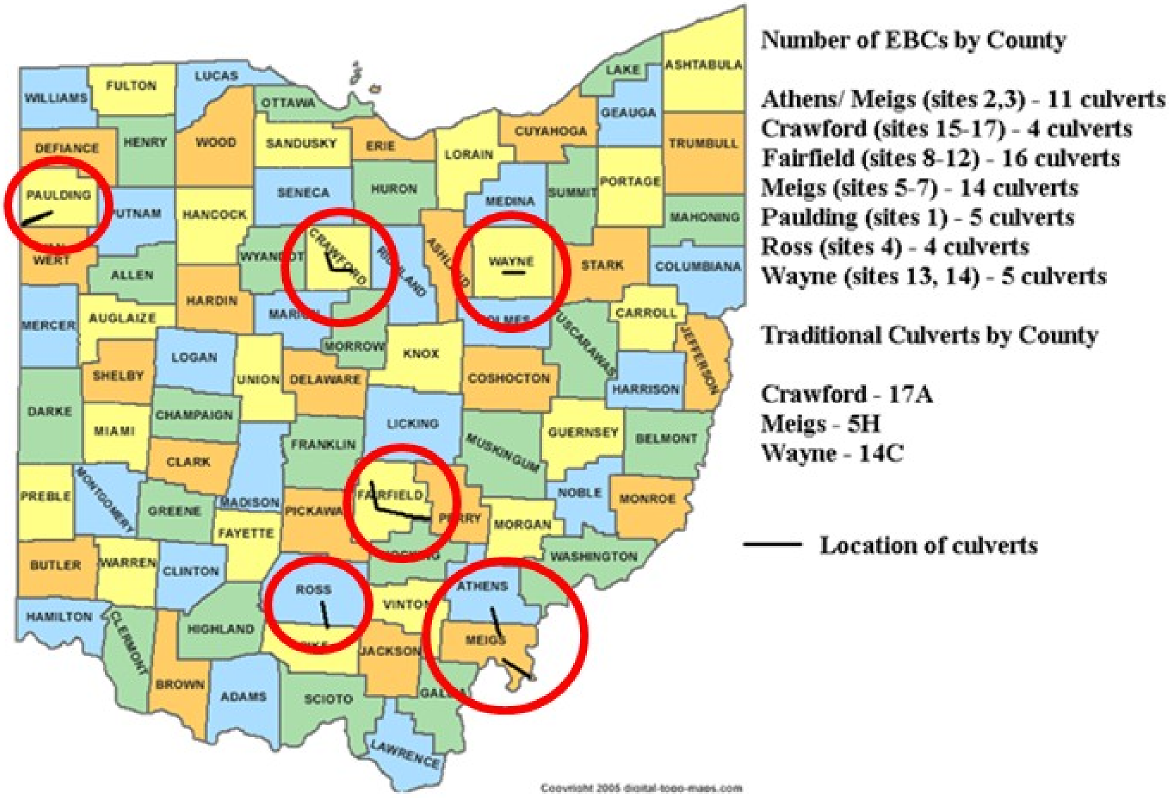

Figure 4.1 Locations of EBCs in Ohio

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[1] “Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common” (ODGS, 1998).

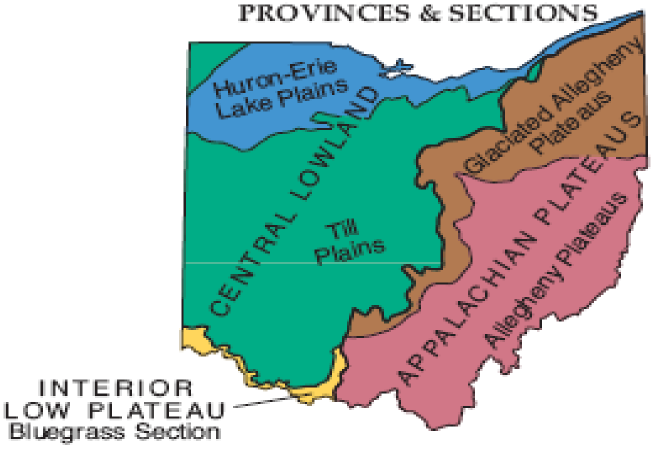

Figure 4.2 Basic Physio-geography of Ohio (ODGS, 1998)

4.3.1 Athens County: In southern Athens County and northern Meigs County there were 11 culverts designated by ODOT as EBC. The culverts in the region are culverts 2Athrough 2G, and 3A through 3D located on US Highway 33. The contract 2 culverts are located in the Hocking Watershed (HUC: 05030204) (USGS, 2009), and the contract 3 culverts are located in the Upper-Ohio Shade Watershed (HUC: 05030202) (USGS, 2009).The general topography of the region is Marietta Plateau[1] (ODGS, 1998). 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 areaof 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 4.2is a summary of the results from the field survey in Athens County.

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[1] "Dissected, high relief plateau; mostly fine-grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS, 1998).

Table 4.2 Athens County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC	Pre-construction QHEI done?
2A	2	511.80	462.61	5.9	6	1.150%	1.124%	0 (culvert bottom lined with 2 in of conc)	0	N	N	Y
2B	1	451.77	453.09	5.9	5	2.900%	2.947%	0 (culvert bottom lined with 5 in of conc)	0	N	N	N
2C	1	534.77	493.95	3.5	3.5	8.240%	7.791%	0	0	N	N	N
2D	1	853.01	823.025	5.5	5.5	2.090%	1.946%	0 (culvert bottom lined with 11 in of conc)	0	N	N	Y
2E	1	539.69	534.51	4.5	4.5	3.560%	3.388%	0	0	N	N	N
2F	1	639.76	nm	3.5	3.5	4.230%	nm	0 at inlet	0	N	N	N
2G	1	410.10	408.48	2.5	2.5	6.690%	6.336%	0	0	N	N	N
3A	1	749.66	749.85	5.9	6	3.160%	3.546%	0 (concrete pad at outlet)	0	Y	N	N
3B	3	825.12	823.129	12	12	0.600%	0.661%	0 (concrete pad at outlet)	0	Y	N	Y
3C	1	311.68	313.795	4.5	4.5	3.190%	3.329%	0 (concrete pad at outlet)	0	Y	N	Y
3D	1	250.98	253.877	5.5	5.5	3.860%	5.644%	0 (concrete pad at outlet)	0	Y	N	Y

As can be seen from Table 4.2, the field survey found that culverts 2D, 2E, 2G, 3A, 3B, and 3C were installed as indicated in the initial design. Culverts 2A and 2C were installed with shorter lengths than designed. Culvert 2B was installed with a diameter of five feet as opposed to the designed six feet. 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 was unable to be surveyed because of a large steep drop-off from the highway embankment to the culvert.

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. Figure 4.3 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. Of all the culverts surveyed in Athens County, the only culvert with sediment present inside the culvert was culvert 3B. 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 4.4, 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.

Figure 4.3 Culvert 2A, showing concrete lining on bottom of culvert

Water upstream of culvert 2E

Water exiting culvert 2E

Figure 4.4 Change in Watercolor in Culvert 2E

4.3.2 Crawford County: In Crawford County there are four culverts identified by ODOT as EBCs (15A, 15B, 16A, and 17B). They are located on US Highway 30. In addition, one traditional culvert (17A) was randomly selected for control. The culverts are located in the Sandusky Watershed (HUC: 04100011) (USGS, 2009). The general topography of the area is Central Ohio Till Plain[2] (ODGS, 1998). The area is mainly flat-rural and the land is primarily used for agriculture. Culverts 15A, 15B, 16A, and 17A are located near Crestline, OH. In the year 2000, Crestline had a population of 5,088 (US Census Bureau, 2010). Culvert 17B is located near Bucyrus, OH. In the year 2000, Bucyrus had a population of 13,244 (US Census Bureau, 2010).

Culverts 15B, 15A, and 17A 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 4.3. Culvert 17A is located on a 1st order stream, 15A, 15B, 16A are located on 2nd order streams, and 17B is located on a 4th order stream. Culverts 15B and 15A were installed in series from 15B to 15A. Culvert 15B was installed on a service road and 15A was installed on the highway. Culvert 17B was installed as designed. Culverts 15A, 15B, and 16C were installed with different slopes than designed. Culvert 15B and 17B had no embedment present at the time of sampling and at 15B the outlet was perched above the downstream. Culverts 15A, and 16A were installed as EBCs. Aside from the perching of 15A, there were no other noted unique features about these culverts.

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[2] "Surface of clayey till, well-defined moraines, with intervening flat lying ground moraine and intermorainal lake basins; no boulder belts; about a dozen silt-, clay-, and till-filled lakes basins range in area from a few to 200 square miles; few large streams; limited sand & gravel outwash" (ODGS, 1998).

Table 4.3 Crawford County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC
15A	2	246.06	248.736	7.38	8	0.340%	0.151%	1	12.5	Y	N
15B	2	118.11	120.951	7.38	8	0.350%	0.429%	0	0	Y	N
16A	2	314.96	320.44	11.81	12	0.340%	1.708%	3	25	Y	Y
17A	1	Unknown	293.162	Unknown	6	Unknown	0.247%	0	0	Unknown	N
17B	4	462.59	461.121	6.4	6	0.620%	0.618%	0	0	Y	N

Nm = not measured   Unknown = Design parameter not known

4.3.3 Fairfield County: In Fairfield County were 16 culverts specified by ODOT as embedded/bankfull. Culverts 8A, 8B, 8C, 9A, 9B, 9C, 9D, 10A, 10B, 11A, 11B, are located on US Highway 33 near Lancaster, OH in the Hocking Watershed (HUC: 05030204) (USGS, 2009). Culverts 12Athrough 12E are located near Canal-Winchester, OH near the entrance and exit ramps from US 33 to Diley Rd located in the Upper Scioto Watershed (HUC: 05060001) (USGS, 2009).Culverts 12A and 12B are located on EichornRd 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 topography of the land at site 12 culverts are classified as Columbus Lowland[3] (ODGS, 1998).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 site 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, OH. The population of Lancaster in 2000 was 35,335 (US Census Bureau, 2010). There are many different topographic classifications in this area. Culverts 8A, 8B, 8C, are located on the Galion Glaciated Low Plateau[4] (ODGS, 1998). Culverts 9B and 9C are located on the Killbuck-Glaciated Pittsburg Plateau[5] (ODGS, 1998). Culverts 9D, 10A, and 10B are located on Illianoian Glaciated Allegheny Plateau[6] (ODGS, 1998).

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[3] "Lowland surrounded in all directions by relative uplands, having a broad regional slope toward the Scioto Valley, many larger streams" (ODGS, 1998).

[4] "Rolling upland transitional between the gently rolling Till Plain and the hilly Glaciated Allegheny Plateu, mantled with thin to thick drift" (ODGS, 1998).

[5] "Ridges and flat uplands generally above 1200', covered with thin drift and dissected by steep valleys, valley segments alternate between broad drift-filled and narrow rock walled-reaches" (ODGS, 1998).

[6] "Dissected, rugged hills, loess and older drift on ridgetops, but absent on bedrock slopes; dissection similar to unglaciated regions of the Allegheny Plateau" (ODGS, 1998).

Culverts 11A and 11B are located on Shawnee-Mississippi Plateau[7] (ODGS, 1998). 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 and the QHEIs were performed in July 2010. Table 4.4 shows the results of the field study. 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.

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[7] "High relief, highly dissected plateau of course and fine grained rock sequences; most rugged area in Ohio; remnants of ancient lacustrine clay-filled Teays drainage system are extensive in lowlands, absent in uplands" (ODGS, 1998).

Table 4.4 Fairfield County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC	Pre-construction QHEI done?
8A	4	236	237.298	Box 8' H x 18' W	Box 8' H x 18' W	0.120%	0.157%	0		N	N	N
8B	3	143	143.278	14	14	0.870%	0.790%	1	0.87	N	Y	Y
8C	2	203	205.753	7	7	0.870%	0.822%	2	0.435	N	Y	N
9A	4	192	190.805	Box 10' H x 20' W	Box 10' H x 20' W	0.280%	0.437%	varies		N	N	Y
9B	3	312	312.133	7	7	0.700%	1.227%	1.75	0.4	Y	hybrid	N
9C	3	90	89.49	6	6	0.700%	0.638%	1.17	0.5982906	Y	Y	N
9D	2	224	225.427	9	9	0.190%	0.171%	0.58	0.32758621	Y	Y	Y
10A	1	280	280.56	5	5	2.510%	4.774%	0.5	5.02	N	hybrid	N
10B	3	259	261.28	10.5	10.5	0.400%	0.367%	0.58	0.68965517	N	hybrid	Y
11A	4	54	52.201	Box 8 H x 21 W	Box 8' H x 21' W	0.480%	0.104%	5.167	52.0875	N	N	N
11B	4	264	261.849	Box 9 H x 18 W	Box 9' H x 18' W	0.360%	0.493%	0	0	N	N	N
12A	2	58	75.485	Box 8' H x 8' W	Box 8' H x 8' W	0.120%	0.088%	1.75	21.875	N	N	N
12B	2	55	55.61	Box 8' H x 8' W	Box 8' H x 8' W	1.380%	1.416%	2.17	27.125	N	N	N
12C	3	210	173.2	20	20	0.070%	0.036%	1.25	0.056	Y	Y	Y
12D	4	276	276.24	8	8	0.370%	0.585%	1.75	0.21142857	Y	Y	Y
12E	4	125	109.74	10.5	10.5	0.160%	0.137%	3.17	0.05047319	Y	Y	N
12F	4	Unknown	nm	Unknown	nm	Unknown	nm	nm	nm	Unknown	nm	N

Nm = not measured   Unknown = Design parameter not known

Culvert 8A has no embedment and there is a large circular culvert approximately 500 feet upstream. The stream immediately enters a wetland area downstream. Because there is not a long enough stretch of stream to survey, a QHEI was not performed at this site. Culvert 8B is downstream of culvert 8C. the stream that passes through combines with another stream upstream of 8B. Because of this 8B is on a higher order stream than 8C. Culverts 9C and 9B are in series. 9C is immediately upstream of culvert 9B. At 11B, it appears the stream has begun scouring the inlet due to a change in orientation of the stream to the culvert. The site 12 culverts are in series from 12A, 12B, further downstream 12E and further downstream 12D and finally 12C. Culvert 12D has another culvert immediately upstream. Because the upstream sample for 12D is still in the reach of the culvert upstream, no samples were taken upstream of 12D and no QHEI was performed for culvert 12D. 12F is a culvert surveyed between culverts 12D and 12C. The purpose of collecting inlet and outlet samples was to measure if there were significant changes in the sedimentation pattern as the stream progresses from 12D to 12C through this smaller culvert.QHEIs were performed at culverts 8B, 8C, 9B & C, 9D, 10A, 10B, 11A, 11B, and 12C

4.3.4 Meigs County: There were 14 culverts specified as embedded/bankfull in Meigs County. The culverts in Meigs County are 5A, 5B,5C,5D,5E,5F,5G,6A,6B,6C,6D,6E,6F,7A, and 7B. Culvert 5H is a traditional culvert was randomly selected for control. These culverts are located in Upper Ohio-Shade Watershed (HUC: 05030202) (USGS, 2009). All of the culverts are located in southeastern Meigs County on US Highway 33 except culverts6C and 6F. Culvert 6C is

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[8] "Dissected, high-relief plateau, mostly fine grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS,1998).

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. 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 topography of the region is the Marietta Plateau[8] (ODGS,1998).

The culverts in Meigs County were surveyed in April 2010 and QHEIs were performed in July and August of 2010. Table 4.5 shows the results of the field survey.All data for 5G was collected using the data collector, but in the field there was a malfunction with the data collector storing the surveyed information. Notes had to be taken and then surveys redrawn for all the culverts using the hand written notes. Because of the equipment malfunction there was not enough data collected to complete the survey for 5F. In addition, the slope and length collected for 5D needs to be verified. 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 from the design length.

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[8] "Dissected, high-relief plateau, mostly fine grained rocks; red shales and red soils relatively common; landslides common; remnants of ancient lacustrine clay-filled Teays drainage system common" (ODGS,1998).

Table 4.5 Meigs County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC	Pre-construction QHEI done?
5A	2	535	535.279	6	6	2.560%	2.523%	1	16.6666667	Y	hybrid	Y
5B	1	378	378.2	5	5	4.640%	4.529%	1.83	36.6	Y	hybrid	Y
5C	1	310	297.764	4	4	5.380%	5.219%	2.75	68.75	Y	hybrid	Y
5D	2	500	478.1778	10	12	2.190%	1.948%	0	0	Y	N	N
5E	2	615	615.9	12	12	0.690%	0.676%	2.42	20.1666667	Y	hybrid	Y
5F	1	650	nm	8	8	1.180%	nm	4	50	Y	Y	N
5G	2	523	524.23	10	12	0.250%	0.179%	0.4167	3.4725	Y	Y	Y
5H	1	Unknown	574.865	Unknown	4	Unknown	4.499%	traditional culvert used for control	0	Unknown	N	N
6A	1	295	296.1269	4	4	2.200%	2.423%	0	0	Y	N	Y
6B	1	264	265.63	3.5	3.5	5.000%	4.070%	0.92	26.2857143	Y	Y	N
6C	2	85	85.59	ellipse 5.67 x 8.17	ellipse 5.67 x 8.17	0.800%	0.748%	2.83	49.9118166	N	N	Y
6D	1	389	387.959	6	6	8.500%	7.458%	0	0	Y	N	Y
6E	2	108	108.2095	ellipse 4.83 x 7.58	ellipse 4.83 x 7.58	0.600%	0.536%	0.67	13.8716356	N	N	Y
7A	1	413	428.753	5	5	3.070%	2.862%	0	0	Y	N	Y
7B	4	477	473.44	21	21	0.270%	0.387%	2.5	11.9047619	Y	Y	Y

Nm = not measured   Unknown = Design parameter not known

Upon field inspection, there was one less culvert installed than what appears on the plans. This culvert was is 6F. The culvert location would have been very close to the culvert 6E. However, the location of the culvert is an area where there is no stream and it appears the function of the culvert would have been to drain field run-off. Because there is no culvert 6F, there is no data presented. 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 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. No sample was taken downstream of the culvert 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. 5F has some embedment at the inlet, but is embedded 50% at the outlet. Of all the culverts surveyed, in this author's opinion, this culvert's field dimensions match closest to the design principles of an EBC. At the outlet, this culvert was embedded deep enough so the stream could pass through the culvert but formed a channel through the embedment where the water made little contact with the culvert itself. Figure 4.5 shows the inlet and outlet of culvert 5F.

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[9] "Flat-lying Ice-Age lake basin with beach ridges, bars, dunes, deltas, and clay flats; contained the former Black Swamp, slightly dissected by modern streams, very low relief" (ODGS,1998)

Culvert 5F Inlet Culvert 5F Outlet

Figure 4.5 Installation of Culvert 5F

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, downstream 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 travelling 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. As shown in figure 4.5, culvert 7A is not embedded and the outlet is perched four feet above the water

[9] "Flat-lying Ice-Age lake basin with beach ridges, bars, dunes, deltas, and clay flats; contained the former Black Swamp, slightly dissected by modern streams, very low relief" (ODGS,1998)

level downstream. Culvert 7B is located on Nease Creek. The depth of the stream was so great at the time of collection, that water and sediment samples could not be collected from the interior of the culvert.

Figure 4.6 Culvert 7A

4.3.5 Paulding County: There were seven culverts surveyed in Paulding County (1A through 1G). The culverts are located on US Highway 24 in southwestern Paulding County near Antwerp, OH, 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 topography of Paulding County is Maumee

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[9] "Flat-lying Ice-Age lake basin with beach ridges, bars, dunes, deltas, and clay flats; contained the former Black Swamp, slightly dissected by modern streams, very low relief" (ODGS,1998)

Lake Plains[9] (ODGS,1998). 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 surveyed culverts in Paulding County are all box culverts and a review of the plans shows only five of these are true culverts (1A through 1E). Two other are listed by ODOT (1F and 1G) are arches that behave like bridges so they were not surveyed. The survey of the Paulding culverts were done in November 2009, with the QHEI and follow-up collection performed in July 2010.The results of the field study are presented in table 4.6.The culverts are in series along North Creek, flowing from 1E to 1A, 1D, 1B and further downstream 1C. North Creek is a 3rd order stream. Culverts 1E, 1A, 1D, and 1B are 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 greater than the design slope. Each of the culverts are 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 where culverts were surveyed.

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[9] "Flat-lying Ice-Age lake basin with beach ridges, bars, dunes, deltas, and clay flats; contained the former Black Swamp, slightly dissected by modern streams, very low relief" (ODGS,1998)

Table 4.6 Paulding County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC	Pre-construction QHEI done?
1A	3	512	510.68	Box 9' H x 14' W	Box 9' H x 14' W	0.048%	0.031%	0.55	3.92857143	N	N	N
1B	3	256	253.9	Box 9' H x 14' W	Box 9' H x 14' W	0.060%	0.193%	0.6	4.28571429	N	N	N
1C	3	78	76.28	Box 12' H x 20' W	Box 12' H x 20' W	0.380%	0.367%	1	7.14285714	N	N	N
1D	3	156	154.22	Box 9' H x 14' W	Box 9' H x 14' W	0.060%	0.162%	0.7	5	N	N	Y
1E	3	96	93.12	Box 9'H x 16' W	Box 9'H x 16' W	0.310%	0.451%	0.25	1.5625	N	N	N

Nm = not measured   Unknown = Design parameter not known

4.3.6 Ross County: There were four culverts in Ross County specified as EBCs by ODOT (4A through 4D). The culverts are located in southeastern Ross County on US Highway 35south of Chillicothe, OH 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. The culverts are located on the Shawnee-Mississippi Plateau[10] (ODGS, 1998).

Culverts 4A, 4B, 4C, and 4D were surveyed in March 2010 with the QHEI performed in July 2010. The results of the field study are presented in table 4.7.Culvert 4D is a box culvert and the other culverts are circular culverts. Culverts 4B and 4C are located on 1st order streams, culvert 4D is on a 2nd order stream, and 4A is on a 4th order stream. 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 an installation similar to that of a traditional culvert. There is a concrete pad at the inlet and outlet of the culvert, which was seen to accelerate the water velocity. In addition to the pad, the culverts had no embedment. Upstream of culvert 4D there is a double barrel culvert installation. Because there is not a long enough reach upstream to perform a QHEI, there was no QHEI performed upstream of culvert 4D.

[10] "High relief, highly dissected plateau of course and fine grained rock sequences; most rugged area in Ohio; remnants of ancient lacustrine clay-filled Teays drainage system are exensive in lowlands, absent in uplands" (ODGS, 1998).

Table 4.7 Ross County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC	Pre-construction QHEI done?
4A	4	390	219.238	12	12	0.770%	1.463%	0	0	Y	N	Y
4B	1	368	372.088	5	5	1.630%	1.619%	0	0	Y	N	Y
4C	1	295	289.72	5	5	2.040%	1.937%	0	0	Y	N	Y
4D	2	84	84.042	Box 8' H x 14' W	Box 8' H x 14' W	0.600%	0.706%	1.833	13.0952381	N	N	Y

Nm = not measured   Unknown = Design parameter not known

4.3.7 Wayne County: There are five culverts in Wayne County classified by ODOT as embedded/bankful. Culverts13A, 13B, 13C, 14A, and 14B 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, OH. 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 topography of the area is classified as the Killbuck-Glaciated Pittsburg Plateau[11] (ODGS,1998).

The culverts in Wayne County were surveyed in October 2009. Because there were no pre-construction QHEI's performed at these sites, no QHEIs were performed at these culverts for this study. The results of the field study are presented in table 4.8. Culverts 13A and 13B are on 1st order streams. Culvert 13C is located on a 4th order stream. Culverts 14A and 14B are located on a 2nd order stream. Culverts 14A and 14B are also located in series flowing from 14A to 14B. 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. Culvert 14C is a traditional culvert used as an experimental control. This culvert is located approximately 1000 feet east of 14A downstream. There is no embedment of the culvert, and the outlet is perched.

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[11] "Ridges and flat uplands generally above 1200', covered with thin drift and dissected by steep valleys, valley segments alternate between broad drift-filled and narrow rock-walled reached, moderate relief" (ODGS,1998).

Table 4.8 Wayne County Field Survey Results

Site	Stream Order	Design Length (ft)	As-built Length (ft)	Design Diameter (ft)	As-built Diameter (ft)	Design Slope (%)	As-built Slope (%)	As-built Highest Embedment Level (ft)	% Deepest Embedment	Designed as circular EBC	Operating as circular EBC	Pre-construction QHEI done?
13A	1	163	162.85	4	4	0.300%	0.301%	0	0	Y	N	N
13B	1	286	284.02	4	4	3.000%	2.943%	0.541	13.525	Y	Hybrid	N
13C	4	560	nm*	9	9	2.500%	nm*	2.67	29.6666667	Y	Hybrid	N
14A	2	282	nm	7		1.140%	nm	0	0	Y	N	N
14B	2	144	144.58	ellipse 5.67 H x 8.83 W	ellipse 5.67 H x 8.83 W	0.340%	0.310%	3.33	58.7301587	N	N	N
14C	1	Unknown	649.653	Unknown	6	Unknown	0.006%	0	0	Unknown	N	N

Nm = not measured   Unknown = Design parameter not known

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. Additionally 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. 14B was installed as an elliptical culvert. The inlet showed signs of scouring but the interior and the outlet of the culvert was significantly embedded.

4.4 Summary of Physical Surveys

The primary observation that was made and measured is that many of the culverts that were designated as EBCs by ODOT are not operating as EBCs. Of the 60 culverts designated by ODOT as embedded-bankfull, only 13 (21.67%) culverts were embedded for the entire length of the culvert. It should be noted that many locations where the culvert was not embedded the entire length featured steep slopes. Results of the analysis regarding slope and embedment are discussed in Chapter 5.

In comparing the as-built dimensions, 18 of the 60 culverts (30%) had field measurements that varied from the design. Most of the variation can be attributed to differing slopes. Of the 18 culverts that had differing dimensions, 12 had significantly different slopes, one had a different diameter, and 5 culverts had a combination of multiple differences. In addition to differing dimensions, 12 culverts are perched. The perching of culverts is further discussed in Chapter 6.

4.5 Laboratory Results

Laboratory analysis was performed on sediment and water samples collected in the field. Analyzes were performed as soon as possible on the collected samples after collection trips. Sediment samples were analyzed to determine the particle-size distribution for each sample and the Total Organic Carbon (TOC) of each sample. 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 presented in Appendix A on CD attached to this document.

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. Sediment samples were placed into stainless steel oven trays and dried at 110° C for 24 hours. After drying, sediment samples were gently hammered to break apart cohesive sediments. Sediment samples were then prepared for total organic carbon testing.

The burn-on-ignition method outlined in Chapter 3 was used to determine the TOC of the sediment. A representative 20g 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 20g 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. Table 4.9 shows the results for the TOC tests on culvert 6E.

Table 4.9 TOC Results for Culvert 6E

Site	Crucible No.	Crucible mass (g)	Crucible and sediment mass before furnace(g)	Crucible and sediment mass after furnace(g)	sediment mass before furnace (g)	sediment mass after furnace (g)	Difference (g)	% reduction
6E Upstream	2	2.227	22.227	21.803	20.000	19.576	0.424	2.120
6E Upstream	22	2.223	22.224	21.782	20.001	19.559	0.442	2.210
6E Upstream	111	2.216	22.217	21.834	20.001	19.618	0.383	1.915
6E Inlet	2	2.254	22.255	21.923	20.001	19.669	0.332	1.660
6E Inlet	9	2.226	22.225	21.884	19.999	19.658	0.341	1.705
6E Inlet	12	2.214	22.214	21.898	20.000	19.684	0.316	1.580
6E Inside	10	2.214	22.215	21.425	20.001	19.211	0.790	3.950
6E Inside	13	2.225	22.225	21.609	20.000	19.384	0.616	3.080
6E Inside	19	2.198	22.197	21.604	19.999	19.406	0.593	2.965
6E Outlet	5	2.193	22.194	21.816	20.001	19.623	0.378	1.890
6E Outlet	11	2.236	22.237	21.772	20.001	19.536	0.465	2.325
6E Outlet	18	2.220	22.219	21.806	19.999	19.586	0.413	2.065
6E Downstream	1	2.212	22.212	21.891	20.000	19.679	0.321	1.605
6E Downstream	7	2.205	22.205	21.900	20.000	19.695	0.305	1.525
6E Downstream	100	2.205	22.204	21.871	19.999	19.666	0.333	1.665

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. Once the rocks were cleaned, the remaining sediment left over after the TOC test was placed in the sieve. Sieve sizes used for analysis were No. 4 (4.750mm), 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.

Table 4.10 shows trial 1 of the sieve analysis for the upstream sample of culvert 5C. The results were used to produce particle-size distributions. Figure 4.7 shows the particle-size distribution for trial 1 of the upstream sample of culvert 5C. Sediment samples were discarded after the sieve analysis.

Table 4.10 Sieve Analysis for Trial 1 Upstream Culvert 5C

sieve no.	sieve opening (mm)	mass of sieve	mass of sieve + sediment	mass retained (g)	% retained	Sum % retained	% passing
4	4.750	578.000	752.400	174.400	23.67	23.67	76.33
10	2.000	644.200	860.800	216.600	29.40	53.07	46.93
16	1.180	341.400	496.400	155.000	21.04	74.10	25.90
35	0.500	398.200	510.400	112.200	15.23	89.33	10.67
60	0.250	434.600	475.000	40.400	5.48	94.82	5.18
140	0.106	341.600	360.400	18.800	2.55	97.37	2.63
200	0.075	240.000	246.000	6.000	0.81	98.18	1.82
pan		487.000	500.400	13.400	1.82	100.00	0.00
	W (g) =			736.800			

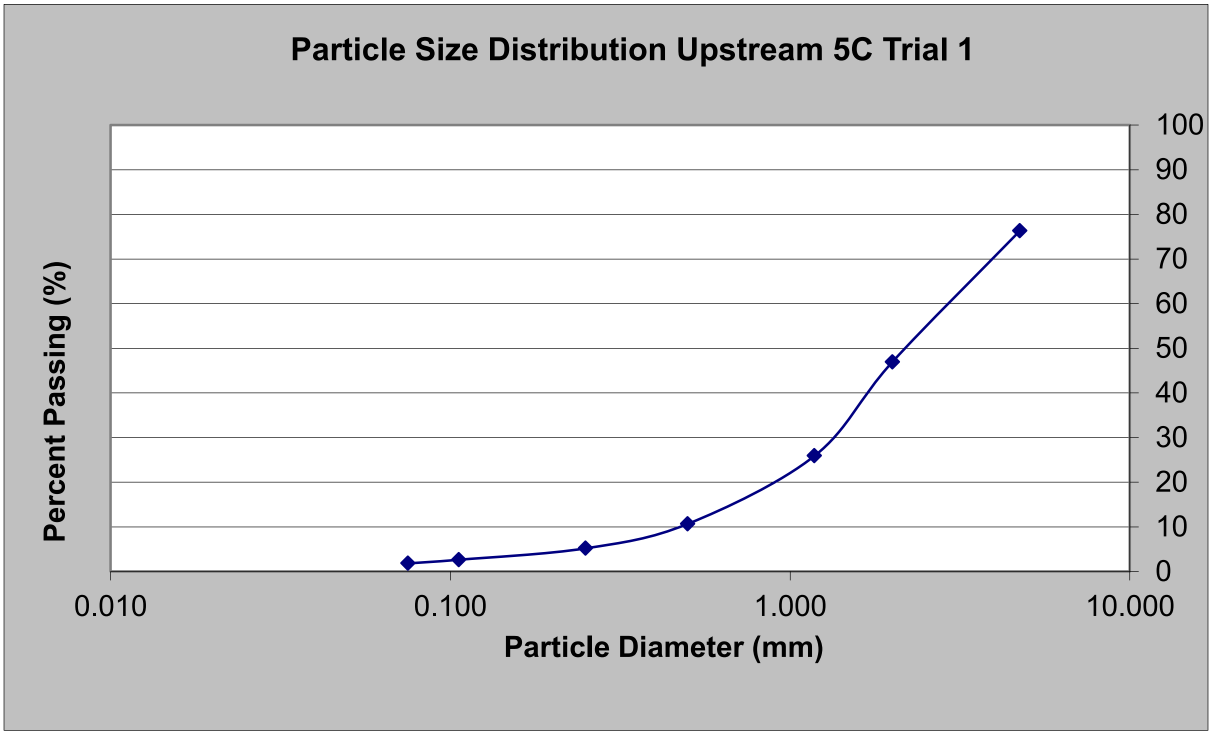

Figure 4.7 Particle Size Distributions Upstream 5C Trial 1

It was seen after resting in the refrigerator, suspended sediments had settled in some water samples. To bring the water back to field conditions, the water sample was gently shaken and allowed to settle for one minute before collecting data. Turbidity was collected using a LaMotte portable turbidimeter model 2020. 10ml of water were placed into a test tube and then in the meter. Five trials were run for each water sample.

To prepare for TSS testing, Whatman Grade 1, 11µm filer papers were dried in an oven at 110°C for two hours and then allowed to cool in a desiccator 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 20ml, 15ml, 10ml, or 5ml were poured through the filter. The filter was then dried again at 110°C overnight. After cooling in the desiccator, the filter re-weighed. Three trials were performed for each water sample. Table 4.11 shows the results of the TSS tests for culvert 8B.

Table 4.11 Total Suspended Solids Results for Culvert 8B

Site	Pan and placement	Dry filter mass (g)	Volume added (ml)	Dry filter and suspended solids (g)	Dry suspended solids (g)	Concentration (mg/l)
8B-Upstream	P2-1	0.195	15	0.1984	0.0034	226.67
8B-Upstream	P2-2	0.202	15	0.2042	0.0022	146. 67
8B-Upstream	P2-3	0.1975	15	0.1995	0.002	133. 33
8B-Inlet	P2-4	0.2013	15	0.2023	0.001	66.667
8B-Inlet	P2-5	0.2002	15	0.2009	0.0007	46. 67
8B-Inlet	P2-6	0.1996	15	0.2013	0.0017	113. 33
8B-Inside	P2-7	0.2057	15	0.2065	0.0008	53. 33
8B-Inside	P2-8	0.2008	15	0.2014	0.0006	40
8B-Inside	P2-9	0.1969	15	0.1976	0.0007	46. 67
8B-Outlet	P2-10	0.2005	15	0.2012	0.0007	46. 67
8B-Outlet	P2-11	0.2053	15	0.206	0.0007	46. 67
8B-Outlet	P2-12	0.2077	15	0.2086	0.0009	60
8B-Downstream	P2-13	0.1964	15	0.1973	0.0009	60
8B-Downstream	P2-14	0.2063	15	0.2067	0.0004	26. 67
8B-Downstream	P2-15	0.2054	15	0.2059	0.0005	33. 33

CHAPTER V

ANALYSIS

In total, there were 63 culverts surveyed and 62 culverts were included in the analysis. Culvert 12F was omitted from analysis because limited data was collected at the culvert and the culvert was used for control. Table 5.1 lists the number of each type of culvert surveyed. In order to compare EBC to traditional culverts only the 47 circular culverts were compared in this study. The data collected on box and elliptical culverts were reserved for further studies on EBCs. Using the field survey and observation data, a determination was made of the type of culvert each installation represented.

Table 5.1 Number of Each Type of Culvert Surveyed

Type	Number
Circular	47
Box	12
Ellipse	3
Total	**62**

A culvert was designated as an EBC when it was embedded in the stream the entire length of the culvert. A culvert was designated as a "traditional culvert" when the culvert is not embedded into stream sediments. It was also observed that some culverts had properties of both types. These culverts were depressed in the stream and had portions of the culvert that were embedded by stream sediments but there were portions of the culvert where sediments had been scoured away. The culverts that had these unique features are defined as hybrid culverts. Table 5.2 shows the classification of the 47 culverts analyzed for this study.

Table 5.2

Number of Circular Culverts Surveyed

Type of Culvert	Number of Culverts
EBC	13
Traditional	24
Hybrid	10

5.1 Shear Stress in the Culvert

As described in Chapter 3 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.

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 of the culvert, and slope. As shown in Equation 5.1 (Forest Service Stream Simulation Working Group, 2008), shear stress can be calculated by using the hydraulic radius, slope of the culvert and the unit weight of water.

$$\tau = R * S * \gamma \quad \textbf{Equation 5.1}$$

τ = shear 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)

The hydraulic radius is a function of the depth of flow in the culvert. To ensure true comparisons between culverts, it is important to have a comparable flow for each culvert. In the case of the Ohio culverts, flow rates were determined using the USGS Stream Stats Ohio. The 2 year, 5 year, and 10 year peak flows were obtained for each stream sampled using the online database. Because most of the culverts are around ten years of age, it was decided to limit analysis to the 10 year peak flow. Flow rates could not be determined for culverts 5H and 2G because the streams are so small and USGS has no data for these streams.

Instead of determining the hydraulic radius using an iterative approach, it was decided to attempt to quantify the shear stress using the known flow rates for each site. Using methods produced by Mangin (2010), Manning's equation was manipulated so the depth of flow in a culvert can be calculated for a given flow (Eqns 3.2 and 3.3).

$$Q^* = \frac{Q}{\sqrt{gD^5}} \qquad \textbf{Equation 5.2}$$

$$d = .32D\left(\left(\frac{Q^*}{\sqrt{S_o}}\right)\left(\frac{K_S}{D}\right)^{\frac{1}{6}} + 0.64\right) \quad \textbf{Equation 5.3}$$

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 the 2 year, 5 year, and 10 year peak flows, depth (d) was calculated for each flow. After obtaining the depth of flow, the area and wetted perimeter were calculated. For the partially full circular culverts, hydraulic radius was calculated using methods produced by Bengtson (2010). Knowing the hydraulic radius, this can be applied to Equation 5.1 to produce the shear stress for each flow at each site. Sample calculations of shear stress are shown in Appendix D

$$h = 2r - d \qquad \textbf{Equation 5.4}$$

$$\theta = 2\arccos\left(\frac{r-h}{r}\right) \qquad \textbf{Equation 5.5}$$

$$A = \pi r^2 - \frac{r^2(\theta - sin\theta)}{2} \qquad \textbf{Equation 5.6}$$

$$P = r * \theta \qquad \textbf{Equation 5.7}$$

$$R = \frac{A}{P} \qquad \textbf{Equation 5.8}$$

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)

5.2 Culvert Functionality

It was measured and observed in the field there are very few culverts embedded throughout the entire length of the culvert. Because less than 28% of the circular culverts are embedded the entire length it is important to examine the relationship between culvert and stream characteristics on the depth of embedment in the culvert. 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 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. The dependent variable for the regression is the deepest percentage of embedment in the culvert. The independent variables are mean particle diameter, length of the culvert, and shear stress in the culvert. The equation of the regression is:

$$Y = \alpha X_1 + \beta X_2 + \gamma X_3 + C$$

Y= deepest percentage of culvert embedment X_1 *= length of culvert* X_2 *= shear stress (lb/ft*^{2}*)* X_3 *=* D_{50} *of the upstream sediment C = intercept*

Regression was performed using multiple trials using either 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 23 embedded culverts were analyzed, the R^2 is 0.297 and the equation for the regression is:

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

Another goal of this study is to determine which variables control the functionality of a culvert. In order to accomplish this task, functionality of the culvert must be defined. By using data collected from the sieve analysis, particle size distributions were created for each culvert. The particle size distributions of the inlet, inside, outlet, and downstream of the culvert were compared to upstream of the culvert in order to identify how sedimentation patterns are changing through the culvert.

An effective culvert 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, the functionality of an EBC can be defined as the ability to allow for storm passage while allowing for uninterrupted sedimentation patterns in the stream through the culvert. The particle size distribution of a functioning culvert shows little change from the upstream to the points along the culvert. Figure 5.1 shows the particle size distribution of a designated as "functioning" culvert. Conversely, a non-functioning EBC disrupts the sedimentation patterns, either washing sediments downstream or depositing sediments within the culvert. The particle size distribution of a non-functioning culvert shows variation from the upstream to the different reaches of the culvert. Figure 5.2 shows the particle size distribution of a designated as "non-functioning" culvert.

In order to do a full analysis on culvert functionality, a statistical analysis approach is needed. The particle distributions lend themselves for comparison using the Kolmogorov-Smirnoz goodness of fit test (Holcomb, 2010). The Kologorov-Smirnoz test compares the distribution of two functions F(y) and G(y) (Scheaffer & McClave, 1995).

The test compares how close G(y) is to F(y). 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 is possible to determine if the distribution of sediment is statistically different between from the upstream sample to the culvert samples. After determining fitness of the distributions, functionality of a culvert can then be determined.

However, a full statistical analysis is beyond the scope of this thesis, a non-statistical approach was used to determine functionality. Functionality was based on the change measured between the upstream sample and the rest of the culvert for each sieve size. If the change in percent passing is less than 20%, the culvert functions in conveying sediments that are retained on that sieve size. If the change is greater than 20%, the culvert is non-functional for that sieve size. For a culvert to be functional, all seven sieve sizes must have a change of less than or equal to 20%. A culvert is near-functional 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 non-functional. The analysis performed on the particle-size distributions is intended to be the first iteration of a multi-iterative approach to define functionality of a culvert eventually using the fitness test.

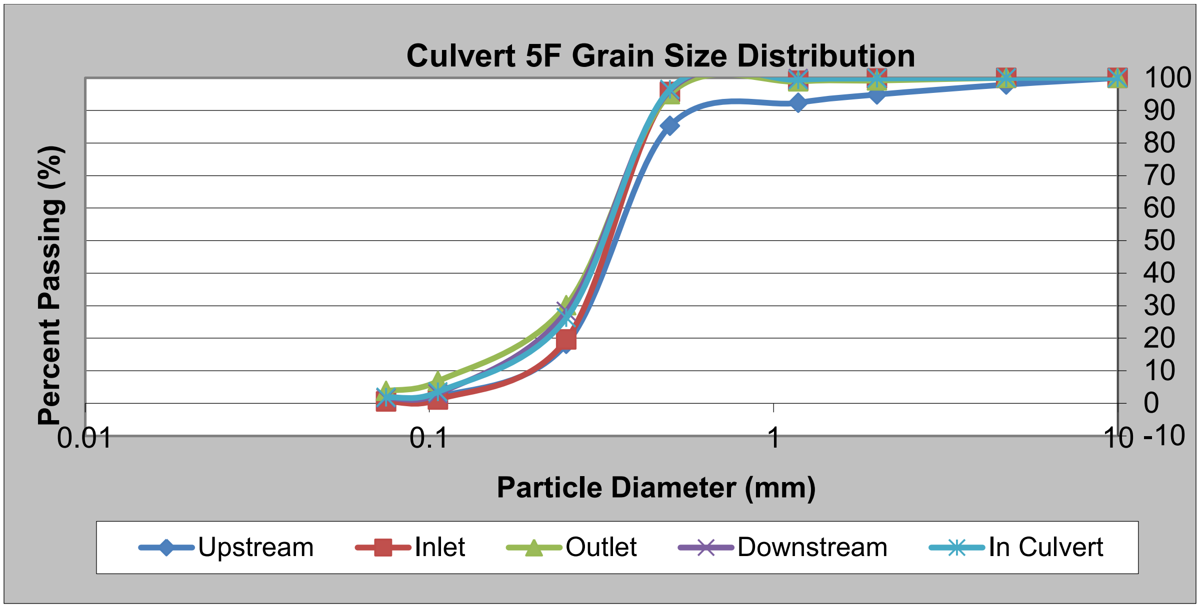

Figure 5.1 Culvert 5F Grain Size Distribution

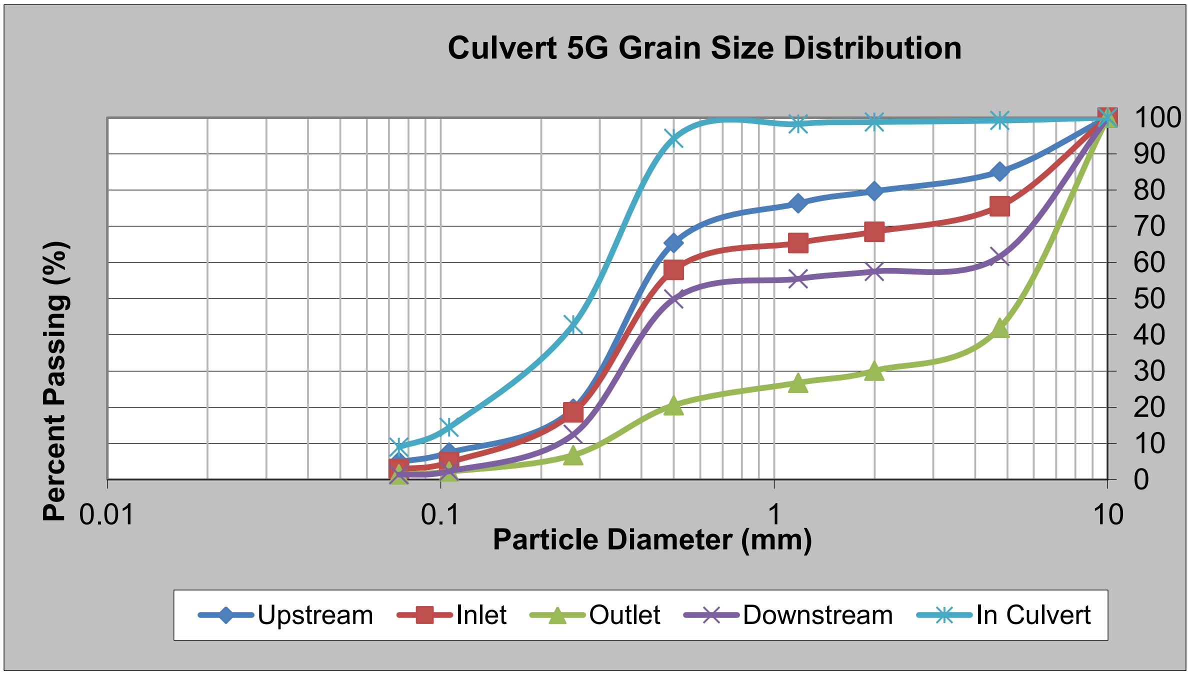

Figure 5.2 Culvert 5G Grain Size Distribution

This calculation was used to determine if a culvert was "functioning." "Functionality" was determined for traditional, EBC, and hybrid culverts. For EBCs and hybrid culverts, "functionality" of a culvert incorporates the sediment particle size distribution for each point along the reach of the culvert. For traditional culverts, "functionality" was determined by comparing the changes from upstream to the inlet and 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 traditional culvert is functional. Figure 5.3 shows an example of the particle size distribution for a traditional culvert. It can be seen though the upstream and downstream faces of the culvert are very different, the change from the upstream to the inlet, and the change from the outlet to the downstream are relatively low.

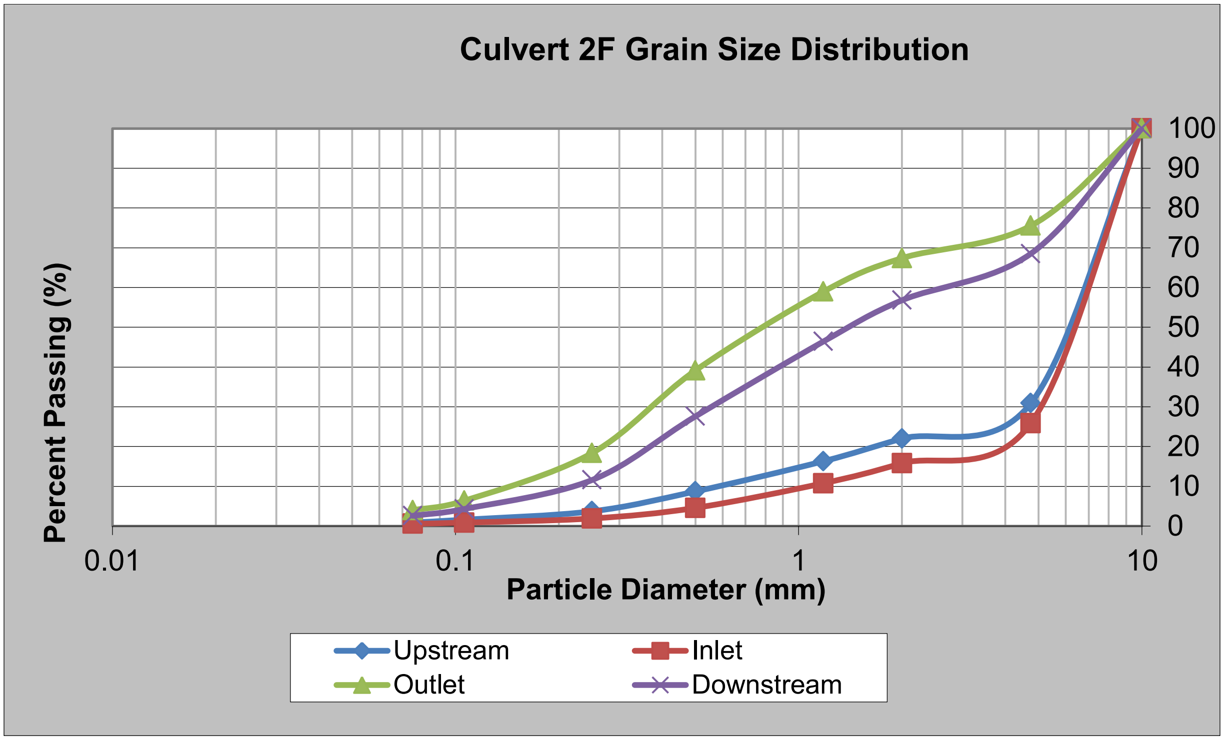

Figure 5.3 Culvert 2F Grain Size Distribution

Exceptions to the definition of functionality occur where one or more portions of the reach of the culvert had sediments that were scoured away (in culverts 4A, 2D, and 17B). Because the hydraulics of the culverts has caused the sediments to be scoured away, the culvert is not effective in allowing for the continuity of sedimentation patterns, and the culverts were designated as "non-functioning". Table 5.3 shows the results of functioning culverts by type.

Table 5.3 Number of Functioning Culverts by Type

Type	Functioning	Near-functioning	Non-Functioning	% Functioning
EBC	2	2	9	15.38
Hybrid	1	1	8	10.00
Traditional	5	1	18	20.83

Using chi squared test for association, an attempt was made to see if the type of culvert had an effect on the functionality of the culvert. The results yield a χ^2 of 0.057 (P=0.972). Likewise, the chi squared test was run to determine if the stream order had an effect on functionality. The result is an χ^2 of 0.386 (P = 0.825). These results show based on the definition of functionality presented, there is no correlation between type of culvert or stream order on the functionality of a culvert. Because a statistical analysis of the particle size distributions is beyond the scope of this project, a qualitative approach will be taken to analyze similarities between functioning culverts of each type.

5.2.1 Shared Similarities of Functioning Culverts by Type: Because the amount of functioning culverts is very low, the results are not significantly significant. Thus, no parameter can be conclusively linked to the "functionality" of a culvert. However, there are some trends that were common amongst the "functioning" culverts can are shown in this section. The functioning traditional culverts are 2C, 2F, 2G, 3C, and 5H. Of these culverts, the shear stress could not be determined for 2G and 5H because there is no flow data available provided by USGS for the streams that pass through 2G and 5H.By examining the physical dimensions of the culverts, it was seen that each of these culverts had some common physical features. Each of these culverts are located in a first order stream, the slope is over 3%, the length of the culvert is over 300ft, the diameter is less than five feet, and shear stress of the peak 2 year flow is less than 2.2 lb/ft^2. As previously stated in this chapter, the shear stress is a major factor in the movement in sediment particles. Also in the functioning traditional culverts, there is no material present in any part of the culvert. Table 5.4 presents the dimensions of the functioning traditional culverts. Shear stress could not be calculated for 2G, and 5H due to the fact the streams are so small, the peak flows have not been calculated by the USGS.

Table 5.4 Properties of Functioning Traditional Culverts

Culvert	Length (ft)	Deepest Embedment Depth (ft)	Diameter (ft)	Slope (%)	order	2yr shear	% deepest embedment
2C	534.77	0	3.5	7.791%	1	2.18779	0
2F	639.76	0 at inlet	3.5	4.230%	1	1.214179	0
2G	410.10	0	2.5	6.336%	1	No data	0
3C	311.68	0 (concrete pad at outlet)	4.5	3.329%	1	1.495562	0
5H	574.865	0	4	4.499%	1	No data	0

The two functioning EBCs are 5F and 12E. The two culverts that are functioning have some similarities. They both have a diameter 8 ft or larger, the 2 year peak shear stress is less than 1 lb/ft^{2}and the culvert is embedded 30% or greater. In addition to the two functioning culverts, 8B which is near-functioning, closely matches these properties. 8B is embedded less than 10% and has a diameter of 14ft. One possible cause in the change in the outlet sedimentation patterns may be attributed to the lack of embedment but cannot be said conclusively until further analysis is performed. Table 5.5 shows the physical properties of the functioning EBC and culvert 8B. Figure 5.4 shows the particle-size distribution for culvert 8B.

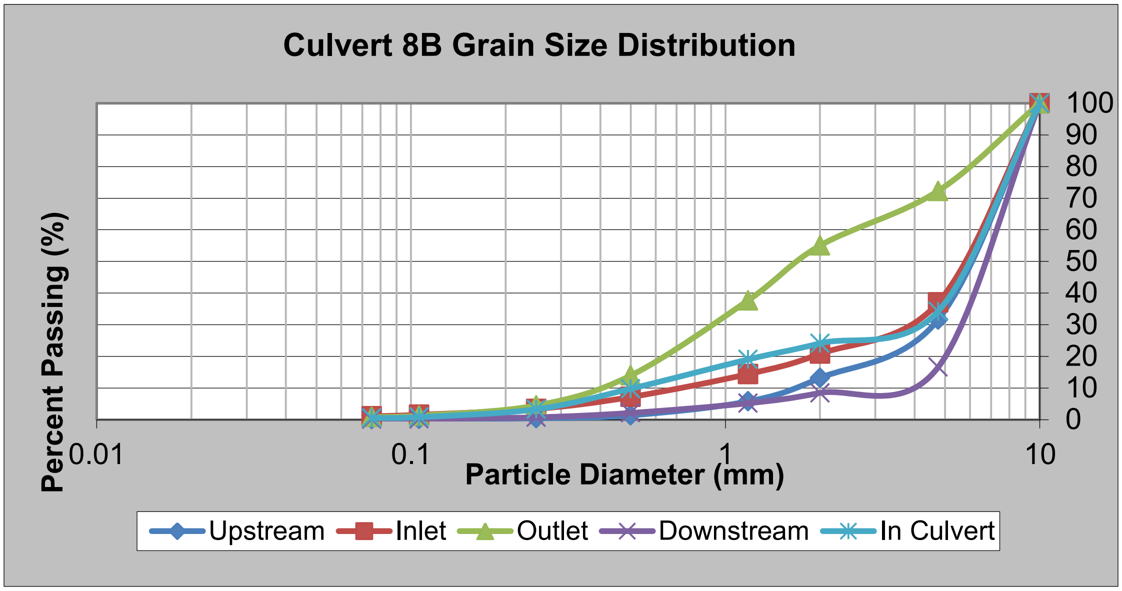

Figure 5.4 Culvert 8B Grain Size Distribution

Table 5.5 Properties of Functioning EBCS and Culvert 8B

Culvert	Length (ft)	Highest Embedment Depth (ft)	Diameter (ft)	Slope (%)	order	2yr shear	% deepest embedment
5F	650	4	8	1.180%	1	0.73632	50
12E	109.74	3.17	10.5	0.160%	4	0.17349	30.19
8B	143.278	1	14	0.0079%	4	1.034579	7.14

5.3 Fine Particle Sedimentation Analysis

As stated in Chapter 3, the percentage of total organic carbon (TOC) in a stream sediment sample is correlated to the amount of fine sediment particles present in that sample. One of the objectives of this study is to determine if the length, slope, and diameter have an effect on the sedimentation patterns of fine particles in the stream. To gauge this, TOC was measured throughout the reach, upstream and downstream at each culvert. For analysis, change in TOC (ΔTOC) from the upstream to the downstream was compared to physical dimensions of length, slope, and diameter size. Scatterplots were produced with length, slope, and diameter as the independent variable and ΔTOC as the dependent variable. Using a linear regression trend line shows 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. Figure 5.5 shows the scatterplot of ΔTOC vs length.

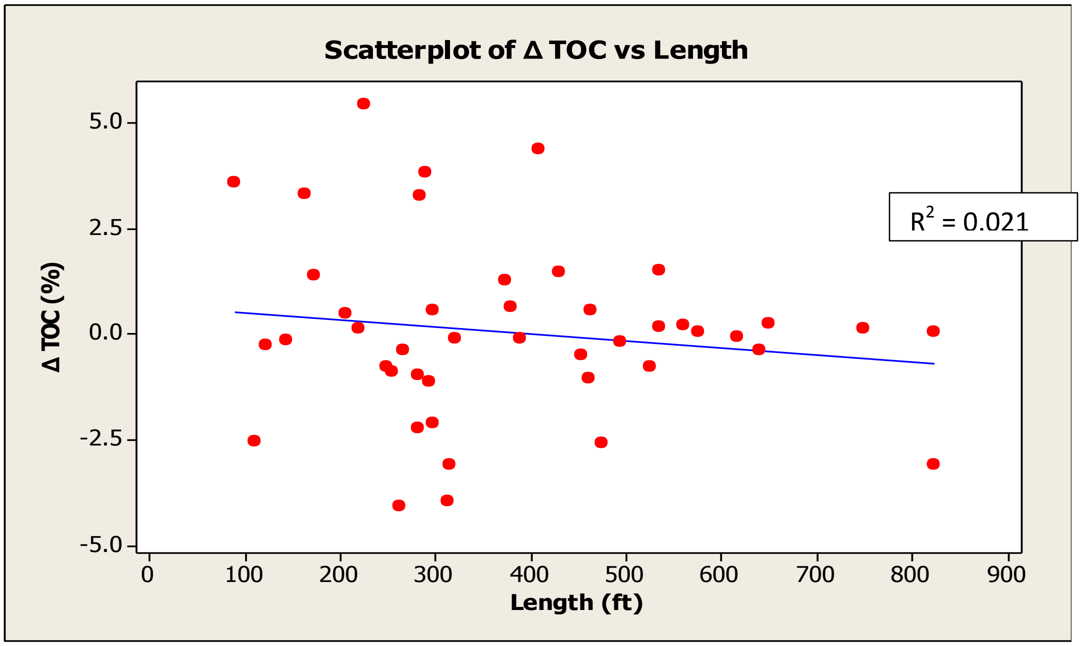

Figure 5.5 Scatterplot of ΔTOC vs Length in All Culverts

For further analysis, ΔTOC was compared to the shear stress of the stream during the 2 year, 5 year, and 10 year peak flows. Using the method previously illustrated for using hydraulic radius, slope of the channel, and the unit weight of water the shear stress was calculated. A scatterplot was produced to compare ΔTOC and the peak flows. A regression line was then applied to the scatterplot. The results show that there is little correlation between ΔTOC and the shear stress of the 2 year, 5 year, and 10 year peak flows. The R^2 of the scatterplots for the 2year, 5year, and 10year peak shear stresses are respectively 0.01, 0.08, and 0.08.

In addition to the change in TOC, analysis was performed on the change in fines measured in the sieve analysis. From the particle-size distribution, fines were defined as particles passing the No. 200 sieve. For all circular culverts, there was no correlation found between the change in percent passing the No. 200 sieve and the length, diameter, slope, and shear stress from the 2year, 5year, 10year peak flows. However, for all functioning culverts, including traditional, hybrid, and EBCs, some correlations were 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 Δ percentage of fines and length is shown in Figure 5.6. Another correlation found was the percentage of fines increase as the slope increases. The R^2 value for the correlation between Δ percentage of fines and slope is 0.65. Related, the scatterplot of fines and diameter is trending towards the percentage of fines decrease as the diameter increases. The R^2 value for the Δ percentage of fines and diameter is 0.361. For shear stress, some small correlations were found. The R^2 value for the Δ percentage of fines and 2year, 5year, 10year peak shear stresses are 0.325, 0.286, 0.265 respectively.

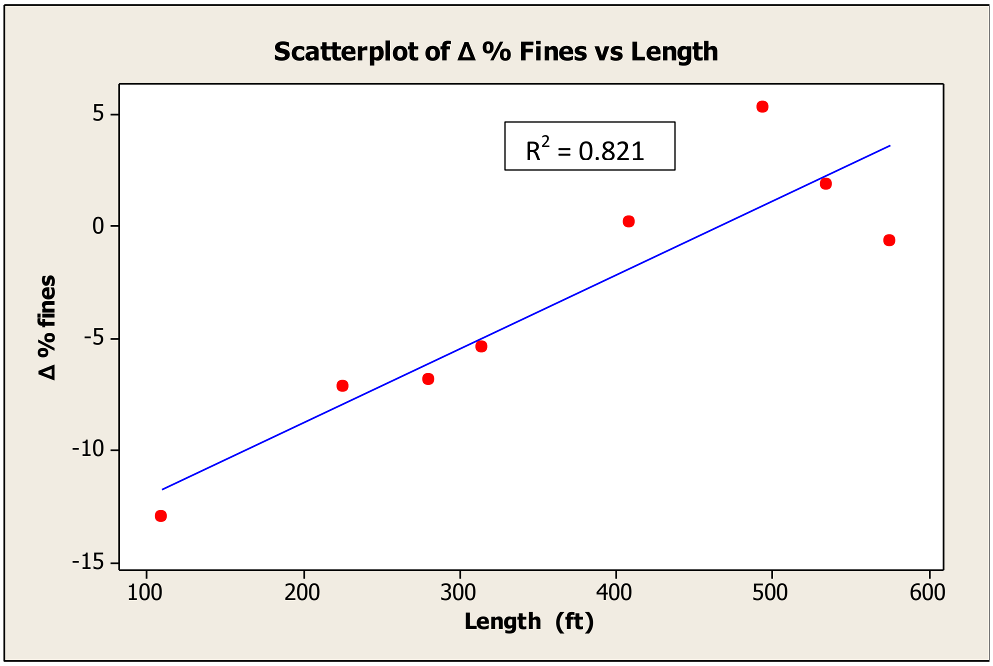

Figure 5.6 Scatterplot of ΔPercentage of Fines vs Length in All Functioning Culverts

5.4 Instantaneous Sediment Transport through the culvert:

The change in Total Suspended Solids and Turbidity from upstream to downstream of the culverts gives insight to the instantaneous sediment transport at the time of collection. Scatterplots were produced comparing ΔTSS and the instantaneous shear calculated from the flow rate at the time of collection. The R^2 value for the graph comparing ΔTSS and instantaneous shear is 0.007. Likewise, ΔTurbidity and instantaneous shear was compared. The R^2value for this graph is 0.017. Thus, the result of the analysis is there is no correlation found between the instantaneous shear and the change in TSS and Turbidity through the reach of the culvert. The same tests comparing ΔTSS and Δturbidity against the instantaneous shear were performed for the functioning culverts. There was no correlation found between Δturbidity and shear, but for the graph comparing ΔTSS and instantaneous shear (Figure 5.7), there is some correlation between the increase in TSS and the increase in shear stress. The R^2 value for the graph is 0.536.

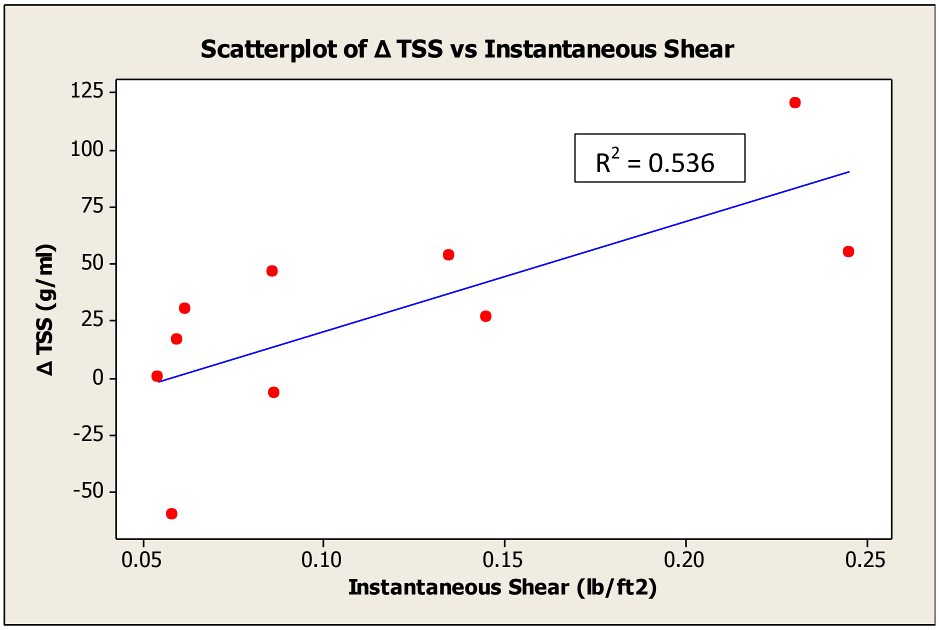

Figure 5.7 Scatterplot of ΔTSS vs Instantaneous Shear in All Functioning Culverts

5.5 The Effect of Embedment Depth on Sedimentation Patterns

In Chapter 2, 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 determine the effect of the depth of embedment on sedimentation patterns. To test how the percentage of embedment affects sediment transport through the culverts, scatterplots were produced comparing percentage of embedment with ΔTOC, ΔTSS, and Δturbidity. Both the percentage of the inlet embedment and percentage of embedment at the maximum embedment depth in the culvert were compared to ΔTOC, ΔTSS, and Δturbidity. The scatterplots for percentage of inlet embedment result in R^2 values less than 0.06. Likewise, the plots for percentage of deepest embedment also result in R^2 values less than 0.06.

All the functioning culverts were analyzed for embedment vs ΔTOC, ΔTSS, and ΔTurbidity. When the traditional culverts are included in the analysis the R^2 values are less than 0.2. However when just comparing the functioning and near-functioning culverts that had any level of embedment, there is some correlation between the percentage of deepest level of embedment and the change in turbidity. The scatterplot results in an R^2 value of 0.74 (Figure 5.7).When comparing percentage of deepest level and the change is TSS, the graph results in an R^2 value of 0.34 (Figure 5.8). Though this value is not large enough to be statistically conclusive, when combined with the results of the turbidity graph, it suggests there may be some correlation between the larger the percentage of embedment, the fewer sediments that are becoming suspended and traveling downstream of the culvert.

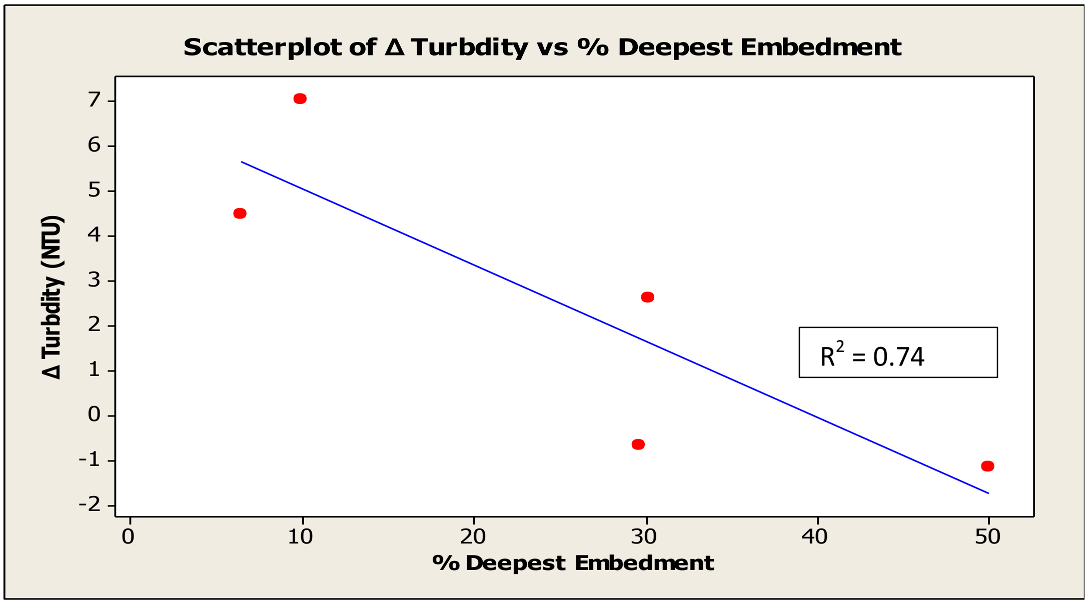

Figure 5.8 Scatterplot of ΔTurbidity vs% Deepest Embedment

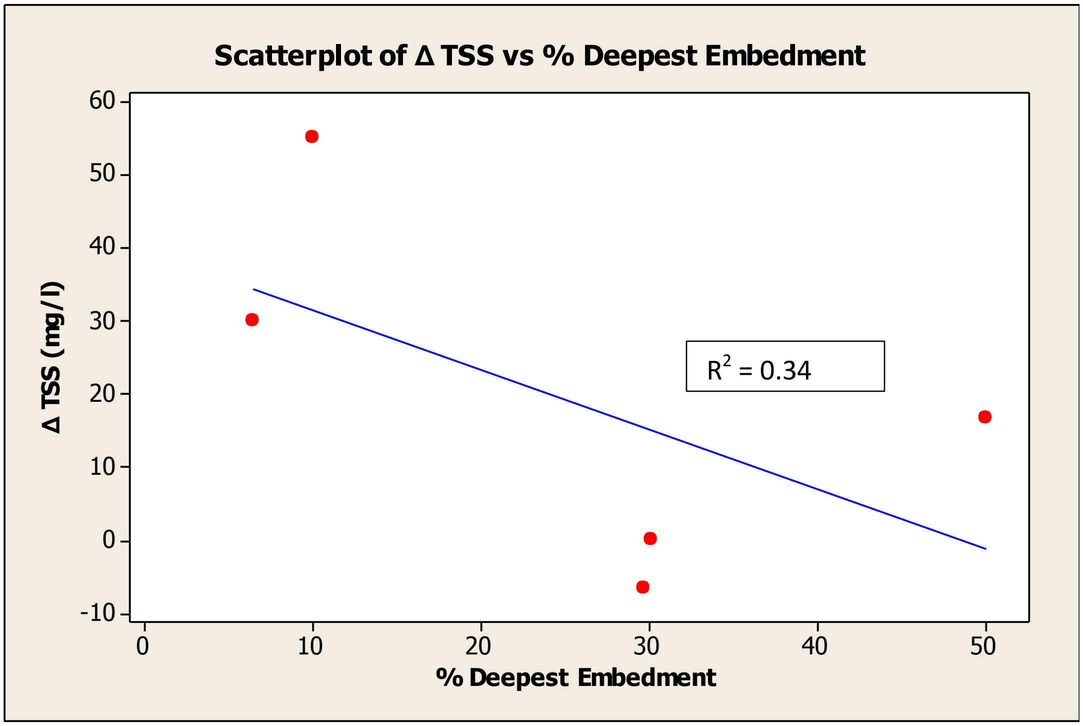

Figure 5.9 Scatterplot of ΔTSS vs %Deepest Embedment

5.6 QHEI Results

Prior to highway construction and culvert installation, QHEIs were performed at 28 sites. The QHEIs were performed by ODOT and the OhioEPA. As part of this field survey, follow up QHEIs were performed at these sites. QHEIs were done for both upstream and downstream of the culvert. At sites 4D and 12D, 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 QHEI collection in the field so there these culverts were no included in the analysis. In total 20 culverts were analyzed using QHEI. Only five of the culverts where a QHEI was performed, met the definition of an EBC.

It is assumed the culvert has had no effect on the upstream habitat conditions. The upstream post-construction QHEI scores reflect the natural change that has occurred in the stream since the culvert was installed. Of the 20 sites surveyed, 11 sites have lower upstream QHEI scores after culvert installation, meaning the stream has naturally degraded since the installation of the culvert. 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 will yield the change caused by the culvert. By performing this analysis, it is seen that at three of the five EBC sites there has been a degradation of the stream environment attributed to the culvert. For the traditional culverts, seven of the 15 sites have experienced degradation due to the culvert. None of the culverts originally assessed are functioning EBCs. Therefore, there is no data on the effect of a functioning EBC on the stream. Table 5.6 shows the change in QHEI scores from upstream to downstream of the culvert

Table 5.6 Change in QHEI Scores from Upstream to Downstream Due to Culvert Installation

Culvert ID	Culvert Type	Δ QHEI
2A	Traditional	25.5
2D	Traditional	5
3C	Traditional	11
3D	Traditional	-6
4A	Traditional	-23
4B	Traditional	-2
4C	Traditional	12.4
5A	Traditional	-10
5B	Traditional	-5.75
5C	Traditional	-7.5
5E	Traditional	8
6A	Traditional	-2
6D	Traditional	14
7A	Traditional	0
17B	Traditional	-3.5

Culvert ID	Culvert Type	Δ QHEI
3B	EBC	13
5G	EBC	-11.5
8B	EBC	-9.5
9D	EBC	13.5
12C	EBC	-2.25

5.7 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 anEBC has on the height of ponding during the 100 year 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

Table 5.7 Stream and Watershed Characteristics

Parameter	Input	Source
Storm Type	SCS Type II	Kuo, 2010
100 storm	5.21 in	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 5.7 were entered into the software, the analysis was run. The 100 year peak flow for the stream at the culvert location is 808 cfs (USGS, 2010). Since the time of concentration (Tc) is not known at this location, iterations of the flood attenuation were run in the model, changing the Tc until the peak flow in the stream hydrograph matched as close as possible the 100 year flow for the stream. Figure 5.10 shows the hydrograph for the stream with no culvert. After the Tc was determined for the stream, the culvert was introduced in the stream using the surveyed data and the model was run again.

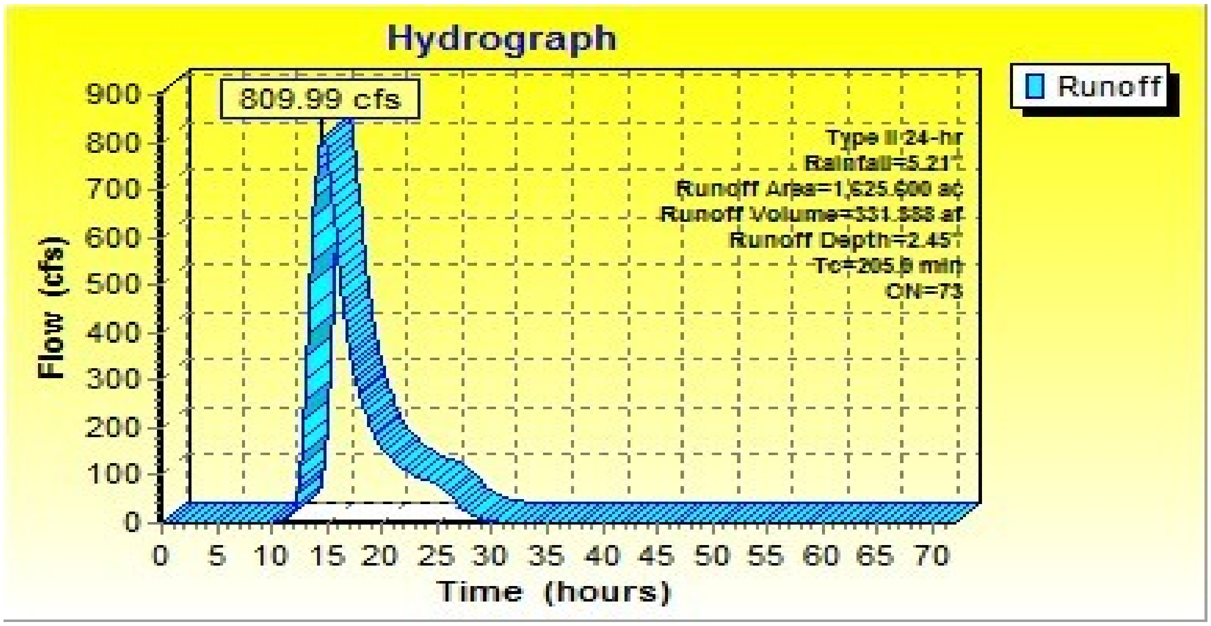

Figure 5.10 Hydrograph of Site 7B with no Culvert

Table 5.8 Results of Hydrologic Modeling for the 100 year storm at Site 7B

	Traditional Culvert	EBC
Maximum flow passing through culvert (cfs)	805.3	797.3
Depth of Ponding (ft)	12.57	12.86

Two trials were run in the model, one with no embedment and the other with 2.5 feet of embedment. The results of the simulation are shown in Table 5.8. Figure 5.11 shows the culvert with no embedment and Figure 5.12 shows the culvert with the embedment measured in the field. It can be seen the embedment of the culvert has minimal effect on the ponding depth. The culvert is embedded 12% of the culvert diameter, the increase in the depth of ponding increases by 0.29 ft (3.5 inches). 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.

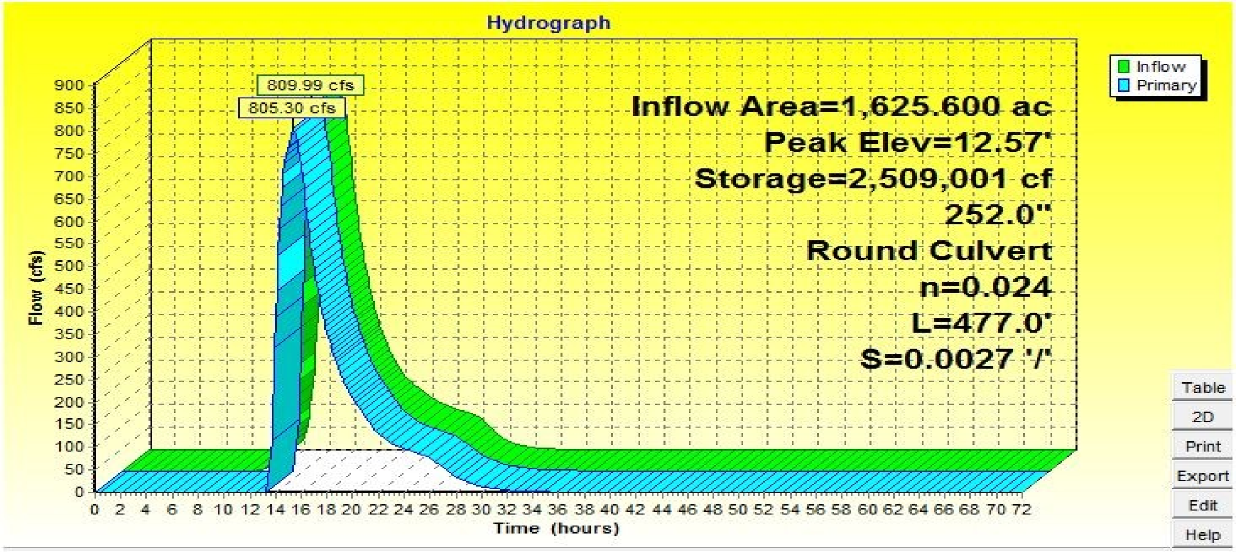

Figure 5.11 Hydrograph of Site Culvert 7B with No Embedment

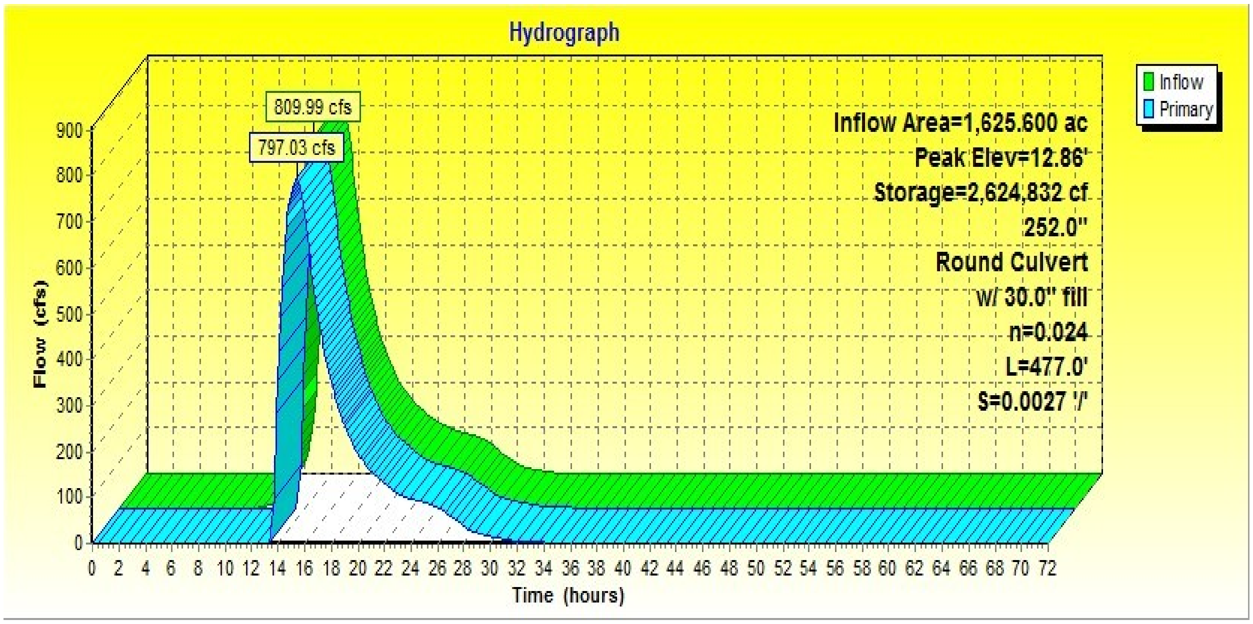

Figure 5.12 Hydrograph of Site Culvert 7B with 2.5 ft of Embedment

CHAPTER VI

OBSERVATIONAL ANALYSIS

The purpose of this section is to illustrate field conditions that may be contributing the lack of functionality and lack of embedment, which prevent these culverts from being EBCs. These observations not intended as conclusions, but rather to show trends that were observed but not measured.

The first major observation is the variation between culvert installations performed under different contracts. 13 culverts are installed as EBCs. This represents less than 28% of the circular culverts studied. However, for culverts that were found not to be EBCs, it appears changes were made either in design or in installation of the culvert. These changes are resulting in conditions that prevent the culvert from operating as an EBC. An example of this comes from the culverts in Athens County. Culverts 2A, 2B, and 2D 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 is operating as a traditional culvert. In culverts

3A, 3B, 3C, and 3D there was a large concrete pad placed at the outlet of the culvert. It is assumed this pad was put in place in order to capture sediments. Thinking logically, the presence of a concrete pad creates an obstruction where suspended sediments and sediment particles traveling along the bedload will become trapped inside the culvert by the pad. Overtime sediments will continue to accumulate until an equilibrium point is met between the movement of sediments and the depth of the bedload. However what is occurring is some sediments are trapped immediately upstream of the pad but no other sediments are trapped in the culvert.

In addition, many of the culverts with slopes greater than 1% had no sediment present inside of the culvert. In the case of the culverts 2B, 2C, 2D, 2E, 2F, and 2G these culverts had both high slopes and are on first order streams. Because the culverts are on first order streams, the culvert diameters are five feet in diameter or smaller. In the ODOT culvert design manual, it is stated that a depressed culvert fill naturally fill with stream sediments. However, there is no sediment accumulation occurring in the culvert. 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 depressed below the stream, once water enters the culvert the water velocity accelerates because the cross-sectional area of the flow was reduced from the stream in the culvert, and the roughness of the culvert was less than the natural stream. The Analysis of Variance (ANOVA) general linear model was used to determine the correlation between culverts with a slope greater than 1% and culverts with no sediment present in the culvert. The analysis results in a P value of 0.06. Thus, at the 90% confidence interval, sediments are being washed through culverts with a slope 1% or greater.

As stated in Chapter 1, increased water velocities exiting the culvert can scour the channel bottom downstream of the culvert causing the culvert to become perched. It was observed that of the 63 culverts sampled, 12 of them were perched. In most instances, the perching is a few inches but in the case 7A, the culvert outlet is perched four feet above the downstream water surface level. Therefore, though most instances of perching can be attributed to scouring, the extreme height of the perch of 7A leads one to suspect the culvert was installed at this height.

It also was noted in some of these 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 in Chapter 2, the health of a stream can be negatively affected by the increase of sediments. It was observed in one culvert sediments eroded from the highway embankment was depositing in the culvert, negating any benefits of possibly minimizing embedding the culvert.

One other issue with culvert placement is that in two cases (3C and 12D) an EBC has been placed immediately downstream of a traditional culvert. In both cases, the EBC is placed in a stream that crosses a local road and then crosses the highway. There was no information provided about the culverts on the local road but it appears the culvert is 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. An attempt was made to collect data upstream of the culvert to analysis but it is unclear how reliable these data are because the stream has not had an opportunity to redevelop into its natural state.

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. In theory, a traditional culvert can disrupt the sedimentation patterns in a stream. If a traditional culvert is placed in a stream the traditional culvert may disrupt sedimentation patterns in the stream. If sedimentation patterns do become disrupted it neutralizes any potential benefits of reducing sedimentation pattern change with an EBC.

Finally, it was noted there was one culvert that was installed that best met all of the design principles of an EBC. Culvert 5F was installed with the same orientation of the stream and at the outlet was embedded 50% of the diameter of the culvert. Though the level of embedment in this culvert exceeds the amount specified by ODOT, the analysis shows there is little disruption of the continuity of sedimentation patterns through the culvert. It was noted during the field study that at the outlet, the stream had created its own channel through the bed sediments and the water was not in contact with the culvert itself at the outlet. Upon further analysis, it was discovered that this is one of only two functioning EBCs surveyed in this study.

CHAPTER VII

DISCUSSION

Applying the definition of culvert functionality presented in Chapter 5, of the 13 culverts that are operating as EBCs in Ohio, 2 culverts are functioning. Using an ANOVA general linear model, the analysis showed there is no correlation between type of culvert or stream order on culvert functionality. As noted in chapter 5, a full statistical analysis is needed on the particle size distributions.

However, this finding is limited because of the 47 circular culverts surveyed only 13 culverts are installed as EBCs. 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 was shown in Chapter 6, there is a correlation at the 90% confidence interval between a culvert slope greater than 1% and no embedment within a culvert.

In Chapter 5, linear regression analysis was performed to determine if stream and culvert characteristics are having an effect on the embedment of the culvert. The results show some relationship between upstream mean particle size, 5 year peak shear stress in the culvert, and culvert length. However, the R^2 is 0.297 and the results only include the culverts with some level embedment present in the culvert. The exact installation date of the culvert is not known. The age can be approximated based on the date of the contract but the exact age of the culverts is not known. Because the exact age of the culverts is not known an analysis on the age of the culverts was not performed.

For culvert functionality, the lack of culverts operating as EBCs does not give a sample where statistical significance can be determined. It was observed that the two functioning EBCs both had over 30% embedment at its highest level in the culvert. By testing functionality and embedment, it can be seen that all the near and non-functioning culverts have maximum embedment levels less than 30%. All other EBCs are embedded, at its deepest point, from 3.47% to 28.57%. It appears the embedment level may be having some effect on the sedimentation patterns through the culvert, but without more functioning EBCs there is not a large enough sample for the results to be statistically significant. Thus, it cannot be said conclusively what effect embedment level is having on the functionality of an EBC.

Though it cannot be determined what factors contribute to functionality, the concept of functionality appears to be important when determining the correlation between sedimentation and characteristics of the culvert. In Chapter 5, it was shown there was no correlation between the Δ percentage of fines and slope, diameter, length, 2 year, 5 year, and 10 year peak shear stress in all culverts. However when the non and near-functioning culverts are eliminated from analysis, a correlation between the length and Δ percentage of fines can be made. In addition, there is some correlation between the Δ percentage of fines and slope, diameter, 2year, 5year, and 10 year peak shear stress.

From Chapter 2, it was shown the amount of fine particles in a stream is dependent on the availability of fine particles in a watershed and the stream, and not on the hydraulic variables of the stream. The scientific literature seems to contradict the results of the study where there is some correlation between the physical characteristics of the stream and the change in fine particles. Perhaps the length of the culvert provides a longer contact time between the flow and the bed sediments causing more fine particles to be mobilized in the flow and deposited downstream. As for the correlations between slope, diameter, shear and the change in fine particles, the correlations found may be explained by the controlling factors in the shear stress of the stream. Perhaps larger diameters provide a larger surface area for fine sediments to deposit. However, higher slopes overcome the lower hydraulic radius in larger diameter culverts and the increased shear stress causes bed sediments to be transported also releasing fine particles trapped underneath larger particles. Further testing is needed to determine the exact cause of the change in percentage of fine particles.

Another trend that only holds for functioning culverts is the change in total suspended sediment and instantaneous shear. This finding is supported by the research that once the shear stress becomes larger than the critical shear stress, a particle will begin to move. As the shear stress continues to increase, the more particles will become mobilized.

In comparing functioning culverts, it was seen there is a correlation between depth of embedment in functioning hybrid and EBCs and smaller changes in Turbidity from upstream to downstream. The turbidity finding is supported by a loose correlation between the change in TSS and the depth of embedment. A possible explanation for the correlation between the change in suspended sediment and embedment level may be the deeper embedment levels provide more surface area of a natural channel bottom 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.

It is interesting that the trends presented hold only in the functional culverts. It may be possible that at these sites, the stream has reached an equilibrium point with the culvert, where the stream is no longer adjusting to the presence of the culvert. It is possible that the sediments being transported at functioning sites are sediments already present in the stream, and not being introduced from erosion around the culvert. For the sites that are not functioning, the stream may still be adjusting to the culvert and sediments are being introduced from erosion of the channel and surrounding banks. As noted in Chapter 6, 11 culverts surveyed in this study have become perched after installation. Future studies may focus on the age of the culvert and functionality of the culvert.

To understand the functionality of culverts and the trends presented, more research is needed in the field of 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 functioning culverts behave the way they do and why non-functioning culverts seem to have no predictable results. Future studies are needed to determine if conditions improve at non-functioning sites over time, or if the culvert has already reached an equilibrium point with the stream.

The results of the QHEI analysis show that of the 20 circular culverts surveyed, only 5 culverts are embedded/bankfull. Of the five EBCs, three resulted in lower QHEI scores attributed to the culvert. Similarly, seven of the 15 traditional culverts resulted in lower QHEI scores attributed to the culvert. Of all of the QHEI assessment performed, no QHEIs were performed on functioning EBCs. Thus, there is no data on the impact a functioning culvert on the surrounding habitat.

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. It is very hard to determine how the stream has reacted to the presence of a functioning EBC, because there is 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.

CHAPTER VIII

CONCLUSION

8.1 Study Findings

The first observation to be made is there are not as many EBCs as designated by ODOT. Of the 60 culverts identified by ODOT, there are only 13 EBCs. Many of the culverts are having stream sediments washed through the culvert. The primary factor attributed to this appears to be the slope of the culvert. It was shown statistically at the 90% confidence interval that less than 10% of the culverts with a slope of 1% or more have sediment deposition occurring in the culvert.

Because of the low number of EBCs and functioning EBCs, the results presented are not statistically significant. Trends were identified and an attempt to define functionality and identify similarities in the physical parameters of the functioning culverts. Based on the results presented, there was no statistical correlation found between the type of culvert, and the functionality of a culvert. Of the 13EBCs, only two were found to be effectively allowing for the continuity of sedimentation patterns through the reach of a culvert. It was observed the two functioning culverts have a maximum embedment level of over 30% and have a culvert diameter of eight feet or more. When comparing these parameters to the other culverts, none of the near or non-functioning culverts had embedment levels over 30%.

Results show there is no correlation between the change in TOC from upstream of the culvert to downstream of the culvert and length, slope or diameter. There is also no correlation between the change in TOC and the shear stresses experienced during the 2 year, 5 year, and 10 year flows. In analyzing the change in percentage of fine particles, there were some correlations found with the length, slope, diameter, 2 year, 5 year, and 10 year shear stresses in the functioning culverts.

A similar analysis was performed on the change on TSS and turbidity and instantaneous shear. When all functioning culverts were analyzed it was shown, there is a small correlation between the increase in instantaneous shear stress and the increase in TSS. When the functioning EBCs and hybrid culverts were analyzed, there was some correlation found between the change in Turbidity and TSS and the percentage of embedment. The five functioning culverts are not a large enough sample, for the results to be statistically significant. It should be noted that all correlations found were only found in functioning culverts and no correlations were found when comparing all circular culverts.

QHEI results were limited due to the fact there are only 13 culverts operating as embedded/bankful. There are only a handful of EBCs that had QHEIs performed prior to installation. Of the five EBCs that had QHEI data available, three culverts have seen degradation downstream of the culverts. None of the five EBCs with QHEI's are defined as functioning. Further analysis is needed to determine what effect a functioning EBC has on the local stream environment.

To summarize the results of this study the following list provides answers to the research questions proposed in Chapter 2.

Question: How is the effectiveness of a bankfull culvert affected by culvert diameter, slope and length?

Answer: No correlation could be found between the culvert length, slope, and width and the functionality of a culvert. Some correlation was found in the measured variables in the functioning culverts.

Question: Does the size of the stream in which the culvert is placed affect culvert effectiveness?

Answer: No correlation could be found between the size of the stream and functionality of the culvert.

Question: How have bankfull culverts affected the overall habitat surrounding a culvert?

Answer: Based on the data collected no conclusions can be made. More data on the change in habitat is needed in on EBCs that are functioning in minimizing the change in sedimentation patterns.

Question: What, if any, impacts do bankfull culverts have on flood attenuation?

Answer: An analysis of flood attenuation for a 21 ft diameter embedded culvert with a drainage area of the stream at the culvert of 2.45 square miles did increase the height of flood attenuation by 3.5 inches.

8.2 Future Work

There is more analysis needed to clarify what effect EBCs have on stream environments. One immediate item of work is a statistical analysis of the particle size distributions. The Kolmogorov-Smirnoz Goodness of Fit Test is needed to determine if the distributions are statistically different. This analysis will yield a better understanding of which culverts are functioning.

More research is needed to understand the dynamics of sedimentation transport through culverts. As stated in the literature review, sedimentation through culverts is poorly understood. Additional knowledge on the physics of sedimentation through a culvert, especially an EBC, may shed insight as to what effect the level of embedment has on the disruption of stream sedimentation. The linear regression performed, showed some correlation between length, shear stress in the culvert, and the mean particle size distribution on the percentage of embedment in the culvert. The analysis did not account for the age of the culvert. Future work could include the exact age of the culvert in the regression analysis.

One parameter that was identified after analysis but was not calculated is the Froude number. It may be useful to compare if the change in sedimentation through the culvert is correlated to the change in Froude number through the culvert. The Froude number is used to determine if the flow critical or sub-critical and incorporates features of the stream such as velocity, and depth. By using Manning’s equation for velocity of an open channel, the velocity in a stream is dependent of the stream slope, cross-sectional area, hydraulic radius, and channel roughness (Kuo, 2010). It may be useful to analyze if the change in particle-size distributions can be attributed to the Froude number of the 2 year, 5 year, and 10 year peak flows. The analysis showed some correlation between the depth of embedment and the change in TSS and turbidity in functioning culverts. More analysis is needed to test if this trend holds true with a larger sample and statistically significant results.

There were not enough QHEIs performed to determine what effect a functioning EBC has on the overall health of a stream. There is no existing data on the habitat quality surrounding these culverts. Assessments are needed to determine baseline data at the functioning sites, and then continued assessment to determine how the habitat develops around the functioning EBCs over time.

In determining the health of the stream, it may be better served to replace the use of QHEI with HHEI in lower order streams. 11 of the 20 circular culverts surveyed are on first order streams. The QHEI is designed to evaluate fish habitat. In these first order streams, the amount of fish presenet is very low. The HHEI may be a more effective tool in evaluating habitats around a culvert in first order streams. These evaluation indexes provide very quick information on the habitat of a stream. In order to gain deeper insight into habitat quality it may also be beneficial to perform an ICI or an IBI on the streams with functioning EBCs and re-evaluate every five years to determine how the installed culvert is interacting with the surrounding environment.

Finally, there is little longitudinal data available on these culverts. As noted in Chapter 7, in many cases the stream may not have reached an equilibrium point with the culvert. It is possible the reason for such varied results in the data can be attributed to the flux occurring in the stream because of the culvert. An age analysis on the functionality of the culverts may be an area of future work. In addition, future studies on these culverts, especially the EBCs and culverts operating as hybrid culverts, will provide data on how sedimentation patterns through the culvert 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.

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APPENDIX A

LABORATORY ANALYSIS DATA

(SEE ATTACHED COMPACT DISC)

APPENDIX B

PHOTOS OF CULVERTS

(SEE ATTACHED COMPACT DISC)

PHOTOS NOT AVAILABLE FOR CULVERT 17B

APPENDIX C

RESULTS OF FIELD SURVEYS

Site ID	Latitude* (Deg)	Longitude* (Deg)	Watershed	Design Length (ft)	As-built Length (ft)	Design Embedment (ft)	As-built Highest Embedment Level (ft)
1A	41.1694972	-84.72995	04100005 - Upper Maumee	512	510.68		0.55
1B	41.1743472	-84.72135	04100005 - Upper Maumee	256	253.9		0.6
1C	41.1874222	-84.68659	04100005 - Upper Maumee	78	76.28		1
1D	41.1694972	-84.72995	04100005 - Upper Maumee	156	154.22		0.7
1E	41.1694972	-84.72995	04100005 - Upper Maumee	96	93.12		0.25
1F	41.1874222	-84.68659	04100005 - Upper Maumee	228	nm		
1G	41.2153833	-84.60905	04100005 - Upper Maumee	224	nm		
2A	39.21385	-82.0634	05030204 - Hocking	511.80	462.61		0 (culvert bottom lined with 2 in of conc)
2B	39.1946083	-82.05457	05030204 - Hocking	451.77	453.09		0 (culvert bottom lined with 5 in of conc)
2C	39.1914417	-82.05297	05030204 - Hocking	534.77	493.95		0
2D	39.1880194	-82.05085	05030204 - Hocking	853.01	823.025		0 (culvert bottom lined with 11 in of conc)
2E	39.1793306	-82.04591	05030204 - Hocking	539.69	534.51		0
2F	39.1793306	-82.04591	05030204 - Hocking	639.76	nm		0 at inlet
2G	39.1595444	-82.03569	05030204 - Hocking	410.10	408.48		0
3A	39.2527694	-82.08005	05030202 - Upper Ohio-Shade	749.66	749.85		0 (concrete pad at outlet)
3B	39.2423722	-82.07631	05030202 - Upper Ohio-Shade	825.12	823.129		0 (concrete pad at outlet)
3C	39.2361861	-82.07392	05030202 - Upper Ohio-Shade	311.68	313.795		0 (concrete pad at outlet)
3D	39.2312167	-82.0692	05030202 - Upper Ohio-Shade	250.98	253.877		0 (concrete pad at outlet)
4A	39.2436056	-82.84272	05060002 - Lower Scioto	390	219.238		0
4B	39.22395	-82.82869	05060002 - Lower Scioto	368	372.088		0
4C	39.22395	-82.82869	05060002 - Lower Scioto	295	289.72		0
4D	39.2030861	-82.81827	05060002 - Lower Scioto	84	84.042		1.833
5A	38.9709722	-81.85637	05030202 - Upper Ohio-Shade	535	535.279	2	1
5B	38.9662806	-81.83547	05030202 - Upper Ohio-Shade	378	378.2	1.5	1.83
5C	38.9662806	-81.83547	05030202 - Upper Ohio-Shade	310	297.764	1.5	2.75
5D	38.9625222	-81.82256	05030202 - Upper Ohio-Shade	500	478.1778	1.9	0
5E	38.9479111	-81.79664	05030202 - Upper Ohio-Shade	615	615.9	1.9	2.42
5F	38.9433361	-81.79266	05030202 - Upper Ohio-Shade	650	nm	2	4
5G	38.9433361	-81.79266	05030202 - Upper Ohio-Shade	523	524.23	2	0.4167
5H	38.9709722	-81.85637	05030202 - Upper Ohio-Shade		574.865		traditional culvert used for control
6A	39.0164083	-81.91664	05030202 - Upper Ohio-Shade	295	296.1269		0
6B	39.0085944	-81.90859	05030202 - Upper Ohio-Shade	264	265.63		0.92
6C	38.9998861	-81.88617	05030202 - Upper Ohio-Shade	85	85.59		varies from 0 to 2.83
6D	38.9998861	-81.88617	05030202 - Upper Ohio-Shade	389	387.959		0
6E	38.9849139	-81.86732	05030202 - Upper Ohio-Shade	108	108.2095		0.67
7A	39.0438444	-81.95637	05030202 - Upper Ohio-Shade	413	428.753	1.25	0
7B	39.0303917	-81.9416	05030202 - Upper Ohio-Shade	477	473.44		2.5
8A	39.7796528	-82.68999	05030204 - Hocking	236	237.298		0
8B	39.7342056	-82.6784	05030204 - Hocking	143	143.278		1
8C	39.7342056	-82.6784	05030204 - Hocking	203	205.753		2
9A	39.7062139	-82.66976	05030204 - Hocking	192	190.805	2	
9B	39.6860139	-82.65794	05030204 - Hocking	312	312.133	1	1.75
9C	39.6860139	-82.65794	05030204 - Hocking	90	89.49	1	1.17
9D	39.6716528	-82.62935	05030204 - Hocking	224	225.427		0.58
10A	39.6692194	-82.62006	05030204 - Hocking	280	280.56		0.5
10B	39.6679139	-82.58993	05030204 - Hocking	259	261.28		0.58
11A	39.6600139	-82.56107	05030204 - Hocking	54	52.201		varies from 4.167 to 5.167
11B	39.6600139	-82.56107	05030204 - Hocking	264	261.849		0
12A	39.8432194	-82.7813	05060001 - Upper Scioto	58	75.485	2	1.75
12B	39.8432194	-82.7813	05060001 - Upper Scioto	55	55.61	2	varies 1.83 to 2.17
12C	39.8432194	-82.7813	05060001 - Upper Scioto	210	173.2	4	1.25
12D	39.8432194	-82.7813	05060001 - Upper Scioto	276	276.24	2	1.75
12E	39.8432194	-82.7813	05060001 - Upper Scioto	125	109.74	2	3.17
12F	39.8432194	-82.7813	05060001 - Upper Scioto		nm		
13A	40.8013222	-81.91118	5040003 - Walhonding	163	162.85	0.583	0
13B	40.7986444	-81.89691	5040003 - Walhonding	286	284.02	0.583	0.541
13C	40.8045611	-81.8656	5040003 - Walhonding	560		1.167	2.67
14A	40.8066278	-81.82544	5040003 - Walhonding	282	nm	1.167	0
14B	40.8066278	-81.82544	5040003 - Walhonding	144	144.58	0.917	3.33
14C	40.8066278	-81.82544	5040003 - Walhonding		649.653		traditional culvert used for control
15A	40.7622611	-81.74518	04100011 - Sandusky	246.06	248.736	2.953	1
15B	40.7622611	-81.74518	04100011 - Sandusky	118.11	120.951	2.953	0
16A	40.76195	-81.76032	04100011 - Sandusky	314.96	320.44		3
17A	40.76195	-81.76032	04100011 - Sandusky		293.162		traditional culvert used for control
17B	40.7771417	-81.92983	04100011 - Sandusky	462.59	461.121	0.984	0

*Locations are approximations using aerial images. Some coordinates may be repeated due to close proximity of culverts

Nm = data not measured

Site ID	Design Diameter (ft)	As-built Diameter (ft)	% deepest embedment	Design Slope (%)	As-built Slope (%)	Age as of 2009	QHEI before culvert installation	QHEI Upstream culvert	QHEI Downstream culvert
1A	Box 9' H x 14' W	Box 9' H x 14' W	3.928571429	0.048%	0.031%	2 yrs	n/a	n/a	n/a
1B	Box 9' H x 14' W	Box 9' H x 14' W	4.285714286	0.060%	0.193%	2 yrs	n/a	n/a	n/a
1C	Box 12' H x 20' W	Box 12' H x 20' W	7.142857143	0.380%	0.367%	2 yrs	n/a	n/a	n/a
1D	Box 9' H x 14' W	Box 9' H x 14' W	5	0.060%	0.162%	2 yrs	15	36	33
1E	Box 9'H x 16' W	Box 9'H x 16' W	1.5625	0.310%	0.451%	2 yrs	n/a	n/a	n/a
1F	arch	arch			nm	2 yrs	n/a	n/a	n/a
1G	arch	arch			nm	2 yrs	n/a	n/a	n/a
2A	5.9	6	0	1.150%	1.124%	8 yrs	67	39.5	65
2B	5.9	5	0	2.900%	2.947%	8 yrs	n/a	n/a	n/a
2C	3.5	3.5	0	8.240%	7.791%	8 yrs	n/a	n/a	n/a
2D	5.5	5.5	0	2.090%	1.946%	8 yrs	54	64	69
2E	4.5	4.5	0	3.560%	3.388%	8 yrs	n/a	n/a	n/a
2F	3.5	3.5	0	4.230%	nm	8 yrs	n/a	n/a	n/a
2G	2.5	2.5	0	6.690%	6.336%	8 yrs	n/a	n/a	n/a
3A	5.9	6	0	3.160%	3.546%	8 yrs	n/a	n/a	n/a
3B	12	12	0	0.600%	0.661%	8 yrs	67	45	58
3C	4.5	4.5	0	3.190%	3.329%	8 yrs	53	29	40
3D	5.5	5.5	0	3.860%	5.644%	8 yrs	57	54.5	48.5
4A	12	12	0	0.770%	1.463%	7 yrs	57	89	66
4B	5	5	0	1.630%	1.619%	7 yrs	47	50	n/a
4C	5	5	0	2.040%	1.937%	7 yrs	50.5	50	62.4
4D	Box 8' H x 14' W	Box 8' H x 14' W	13.0952381	0.600%	0.706%	7 yrs	34	n/a	36
5A	6	6	16.66666667	2.560%	2.523%	8 yrs	47	52	42
5B	5	5	36.6	4.640%	4.529%	8 yrs	39.5	48	42.25
5C	4	4	68.75	5.380%	5.219%	8 yrs	58	49	41.5
5D	10	12	0	2.190%	1.948%	8 yrs	n/a	n/a	n/a
5E	12	12	20.16666667	0.690%	0.676%	8 yrs	52.5	50.5	58.5
5F	8	8	50	1.180%	nm	8 yrs	n/a	n/a	n/a
5G	10	12	3.4725	0.250%	0.179%	8 yrs	48	59	47.5
5H		4	0		4.499%		n/a	n/a	n/a
6A	4	4	0	2.200%	2.423%	8 yrs	57	46.5	44.5
6B	3.5	3.5	26.28571429	5.000%	4.070%	8 yrs	n/a	n/a	n/a
6C	ellipse 5.67 x 8.17	ellipse 5.67 x 8.17		0.800%	0.748%	8 yrs	69	43.75	41
6D	6	6	0	8.500%	7.458%	8 yrs	59	33.5	47.5
6E	ellipse 4.83 x 7.58	ellipse 4.83 x 7.58		0.600%	0.536%	8 yrs	58.25	35	42.75
7A	5	5	0	3.070%	2.862%	8 yrs	41.5	49	49
7B	21	21	11.9047619	0.270%	0.387%	8 yrs	58.5	n/a	52
8A	Box 8' H x 18' W	Box 8' H x 18' W	0	0.120%	0.157%	8 yrs	41	n/a	n/a
8B	14	14	7.142857143	0.870%	0.790%	8 yrs	56	77.5	68
8C	7	7	28.57142857	0.870%	0.822%	8 yrs	n/a	n/a	n/a
9A	Box 10' H x 20' W	Box 10' H x 20' W		0.280%	0.437%	8 yrs	34	65	62
9B	7	7	25	0.700%	1.227%	8 yrs	n/a	n/a	n/a
9C	6	6	19.5	0.700%	0.638%	8 yrs	n/a	n/a	n/a
9D	9	9	6.444444444	0.190%	0.171%	8 yrs	36	33.5	47
10A	5	5	10	2.510%	4.774%	7 yrs	n/a	n/a	n/a
10B	10.5	10.5	5.523809524	0.400%	0.367%	7 yrs	71	n/a	66
11A	Box 8 H x 21 W	Box 8' H x 21' W	52.0875	0.480%	0.104%	7 yrs	n/a	n/a	n/a
11B	Box 9 H x 18 W	Box 9' H x 18' W	0	0.360%	0.493%	7 yrs	n/a	n/a	n/a
12A	Box 8' H x 8' W	Box 8' H x 8' W	21.875	0.120%	0.088%	7 yrs	n/a	n/a	n/a
12B	Box 8' H x 8' W	Box 8' H x 8' W	27.125	1.380%	1.416%	7 yrs	n/a	n/a	n/a
12C	20	20	6.25	0.070%	0.036%	7 yrs	39.25	51.25	49
12D	8	8	21.875	0.370%	0.585%	7 yrs	32.5	n/a	45
12E	10.5	10.5	30.19047619	0.160%	0.137%	7 yrs	n/a	n/a	n/a
12F					nm	7 yrs	n/a	n/a	n/a
13A	4	4	0	0.300%	0.301%	5 yrs	n/a	n/a	n/a
13B	4	4	13.525	3.000%	2.943%	5 yrs	n/a	n/a	n/a
13C	9	9	29.66666667	2.500%		5 yrs	n/a	n/a	n/a
14A	7		0	1.140%	nm	5 yrs	n/a	n/a	n/a
14B	ellipse 5.67 H x 8.83 W	10	58.73015873	0.340%	0.310%	5 yrs	n/a	n/a	n/a
14C	6	6	0		0.006%	5 yrs	n/a	n/a	n/a
15A	7.38	8	12.5	0.340%	0.151%	8 yrs	n/a	n/a	n/a
15B	7.38	8	0	0.350%	0.429%	8 yrs	n/a	n/a	n/a
16A	11.81	12	25	0.340%	1.708%	6 yrs	58	56	46
17A		6	0		0.247%	6 yrs	n/a	n/a	n/a
17B	6.4	6	0	0.620%	0.618%	6 yrs	70	n/a	n/a

APPENDIX D

SAMPLE CALCULATIONS OF SHEAR STRESS

Sample Calculations for Culvert 2B

Find Shear Stress for 2 year peak flow

Culvert Data

Diameter = 5 ft Slope = 0.011251 ft/ft Q_2 = 63.8 cfs g = 32.2ft/s^2γ = 62.3 lb/ft^3

Ks = 0.01625 (material type unavailable, assumed steel culvert)

Find dimensionless flow rate (Q*)

$$Q^* = \frac{Q}{\sqrt{gD^5}}$$

$$Q^* = \frac{63.8}{\sqrt{32.32*5^5}}$$ Q* = 0.127

Find depth of flow (d)

$$d = .32D\left(\left(\frac{Q^*}{\sqrt{S_o}}\right)\left(\frac{K_s}{D}\right)^{\frac{1}{6}} + 0.64\right)$$

$$d = .325\left(\left(\frac{0.127}{\sqrt{0.011251}}\right)\left(\frac{0.01625}{5}\right)^{\frac{1}{6}} + 0.64\right)$$ d = 2.09 ft

Find Hydraulic Radius (R)

$$h = 2r - d$$

$h = 2(2.5) - 2.09$h = 2.91 ft

$$\theta = 2\arccos(\frac{r - h}{r})$$

$$\theta = 2\arccos(\frac{2.5 - 2.91}{2.5})\theta = 3.47\ radians$$

$$A = \pi r^2 - \frac{r^2(\theta - sin\theta)}{2}$$

$A = \pi 2.5^2 - \frac{2.5^2(3.47 - sin3.47)}{2}$ A = 7.78 sqft

$P = r * \theta$

$P = 2.5 * 3.47$ P = 7 ft

$R = \frac{A}{P}$

$R = \frac{7.78}{7}$ R = 1.16

Find peak 2 year shear stress of the flow (τ)

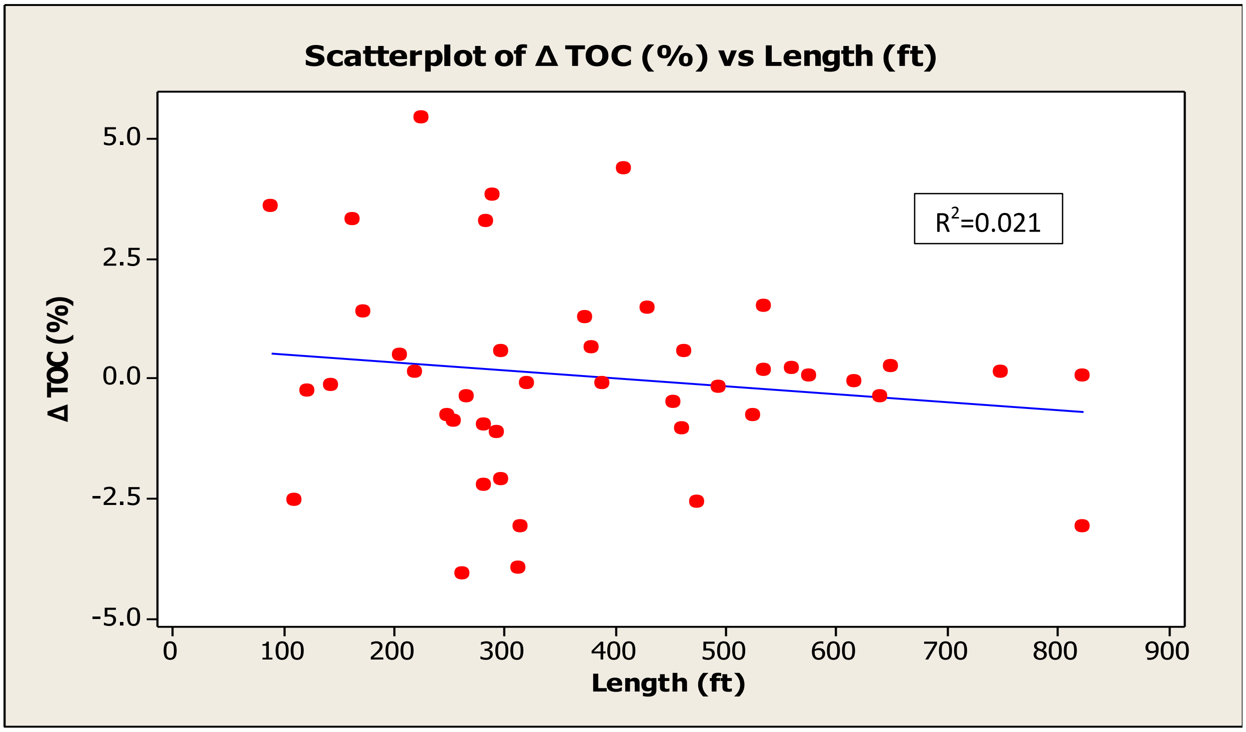
$$\tau = R * S * \gamma$$

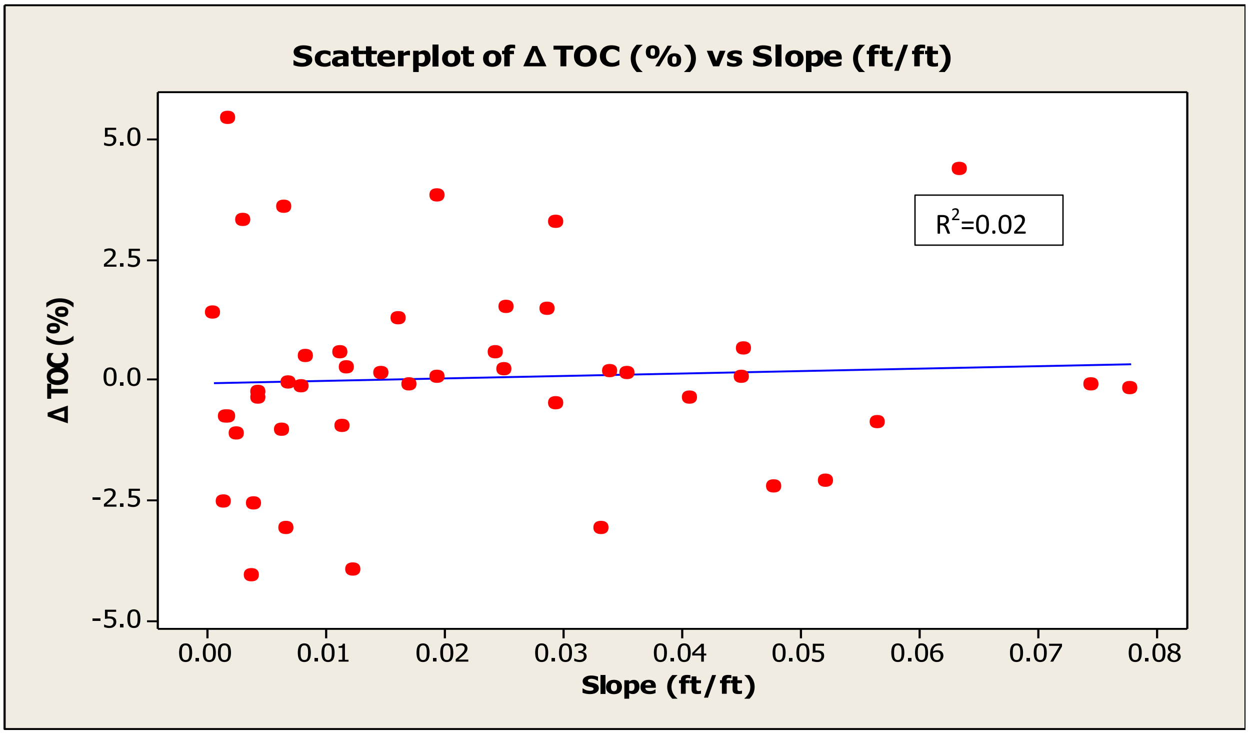
$\tau = 1.16 * 0.01125 * 62.3$ $\tau = 0.814$ lb/ft^2

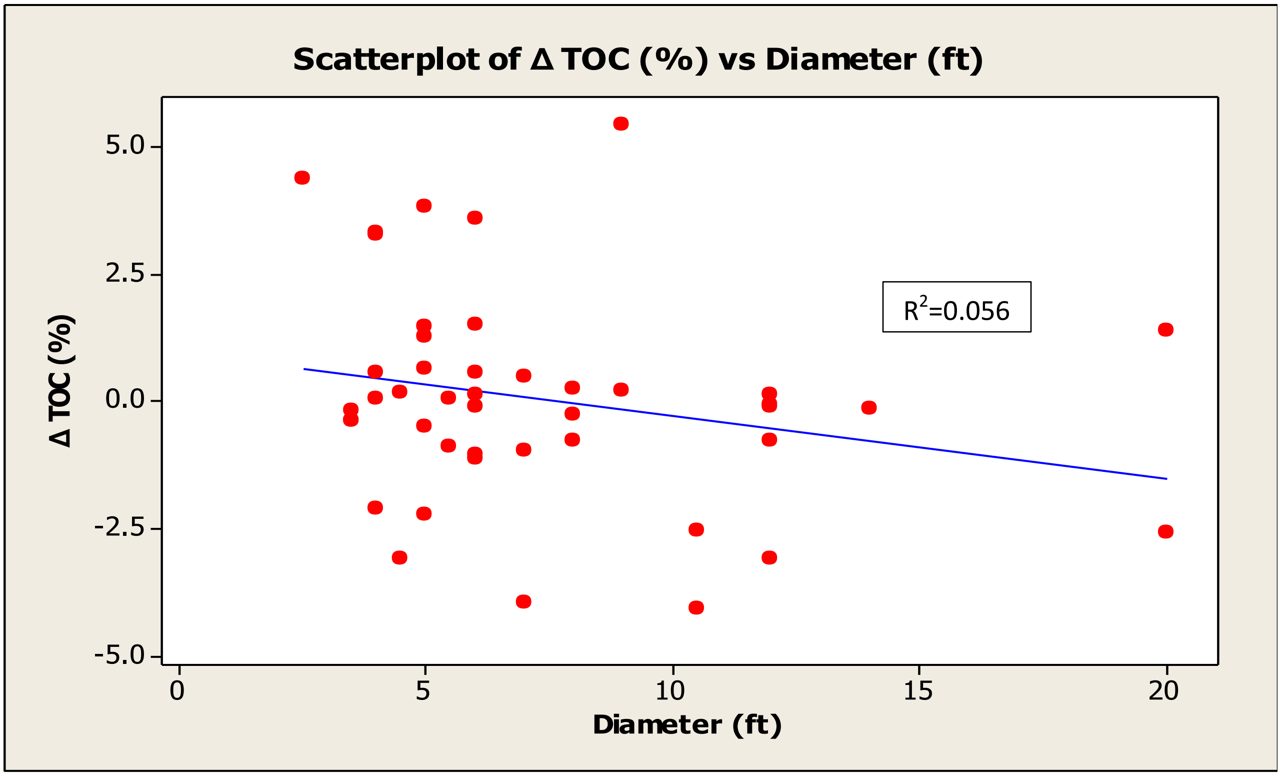
APPENDIX E

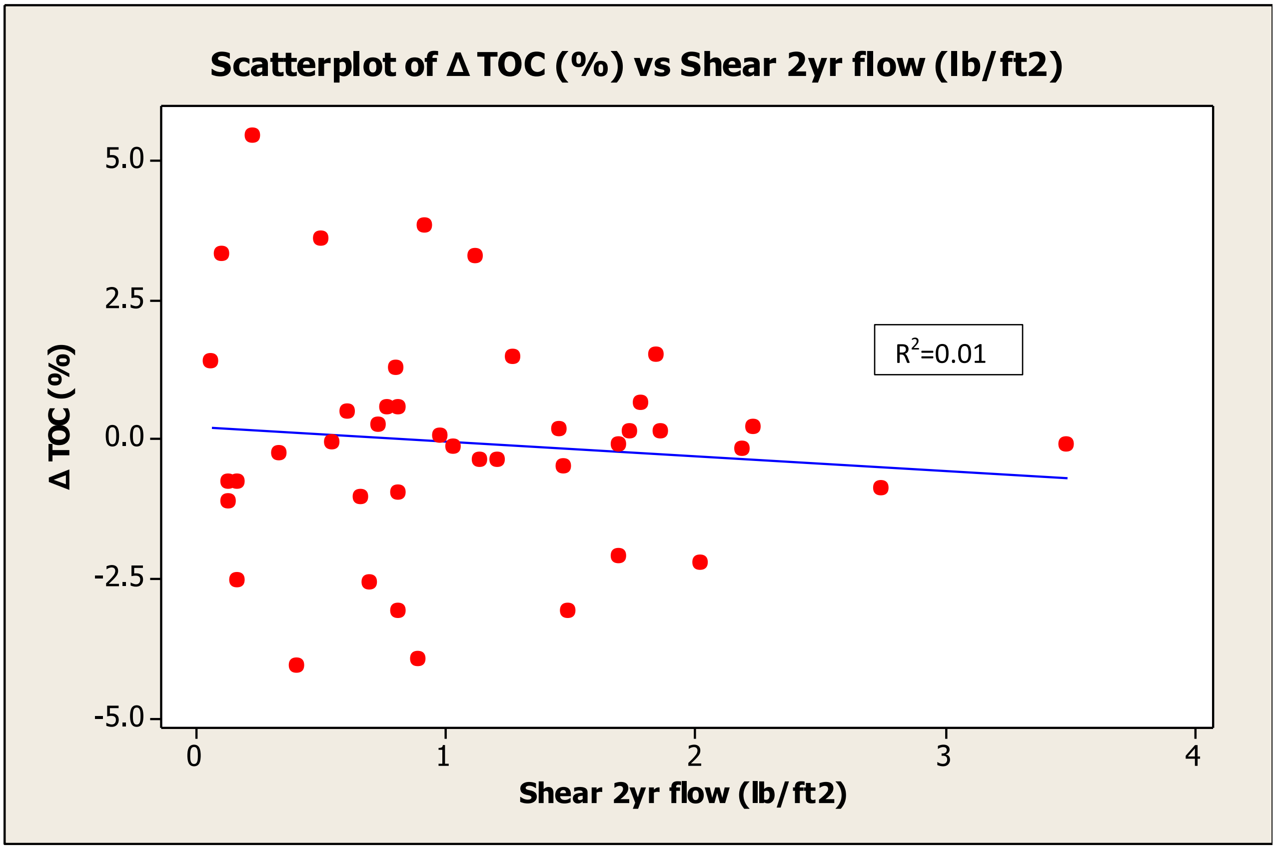
SCATTERPLOTS FROM DATA ANALYSIS

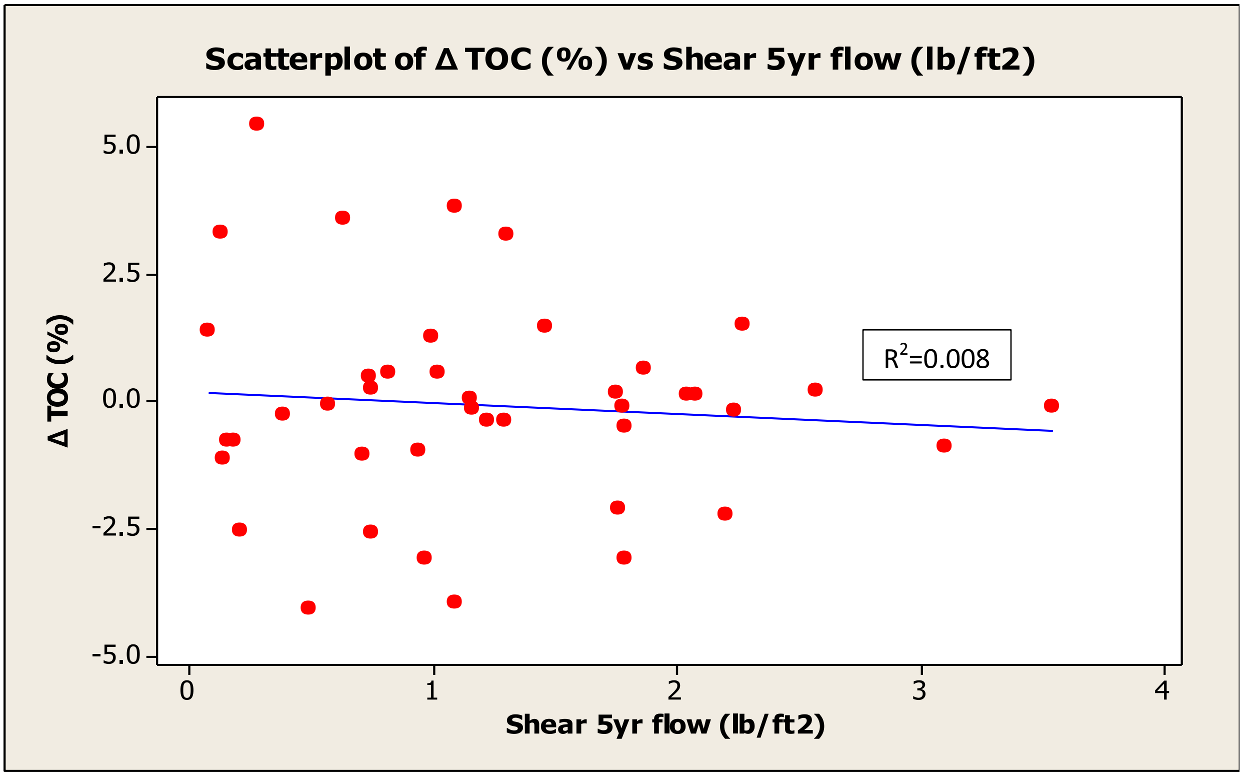
E.1 All Circular Culverts

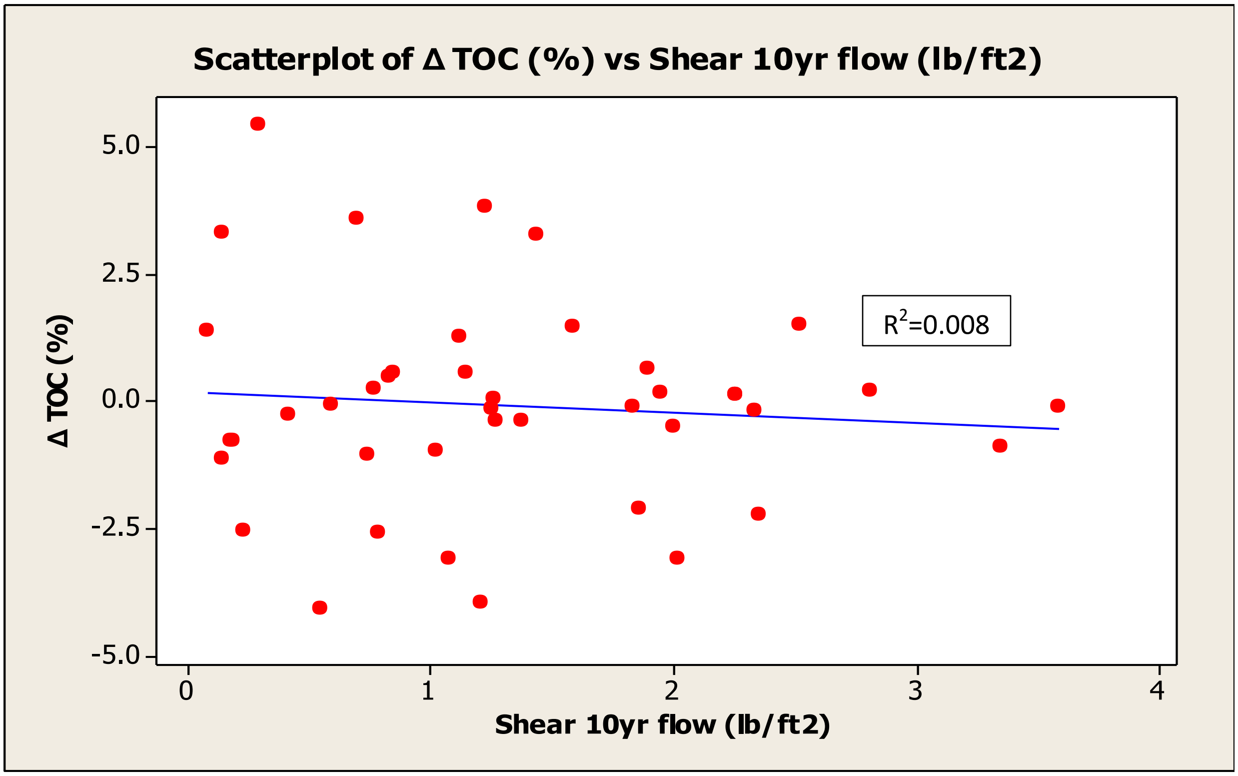


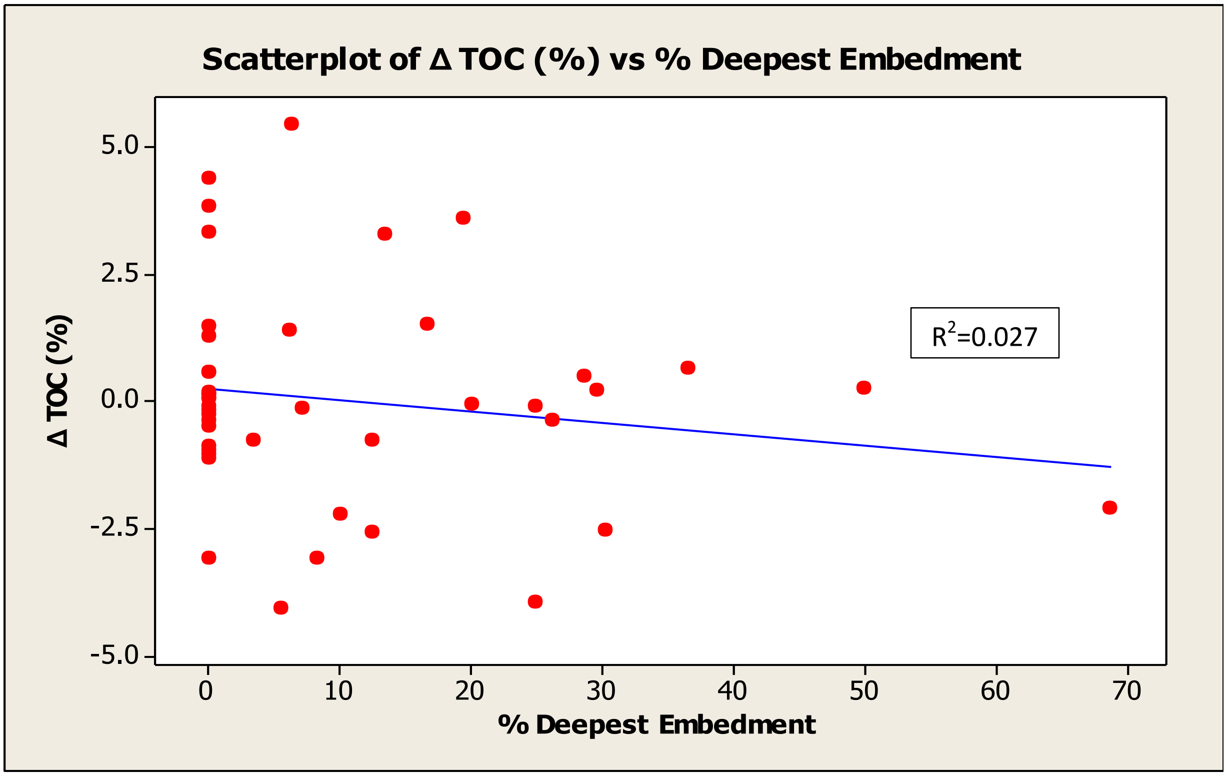


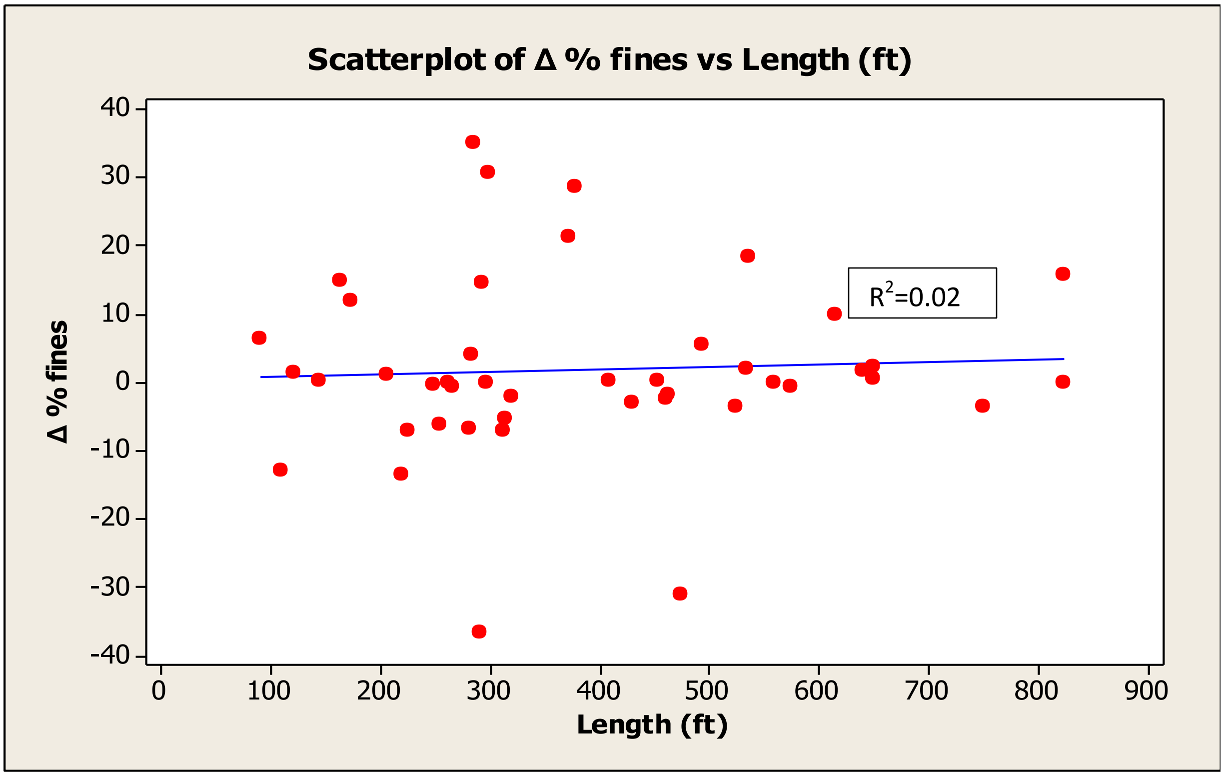

Scatterplot of Δ TOC (%) vs Diameter (ft)
Δ TOC (%)
5.0
2.5
0.0
-2.5
-5.0
0
5
10
15
20
Diameter (ft)
R²=0.056

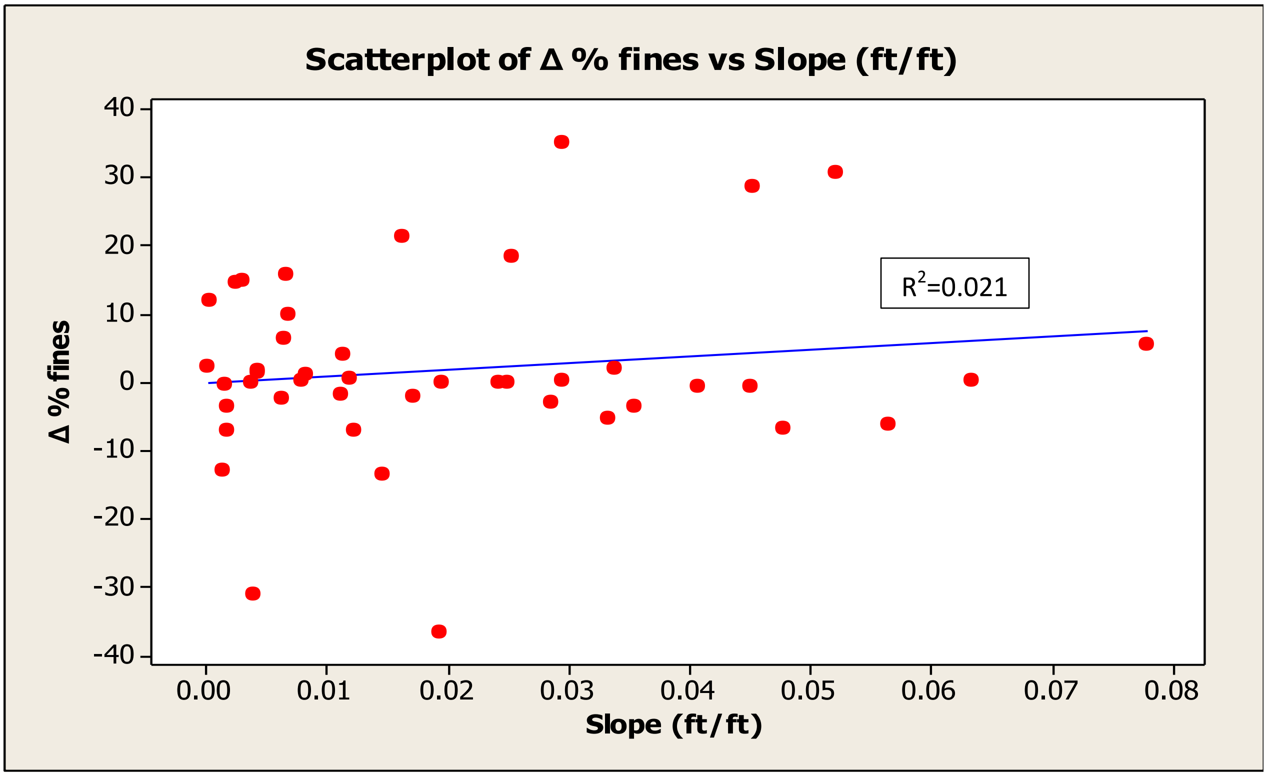

Scatterplot of Δ TOC (%) vs Shear 2yr flow (lb/ft2)
Δ TOC (%)
5.0
2.5
0.0
-2.5
-5.0
0
1
2
3
4
Shear 2yr flow (lb/ft2)
R²=0.01

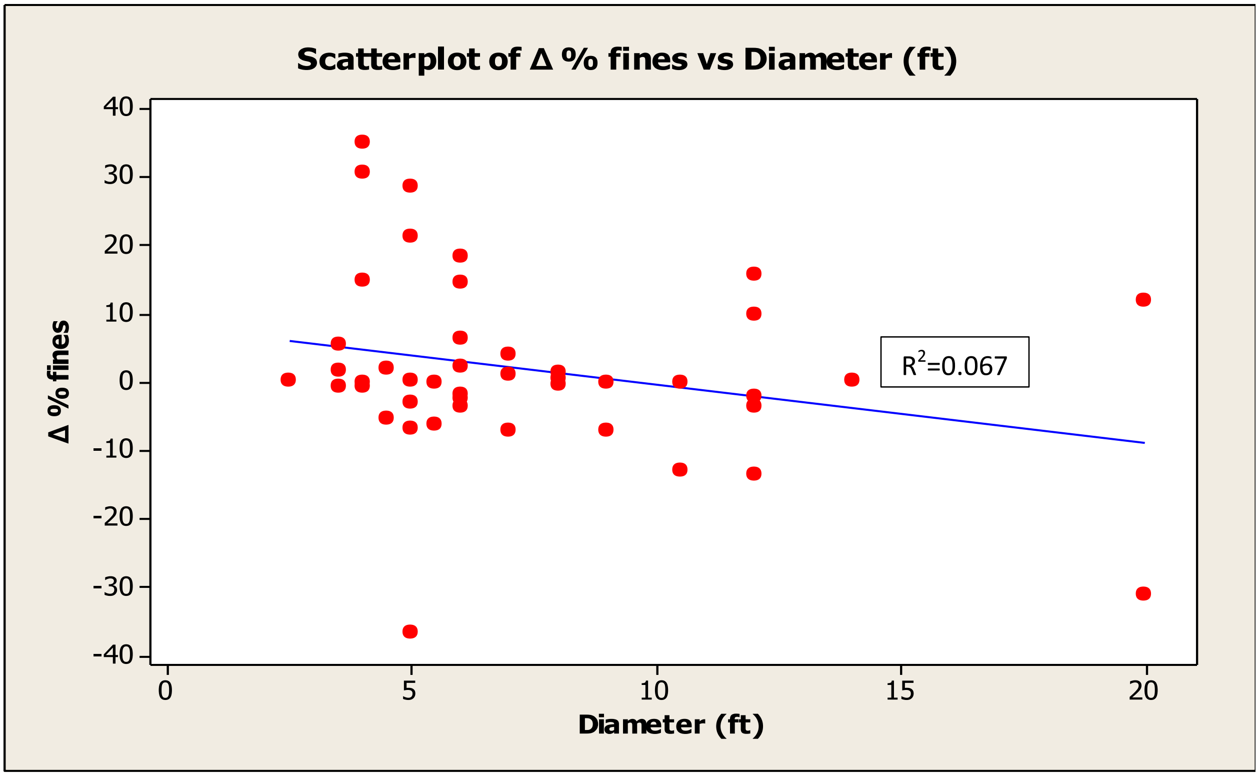

Scatterplot of Δ TOC (%) vs Shear 5yr flow (lb/ft2)
Δ TOC (%)
5.0
2.5
0.0
-2.5
-5.0
0
1
2
3
4
Shear 5yr flow (lb/ft2)
R^2=0.008

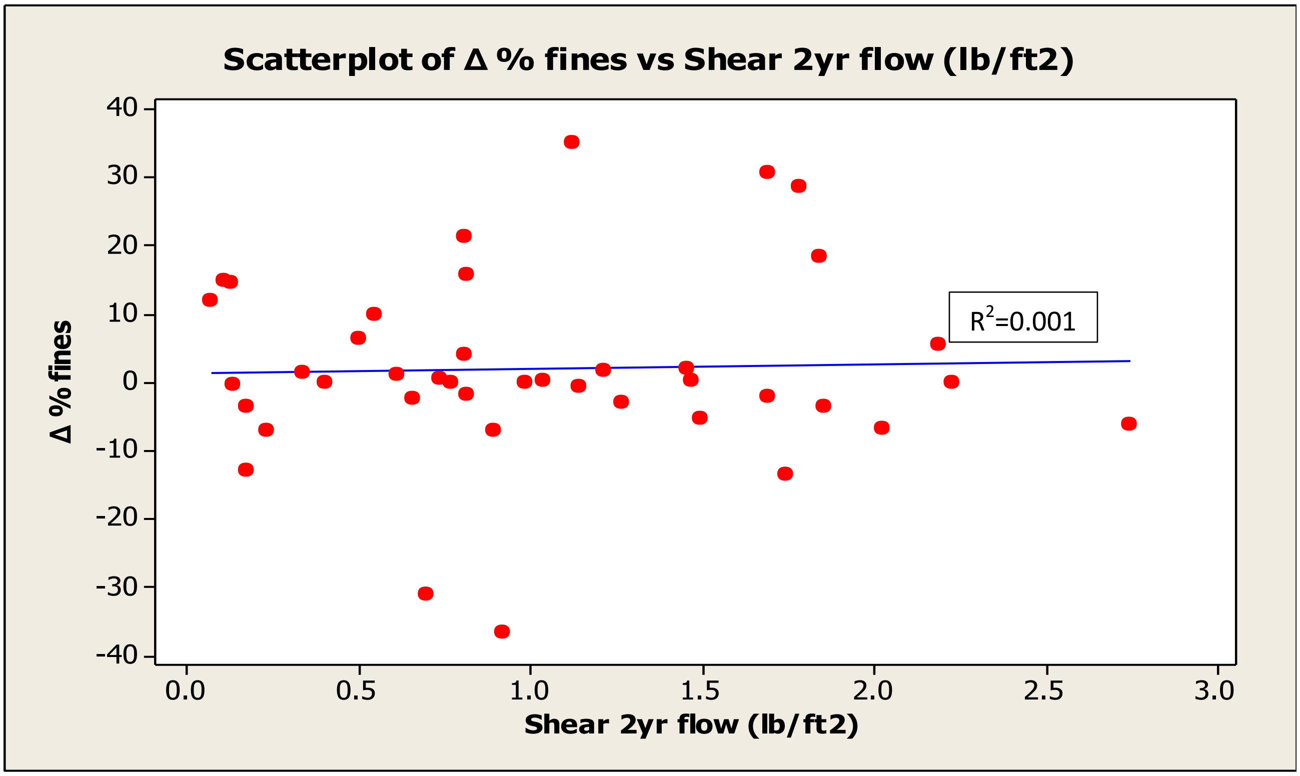

Scatterplot of Δ TOC (%) vs Shear 10yr flow (lb/ft2)
Δ TOC (%)
5.0
2.5
0.0
-2.5
-5.0
0
1
2
3
4
Shear 10yr flow (lb/ft2)
R^2=0.008

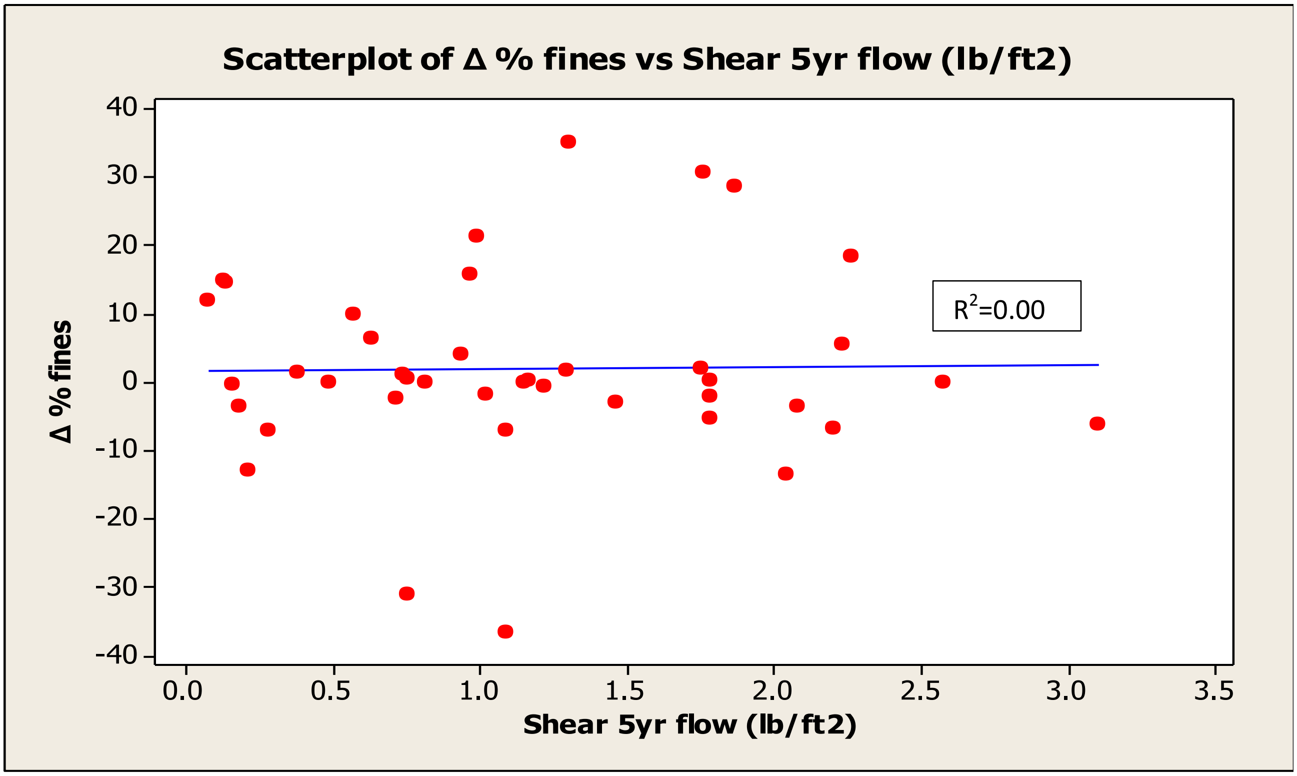

Scatterplot of Δ TOC (%) vs % Deepest Embedment
Δ TOC (%)
5.0
2.5
0.0
-2.5
-5.0
0
10
20
30
40
50
60
70
% Deepest Embedment
R^2=0.027

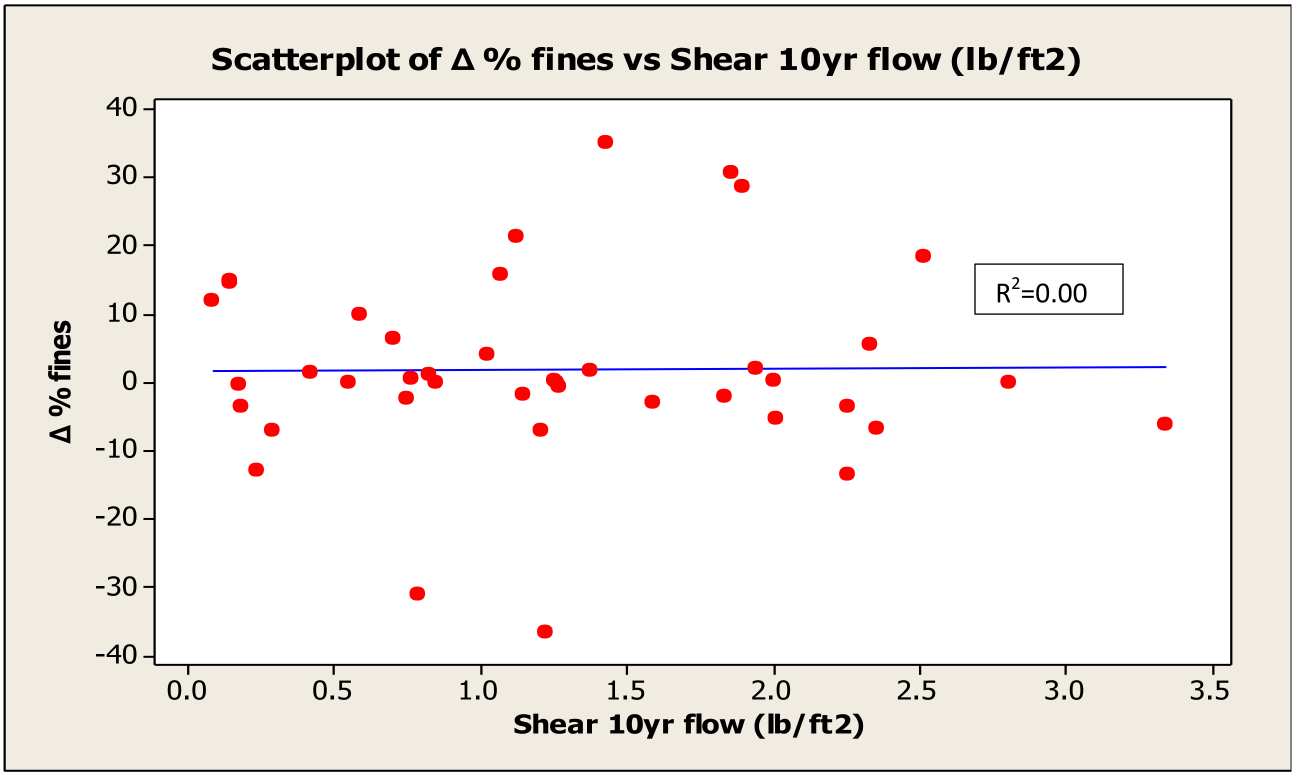

Scatterplot of Δ % fines vs Length (ft)
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0
100
200
300
400
500
600
700
800
900
Length (ft)
R^2=0.02

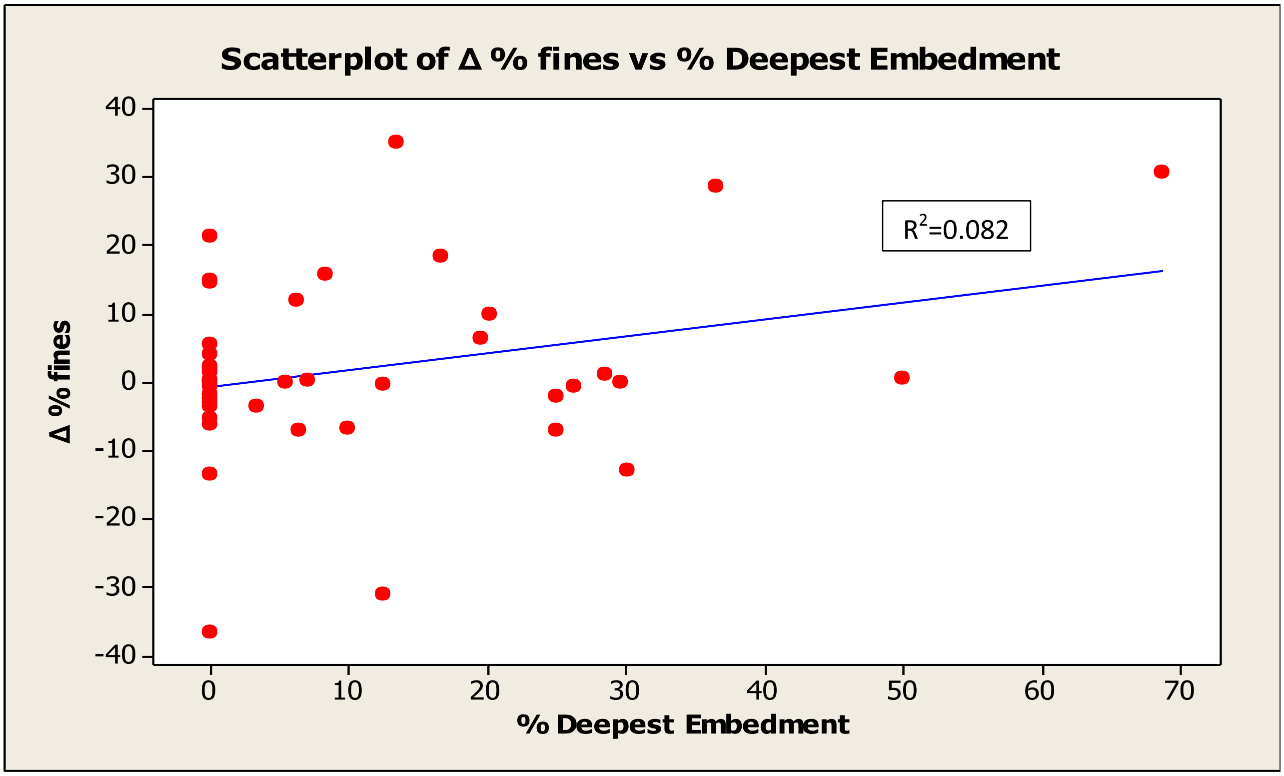

Scatterplot of Δ % fines vs Slope (ft/ft)
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Slope (ft/ft)
R^2=0.021

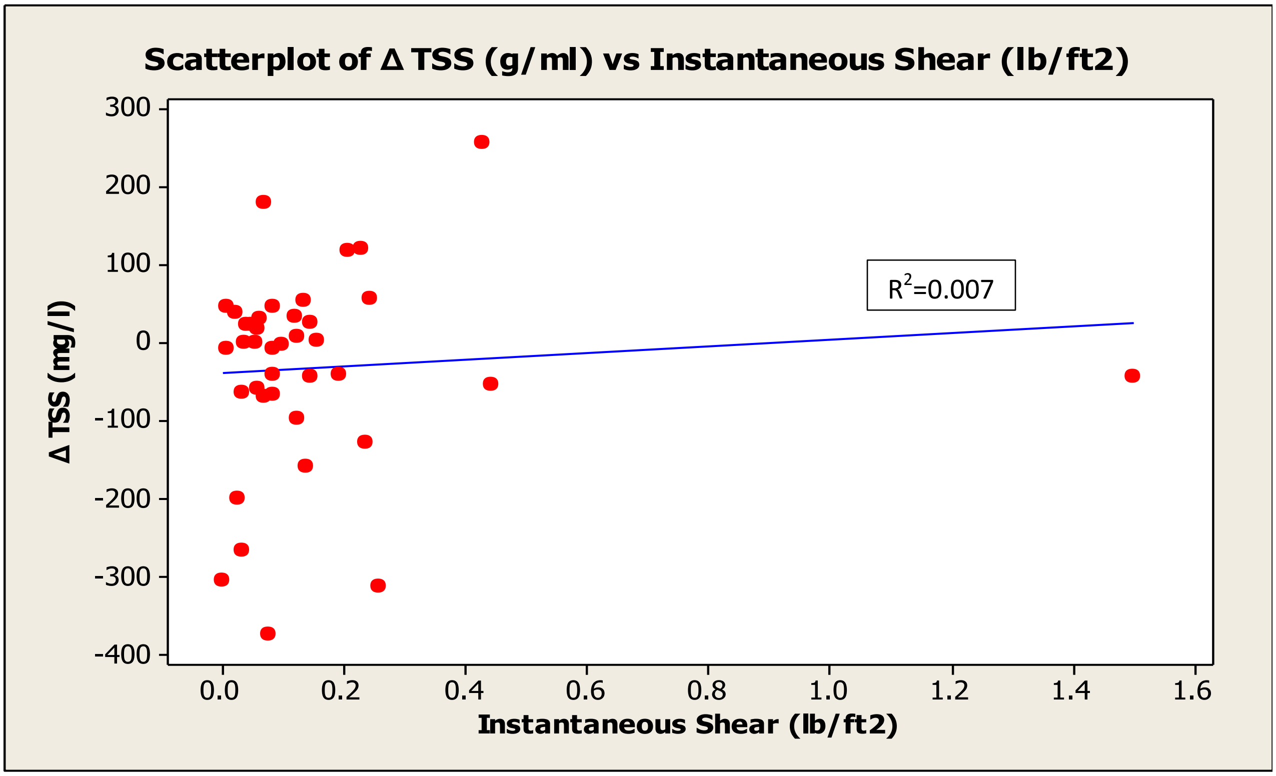

Scatterplot of Δ % fines vs Diameter (ft)
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0
5
10
15
20
Diameter (ft)
R^2=0.067

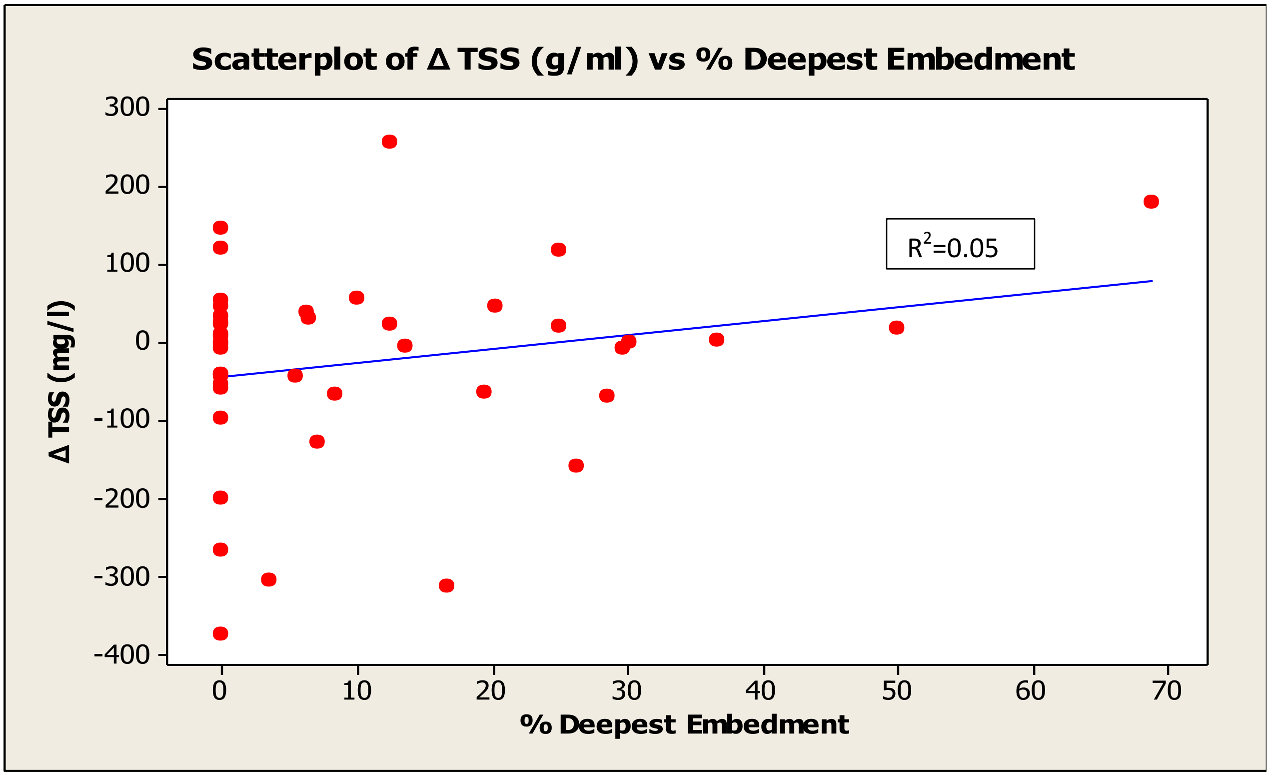

Scatterplot of Δ % fines vs Shear 2yr flow (lb/ft2)
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Shear 2yr flow (lb/ft2)
R^2=0.001

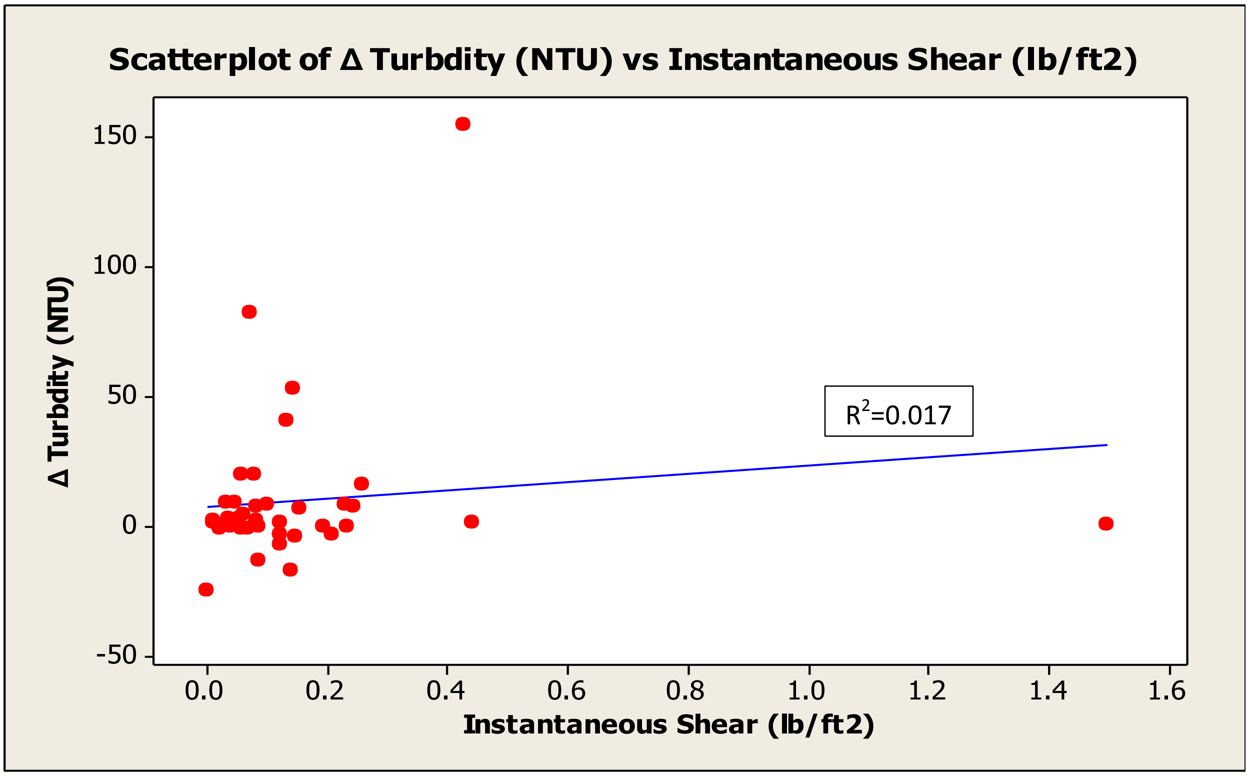

Scatterplot of Δ % fines vs Shear 5yr flow (lb/ft2)
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Shear 5yr flow (lb/ft2)
R^2=0.00

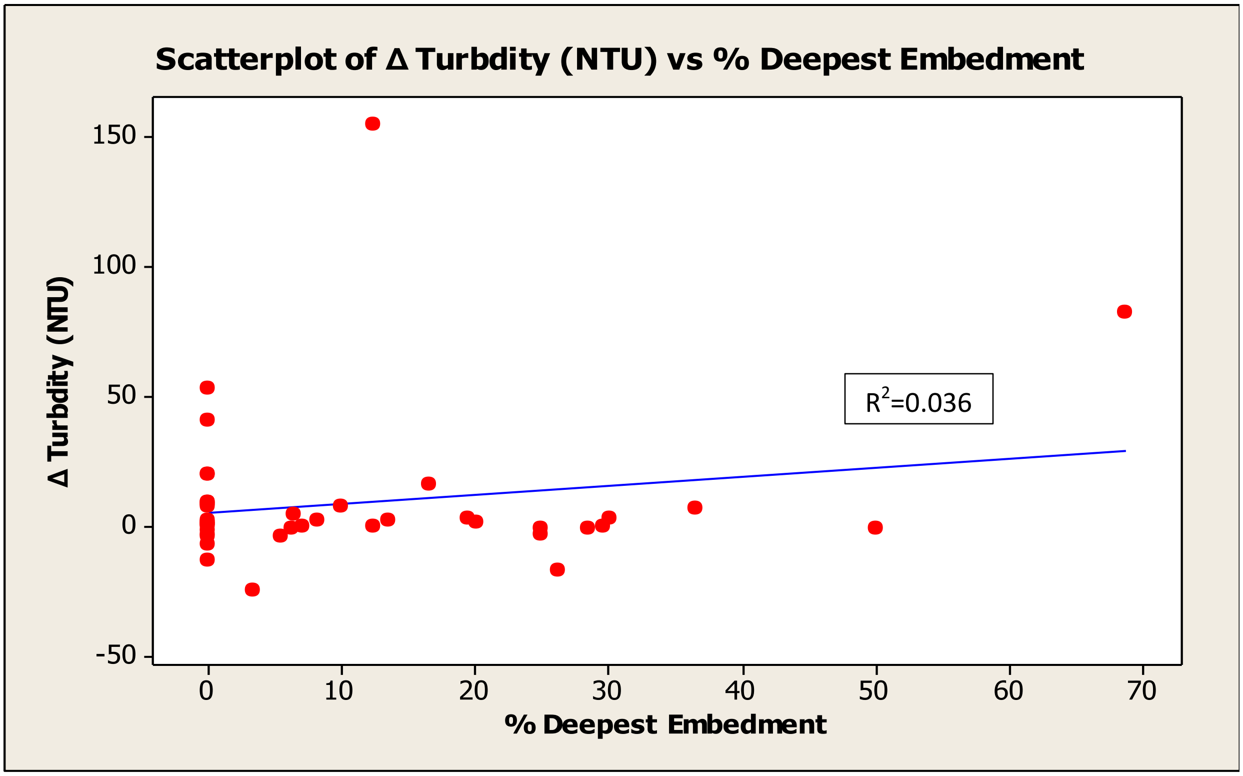

Scatterplot of Δ % fines vs Shear 10yr flow (lb/ft2)
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Shear 10yr flow (lb/ft2)
R^2=0.00


Scatterplot of Δ % fines vs % Deepest Embedment
Δ % fines
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70
% Deepest Embedment
R^2=0.082

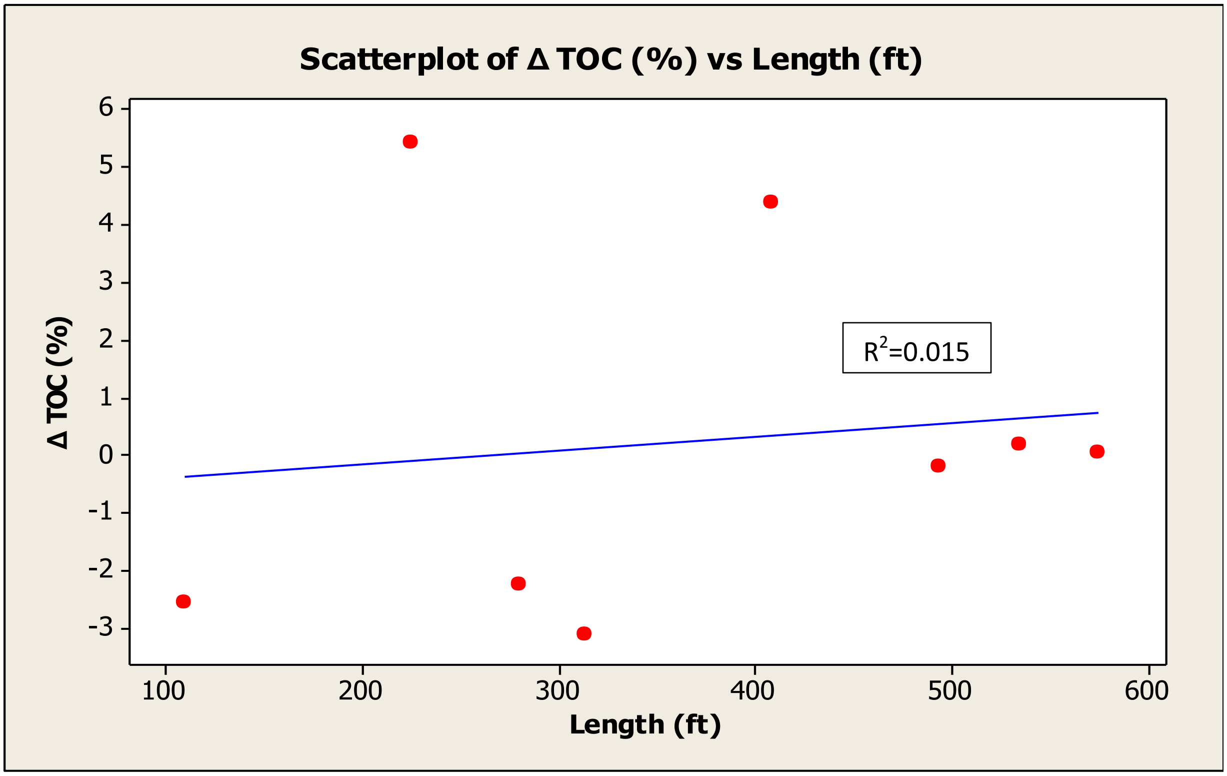

Scatterplot of Δ TSS (g/ml) vs Instantaneous Shear (lb/ft2)
Δ TSS (mg/l)
300
200
100
0
-100
-200
-300
-400
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Instantaneous Shear (lb/ft2)
R^2=0.007

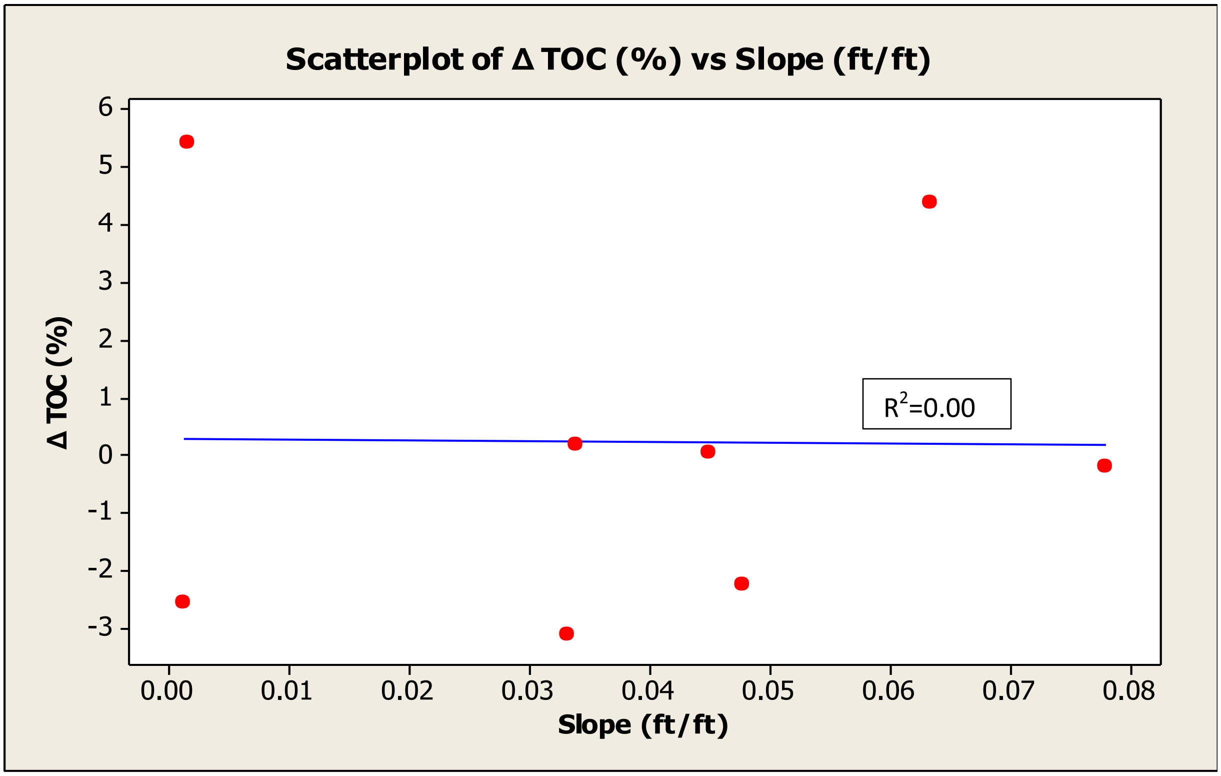

Scatterplot of Δ TSS (g/ml) vs % Deepest Embedment
Δ TSS (mg/l)
300
200
100
0
-100
-200
-300
-400
0
10
20
30
40
50
60
70
% Deepest Embedment
R^2=0.05

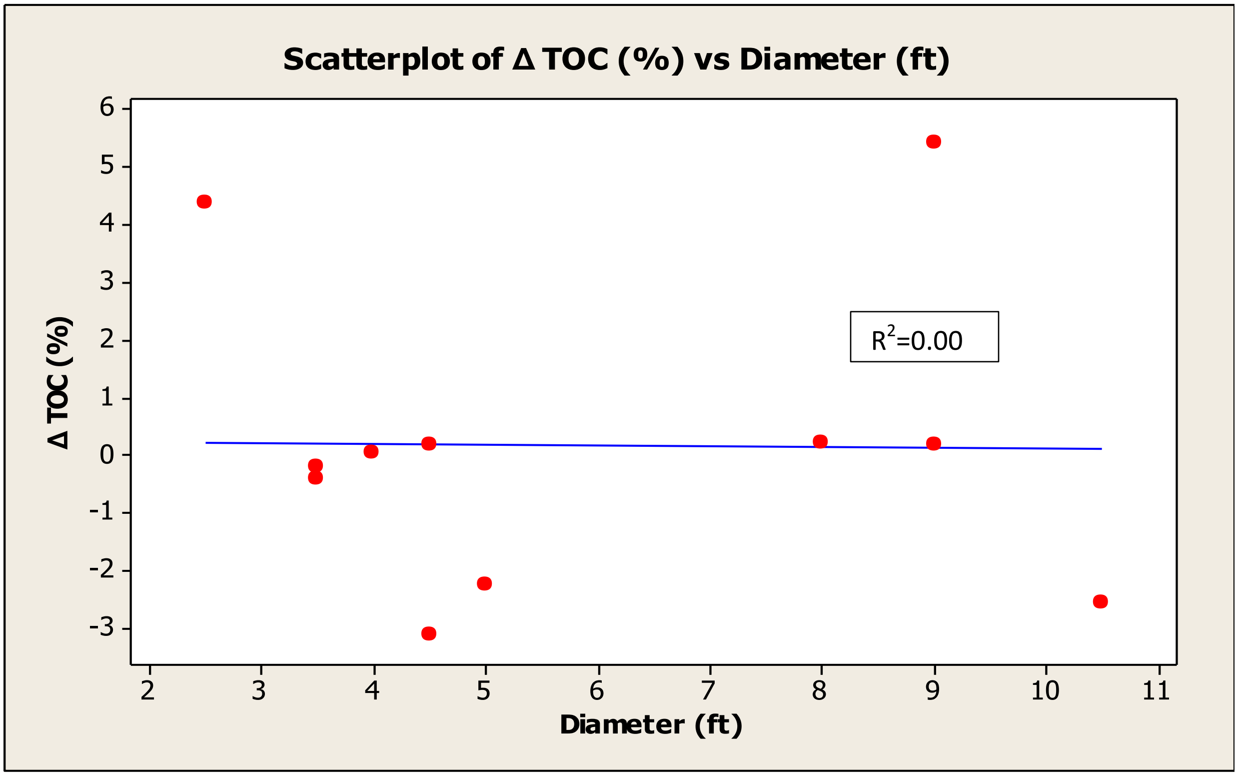

Scatterplot of Δ Turbdity (NTU) vs Instantaneous Shear (lb/ft2)
Δ Turbdity (NTU)
150
100
50
0
-50
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Instantaneous Shear (lb/ft2)
R^2=0.017

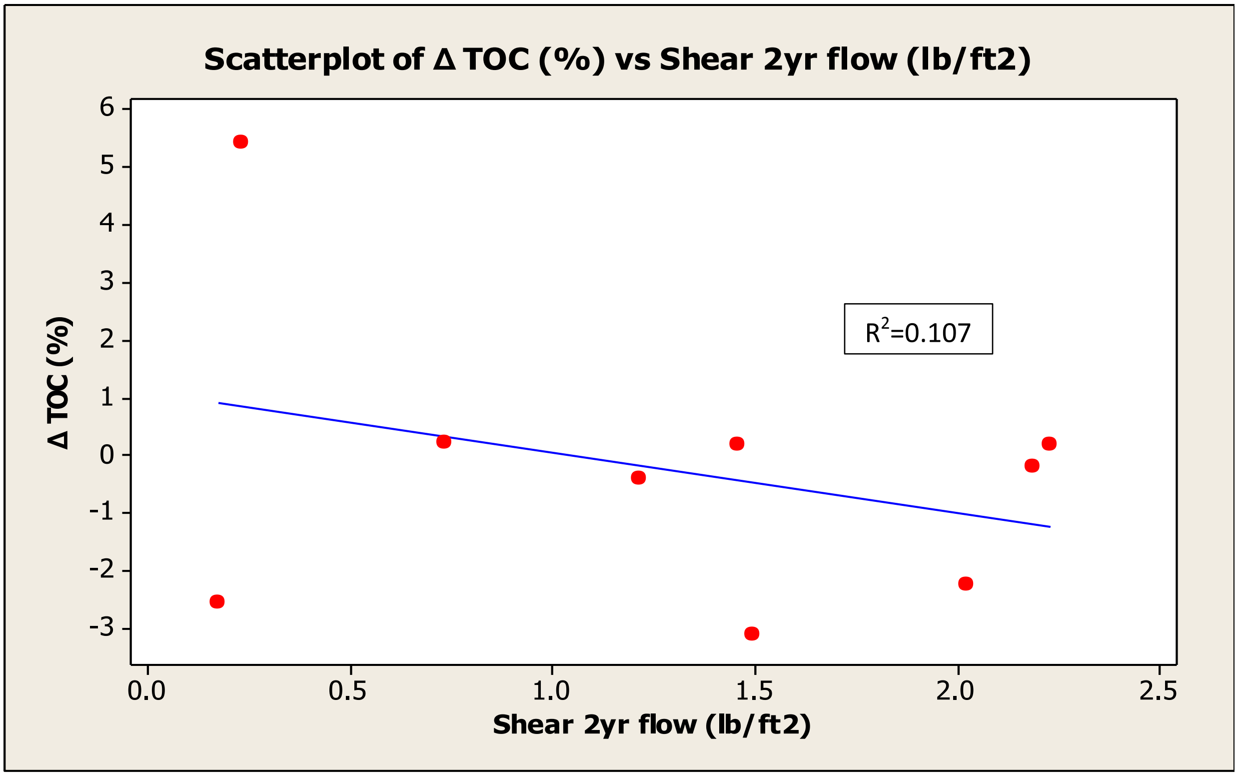


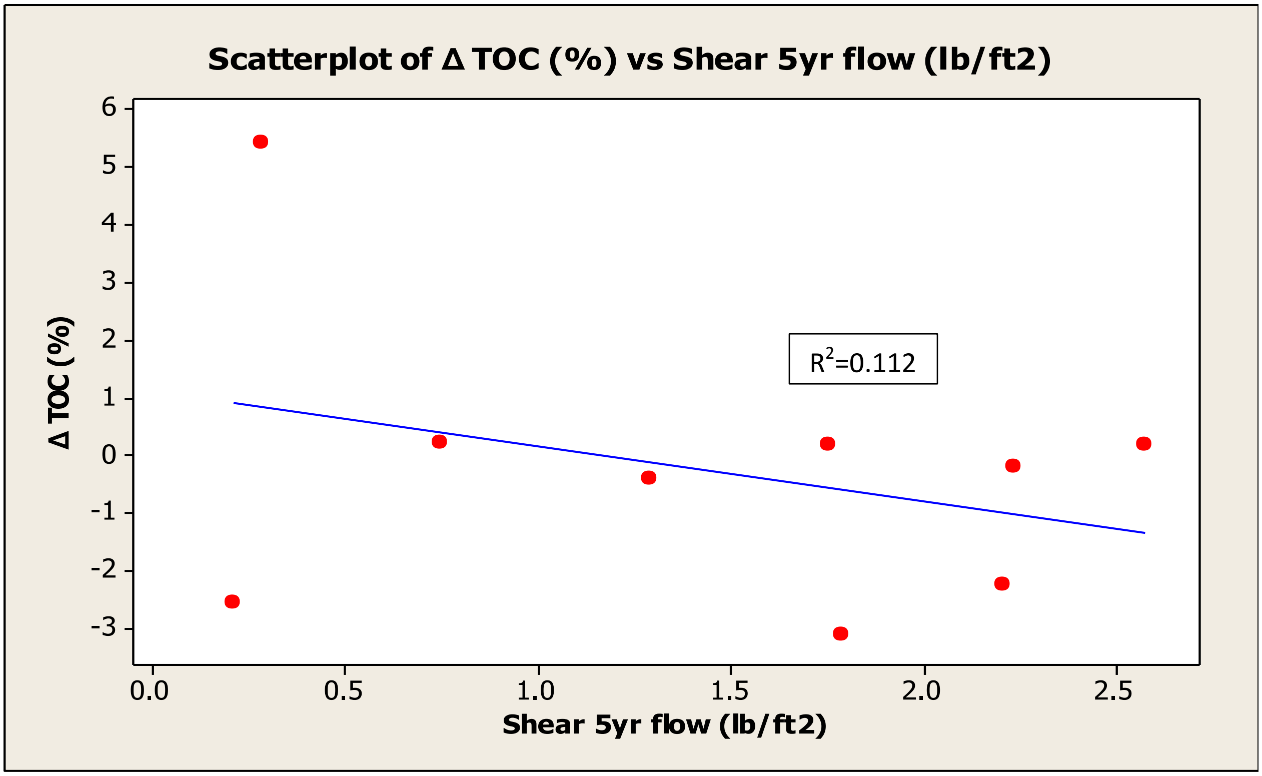
E.2 All Circular Functioning Culverts

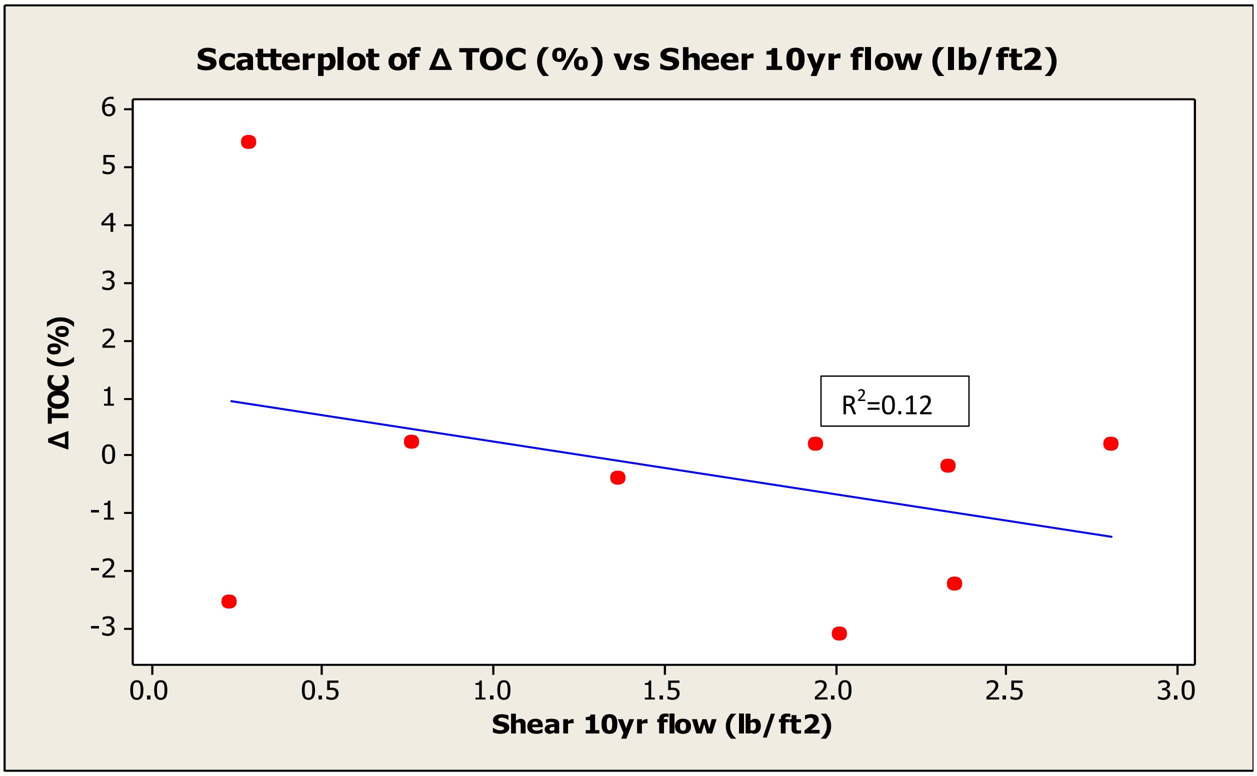


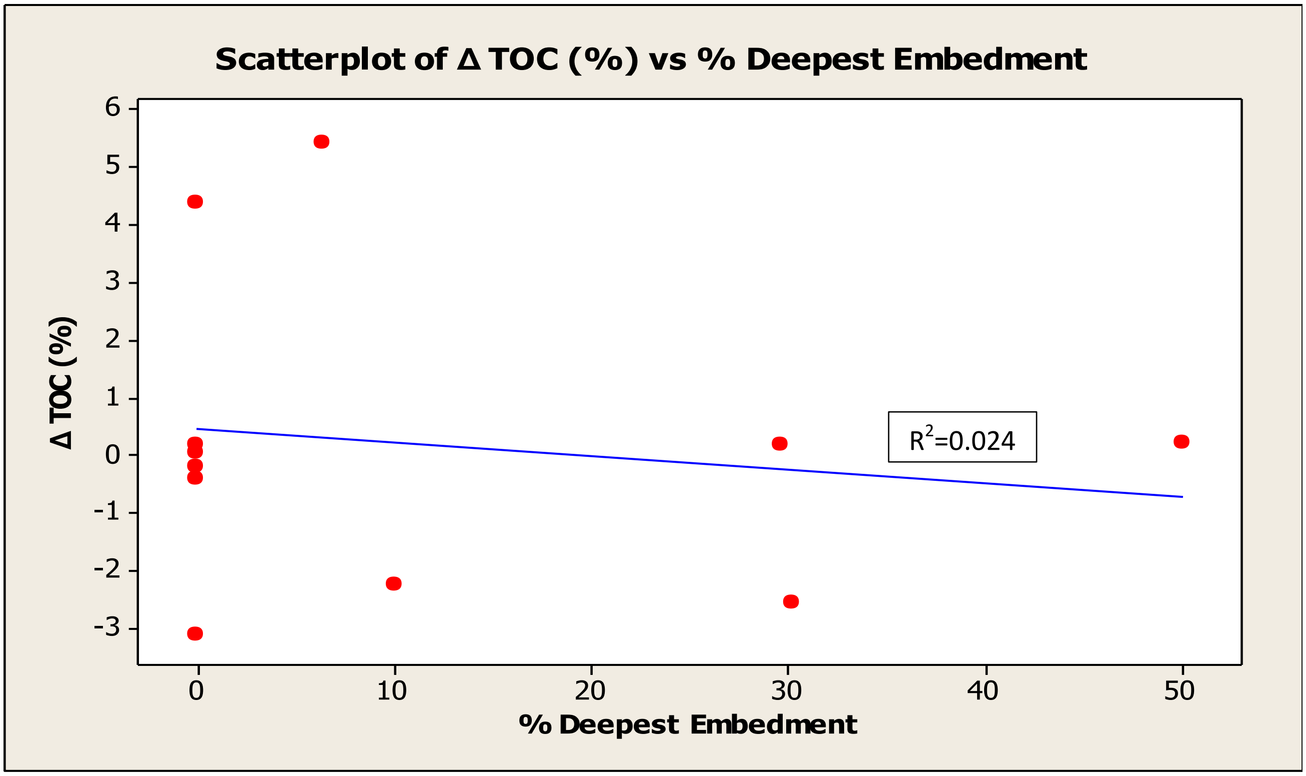

Scatterplot of Δ TOC (%) vs Slope (ft/ft)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R²=0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Slope (ft/ft)

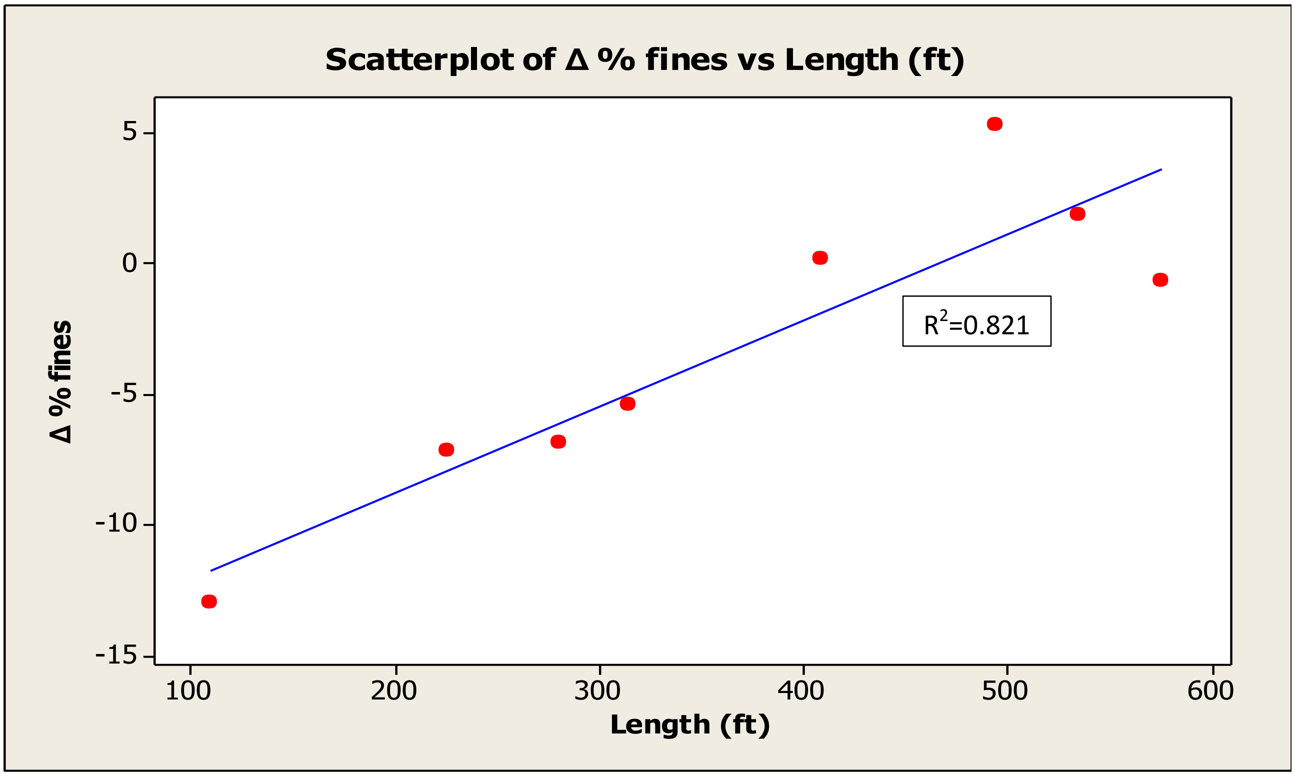

Scatterplot of Δ TOC (%) vs Diameter (ft)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R²=0.00
2
3
4
5
6
7
8
9
10
11
Diameter (ft)

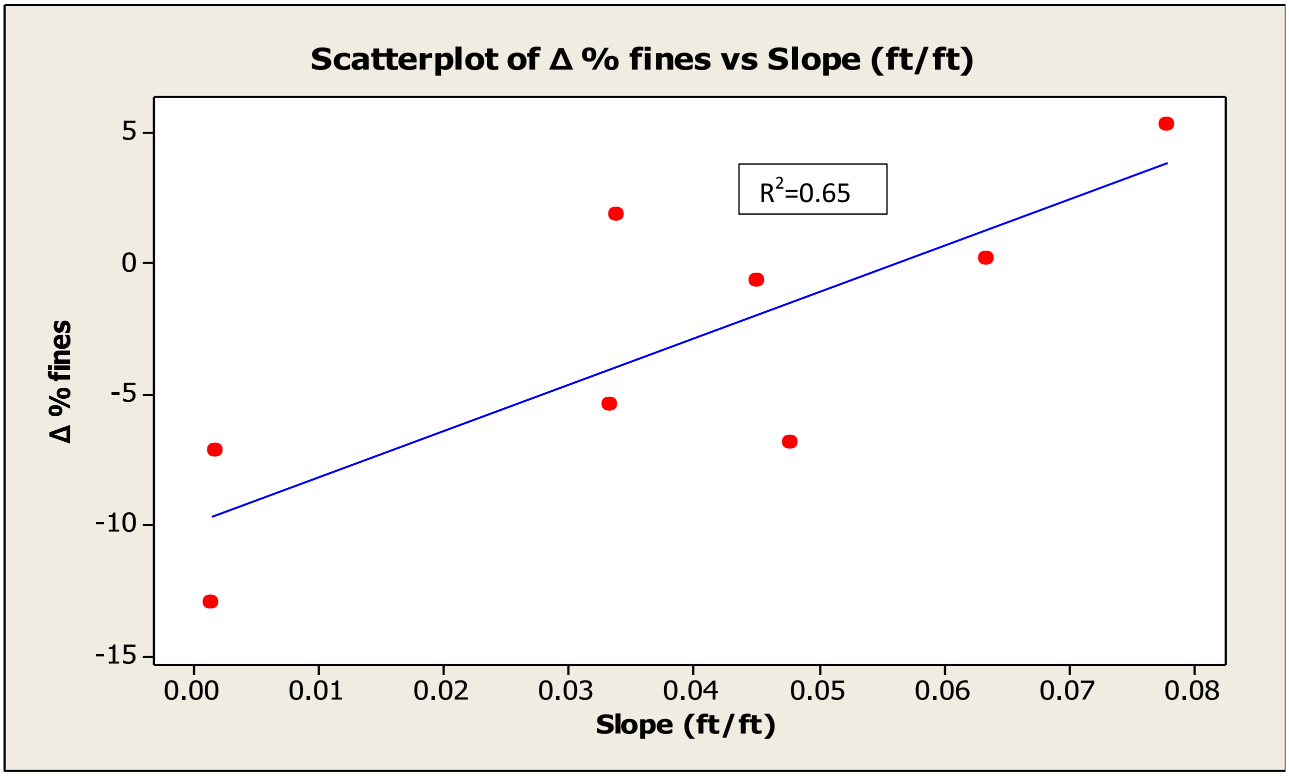

Scatterplot of Δ TOC (%) vs Shear 2yr flow (lb/ft2)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R^2=0.107
0.0
0.5
1.0
1.5
2.0
2.5
Shear 2yr flow (lb/ft2)

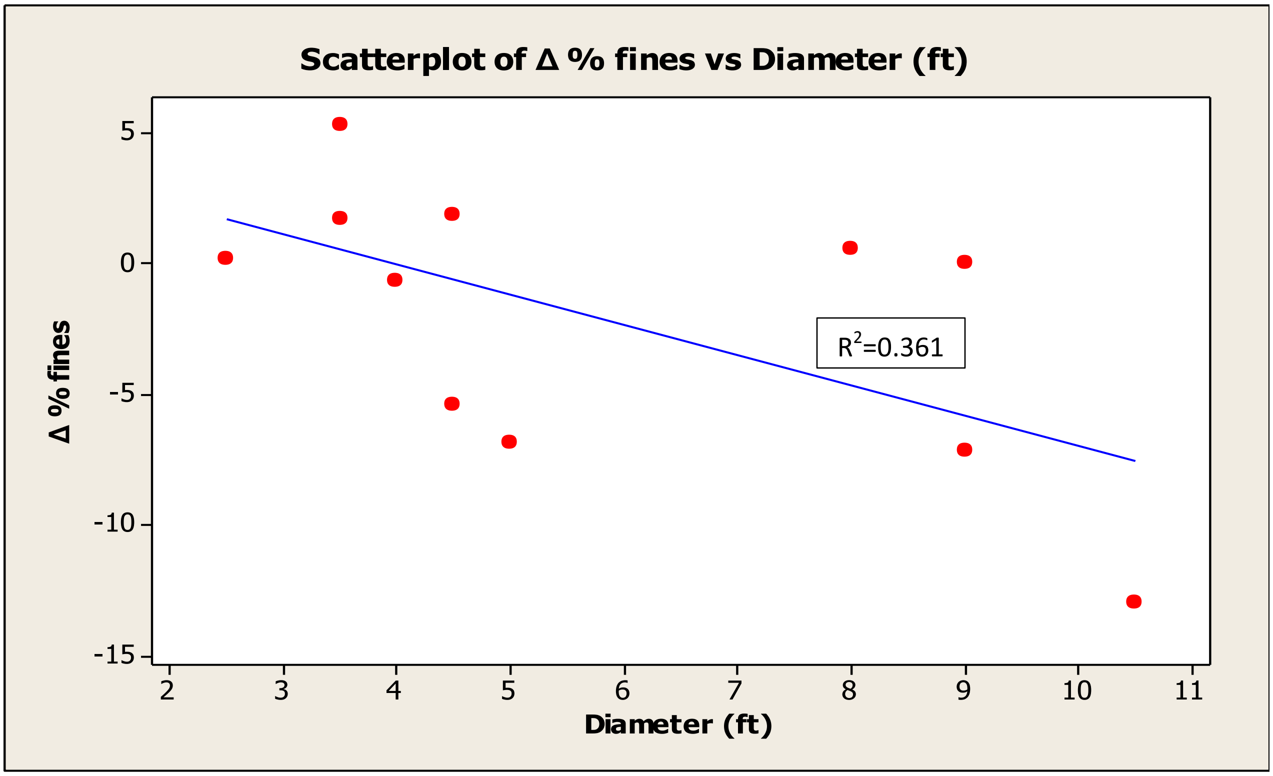

Scatterplot of Δ TOC (%) vs Shear 5yr flow (lb/ft2)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R²=0.112
0.0
0.5
1.0
1.5
2.0
2.5
Shear 5yr flow (lb/ft2)

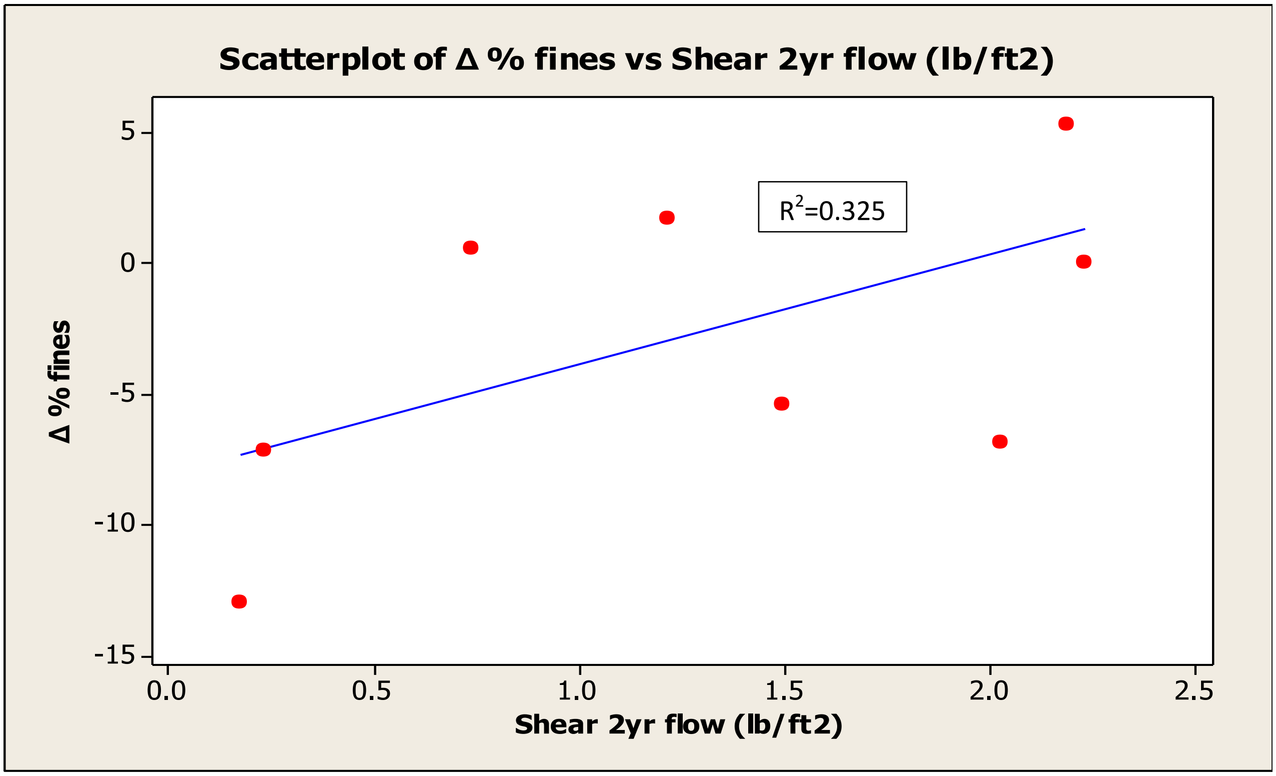

Scatterplot of Δ TOC (%) vs Sheer 10yr flow (lb/ft2)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R²=0.12
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Shear 10yr flow (lb/ft2)

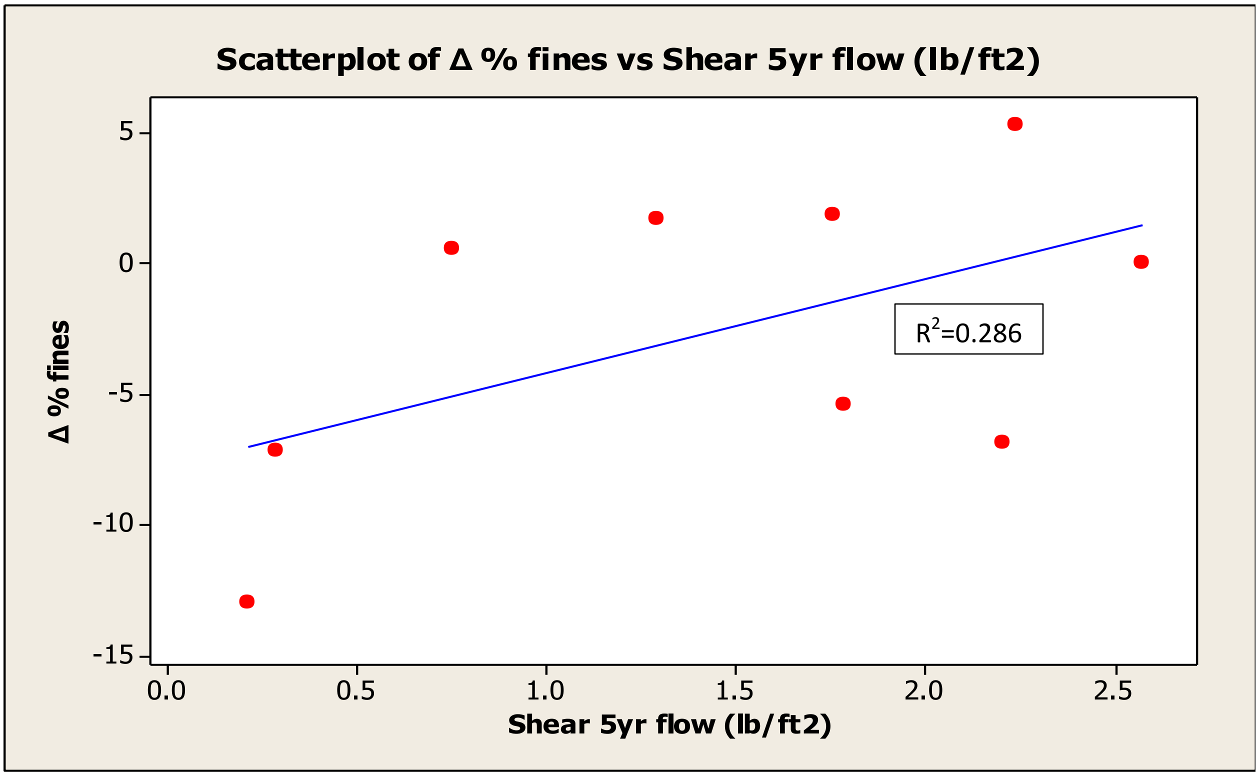

Scatterplot of Δ TOC (%) vs % Deepest Embedment
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
% Deepest Embedment
R^2=0.024

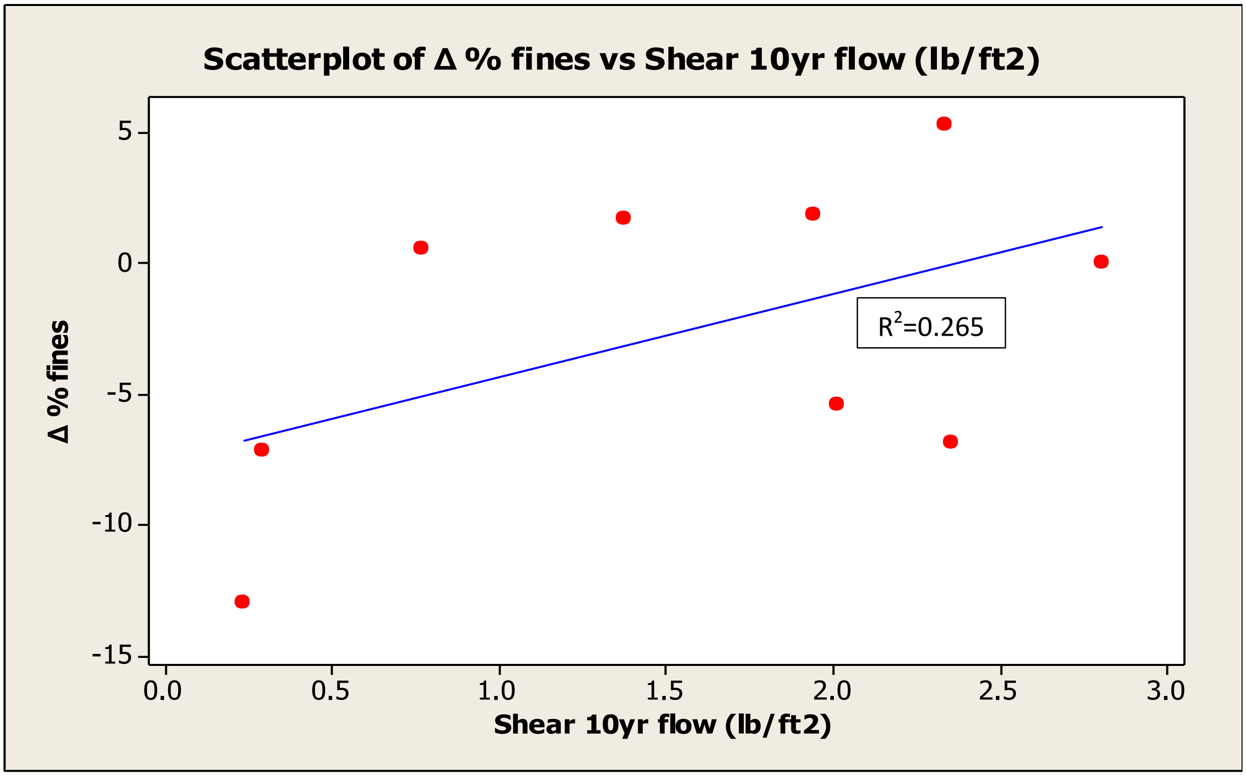

Scatterplot of Δ % fines vs Length (ft)
Δ % fines
5
0
-5
-10
-15
100
200
300
400
500
600
Length (ft)
R^2=0.821

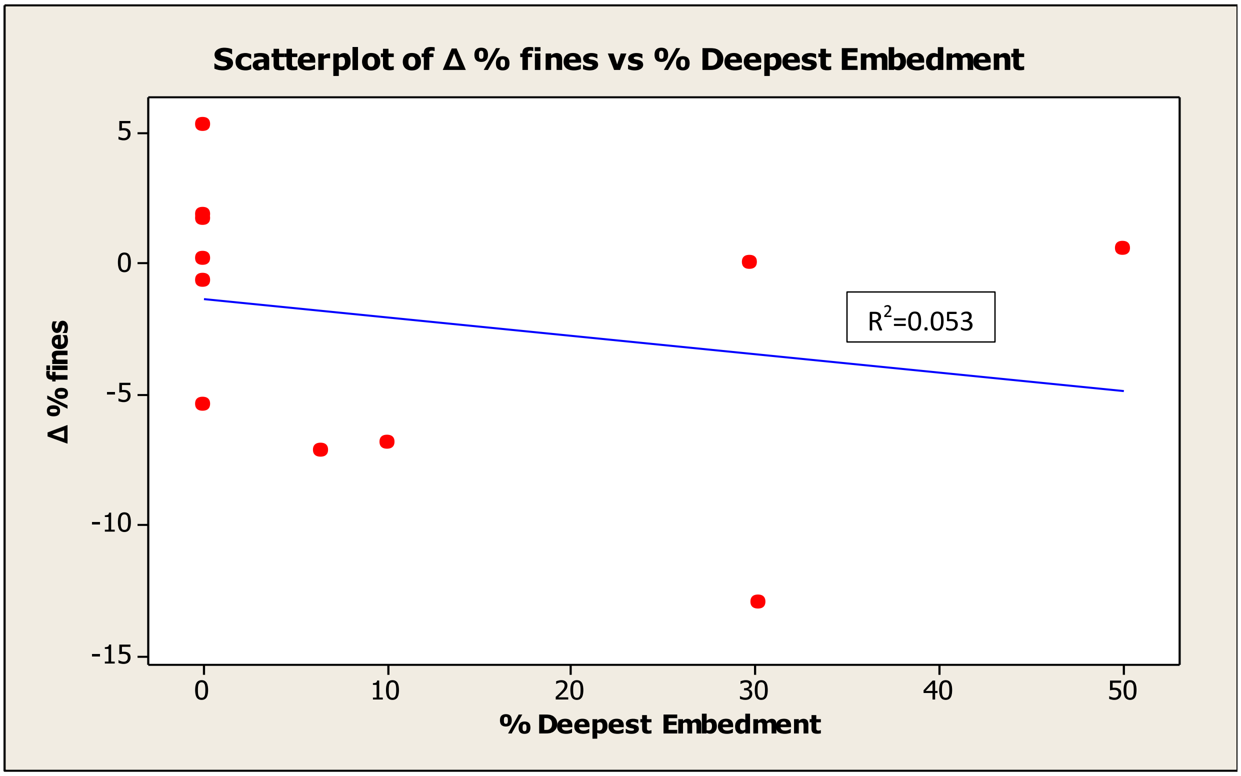

Scatterplot of Δ % fines vs Slope (ft/ft)
R^2=0.65
Δ % fines
5
0
-5
-10
-15
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Slope (ft/ft)

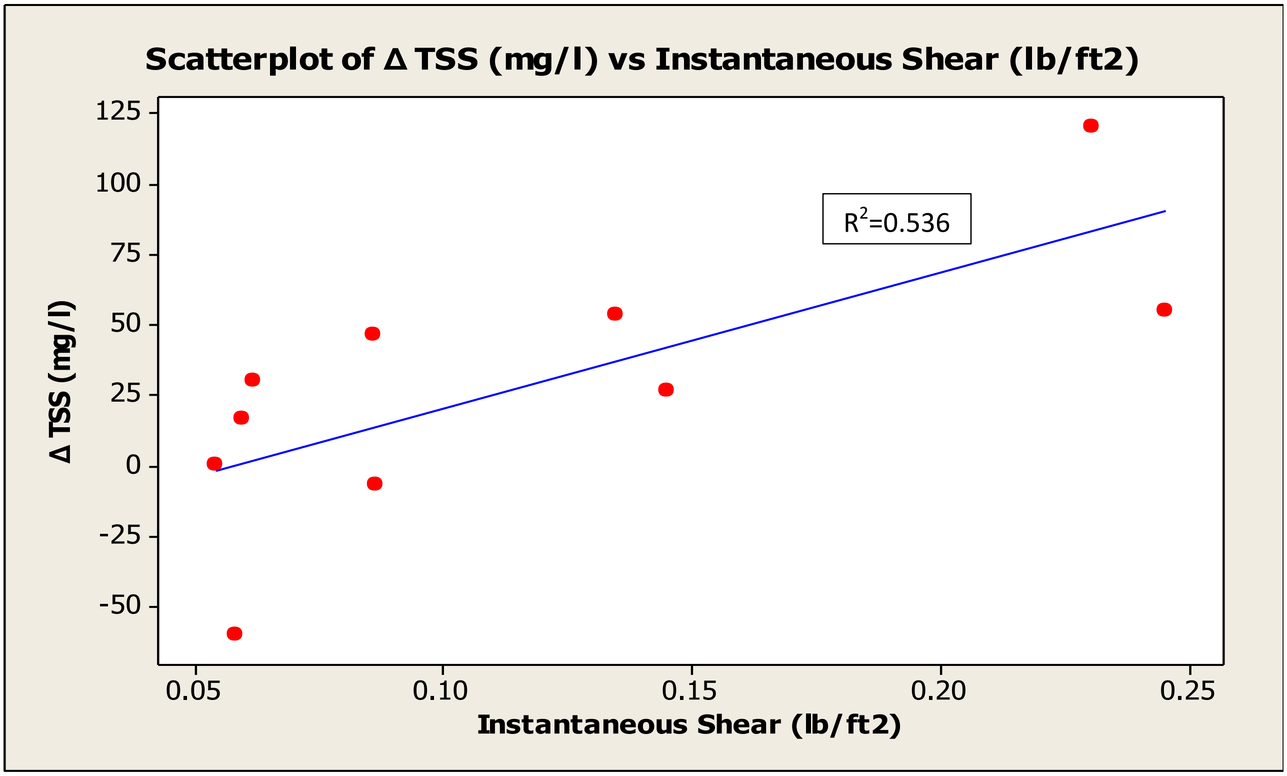

Scatterplot of Δ % fines vs Diameter (ft)
R^2=0.361
Δ % fines
5
0
-5
-10
-15
2
3
4
5
6
7
8
9
10
11
Diameter (ft)

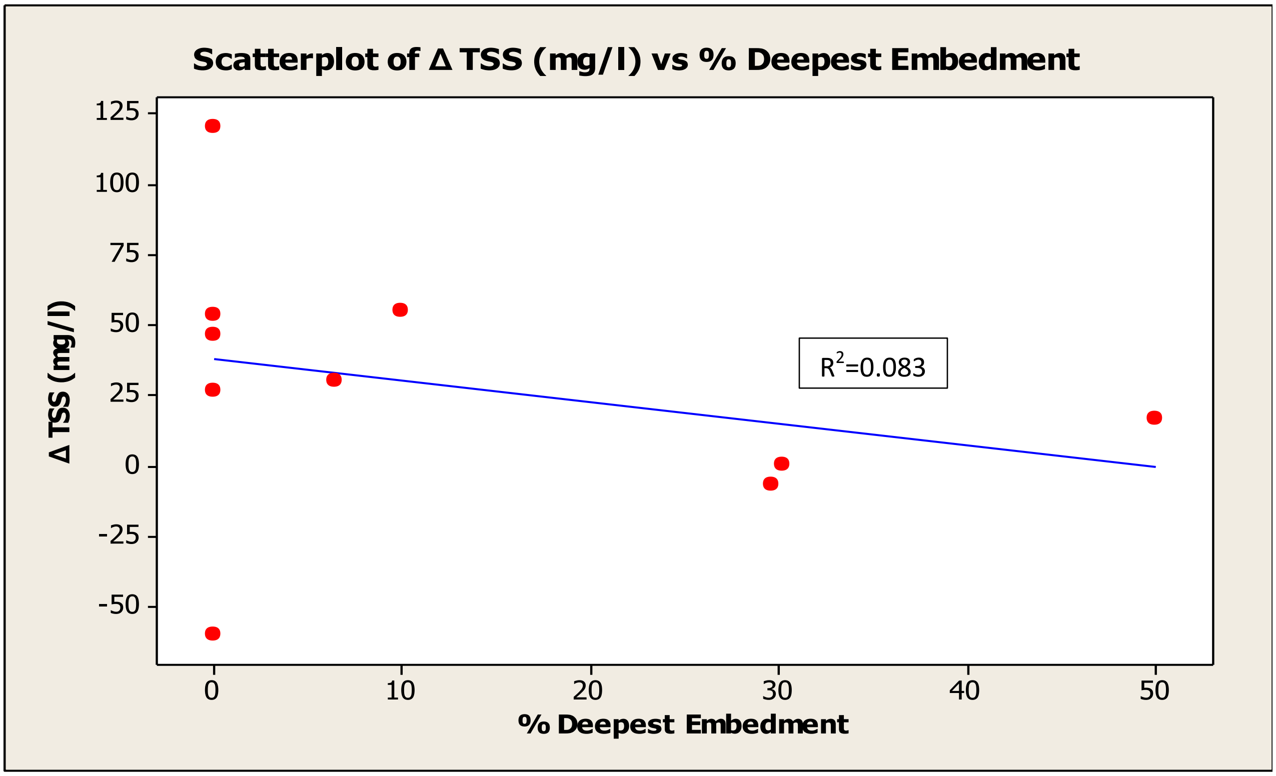

Scatterplot of Δ % fines vs Shear 2yr flow (lb/ft2)
R^2=0.325
5
0
-5
-10
-15
Δ % fines
0.0
0.5
1.0
1.5
2.0
2.5
Shear 2yr flow (lb/ft2)

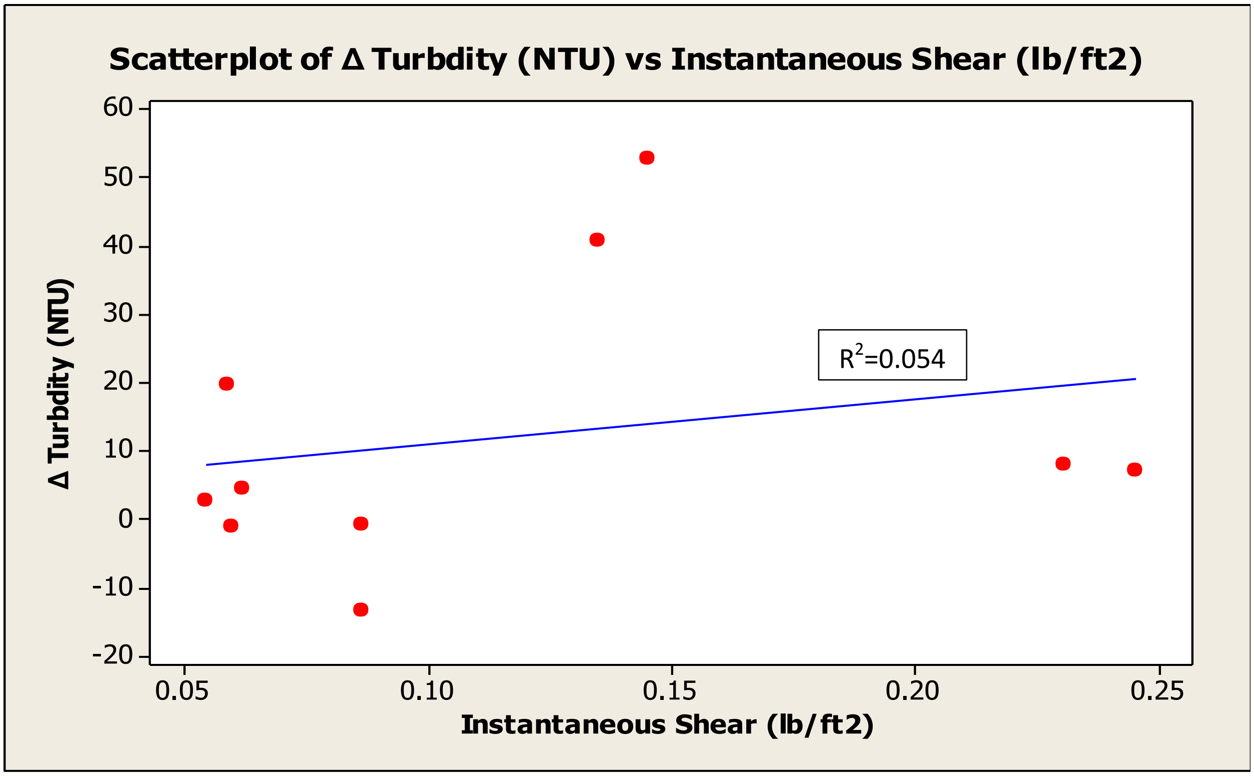

Scatterplot of Δ % fines vs Shear 5yr flow (lb/ft2)
R^2=0.286
5
0
-5
-10
-15
Δ % fines
0.0
0.5
1.0
1.5
2.0
2.5
Shear 5yr flow (lb/ft2)

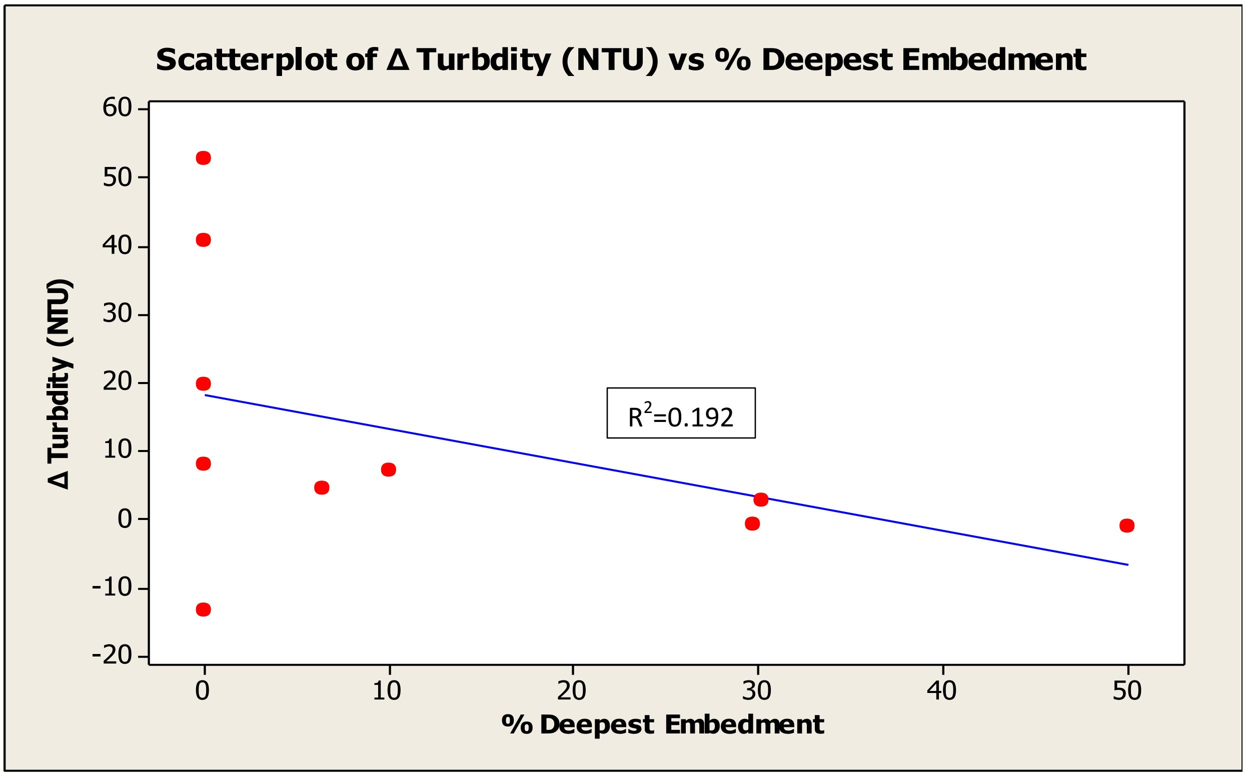

Scatterplot of Δ % fines vs Shear 10yr flow (lb/ft2)
Δ % fines
5
0
-5
-10
-15
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Shear 10yr flow (lb/ft2)
R^2=0.265


Scatterplot of Δ % fines vs % Deepest Embedment
Δ % fines
5
0
-5
-10
-15
0
10
20
30
40
50
% Deepest Embedment
R^2=0.053

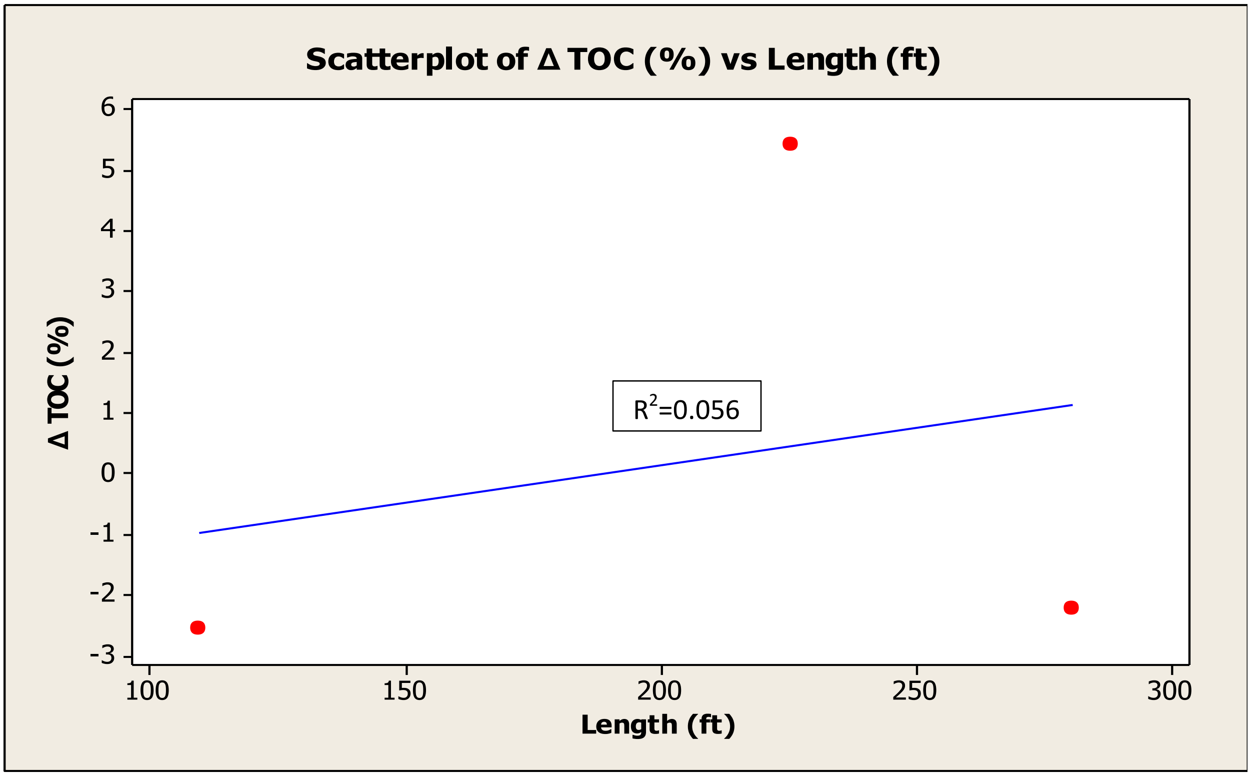

Scatterplot of Δ TSS (mg/l) vs Instantaneous Shear (lb/ft2)
Δ TSS (mg/l)
125
100
75
50
25
0
-25
-50
0.05
0.10
0.15
0.20
0.25
Instantaneous Shear (lb/ft2)
R^2=0.536

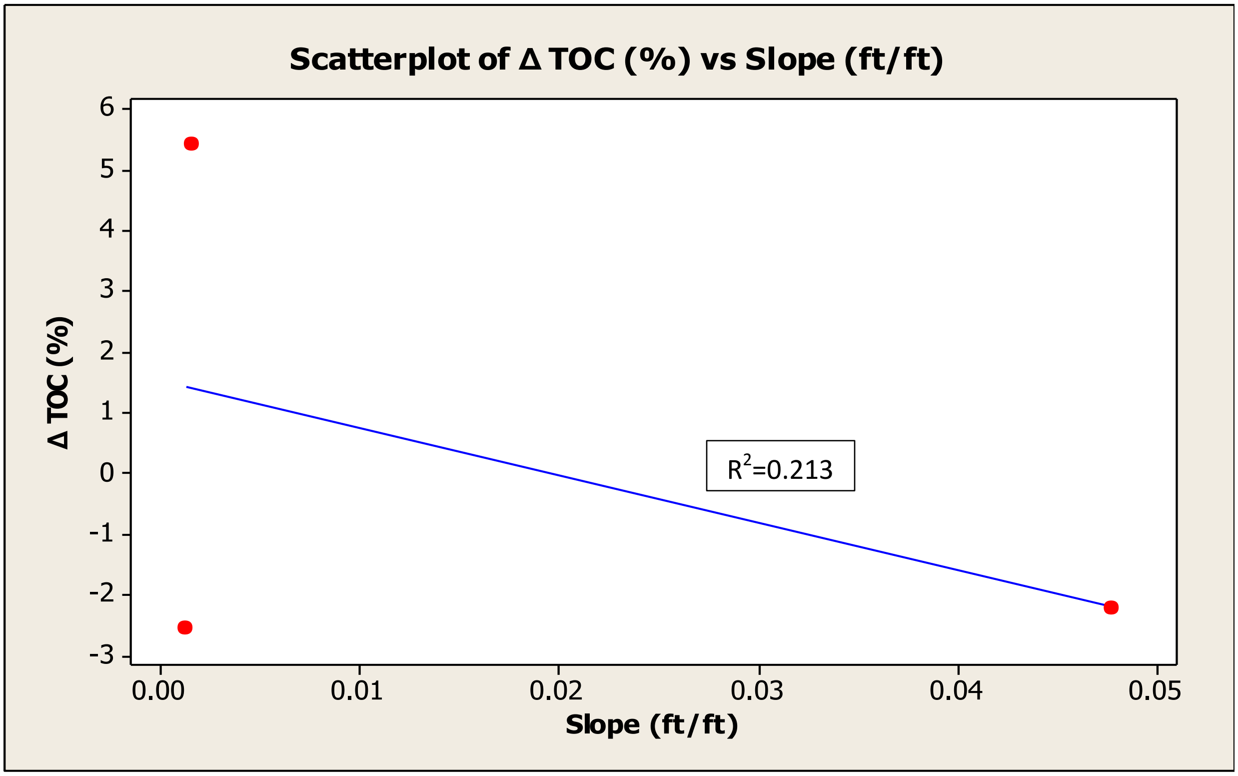

Scatterplot of Δ TSS (mg/l) vs % Deepest Embedment
Δ TSS (mg/l)
125
100
75
50
25
0
-25
-50
0
10
20
30
40
50
% Deepest Embedment
R^2=0.083

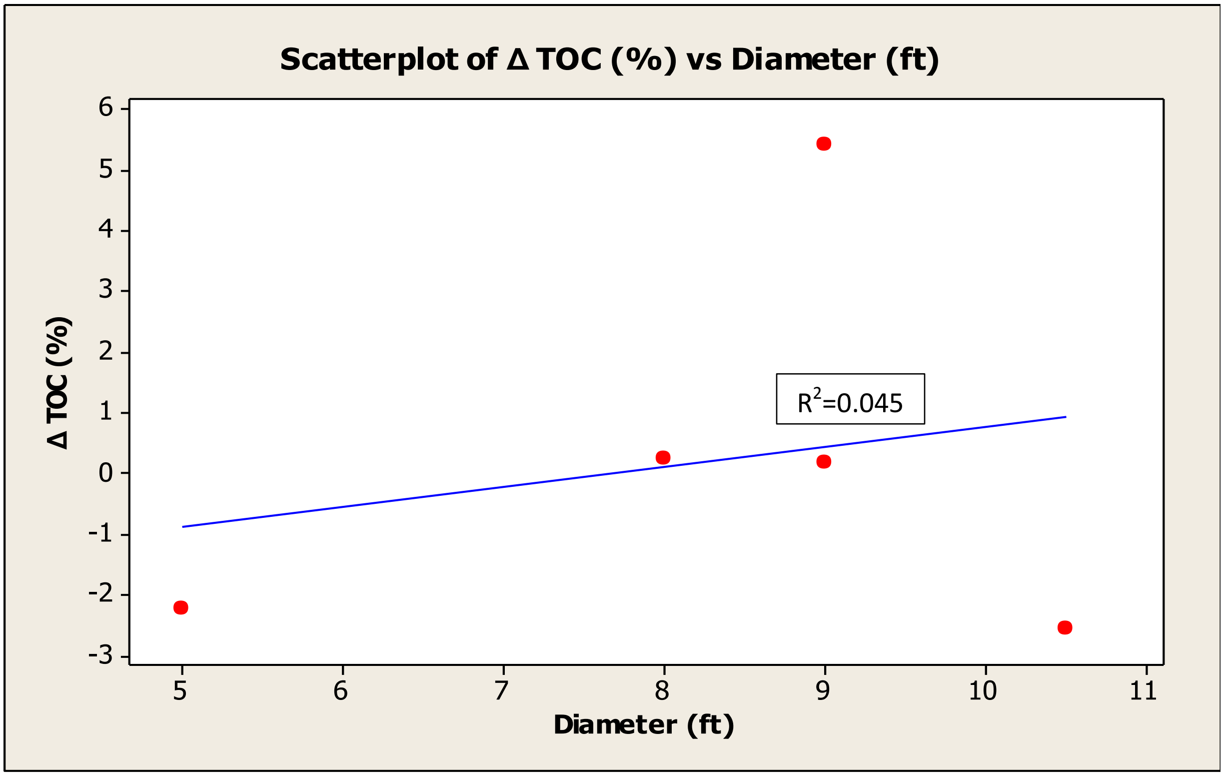

Scatterplot of Δ Turbdity (NTU) vs Instantaneous Shear (lb/ft2)
Δ Turbdity (NTU)
60
50
40
30
20
10
0
-10
-20
0.05
0.10
0.15
0.20
0.25
Instantaneous Shear (lb/ft2)
R²=0.054

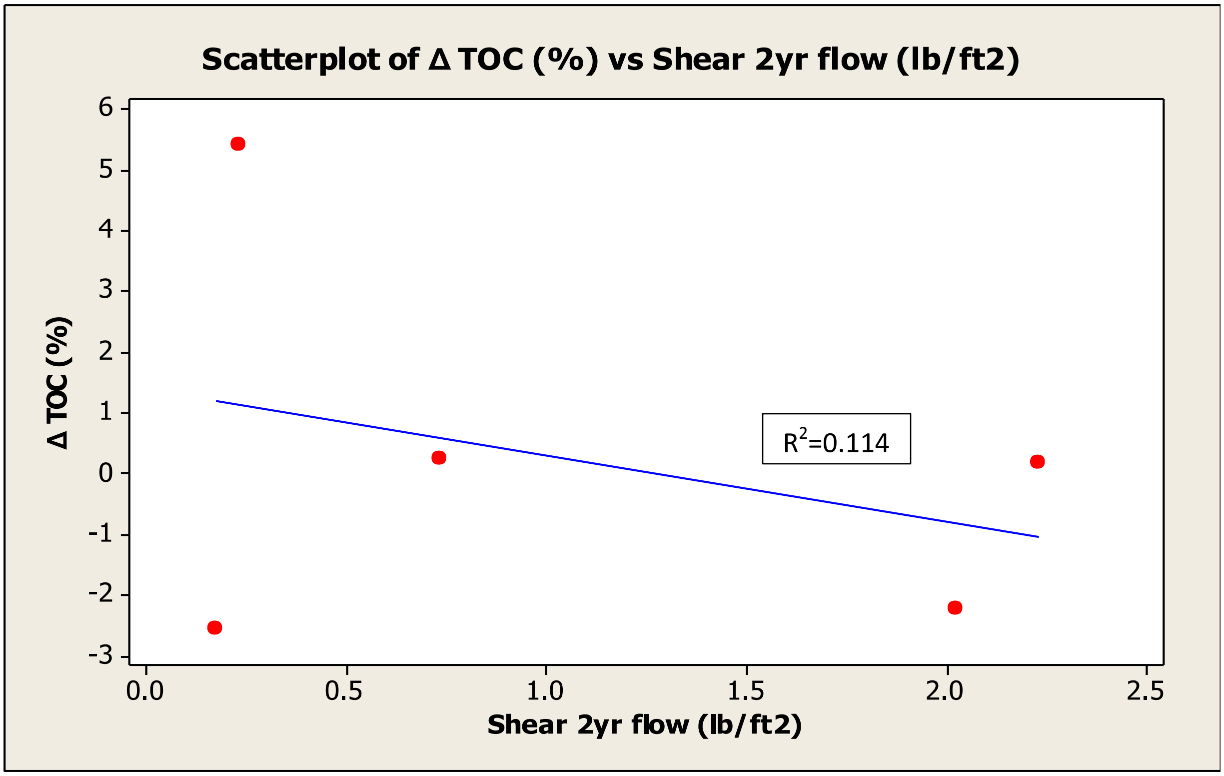

Scatterplot of Δ Turbdity (NTU) vs % Deepest Embedment
Δ Turbdity (NTU)
60
50
40
30
20
10
0
-10
-20
0
10
20
30
40
50
% Deepest Embedment
R²=0.192

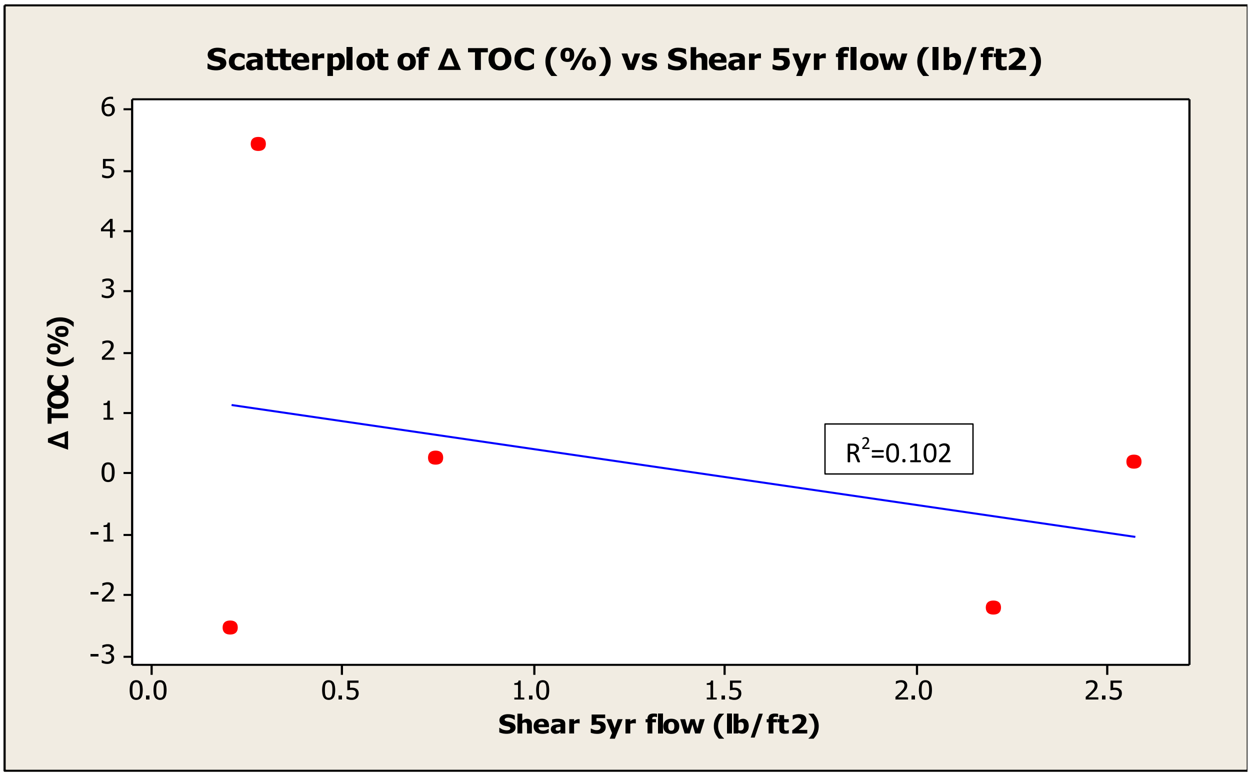
E.3 All Circular Embedded and Hybrid Functioning Culverts

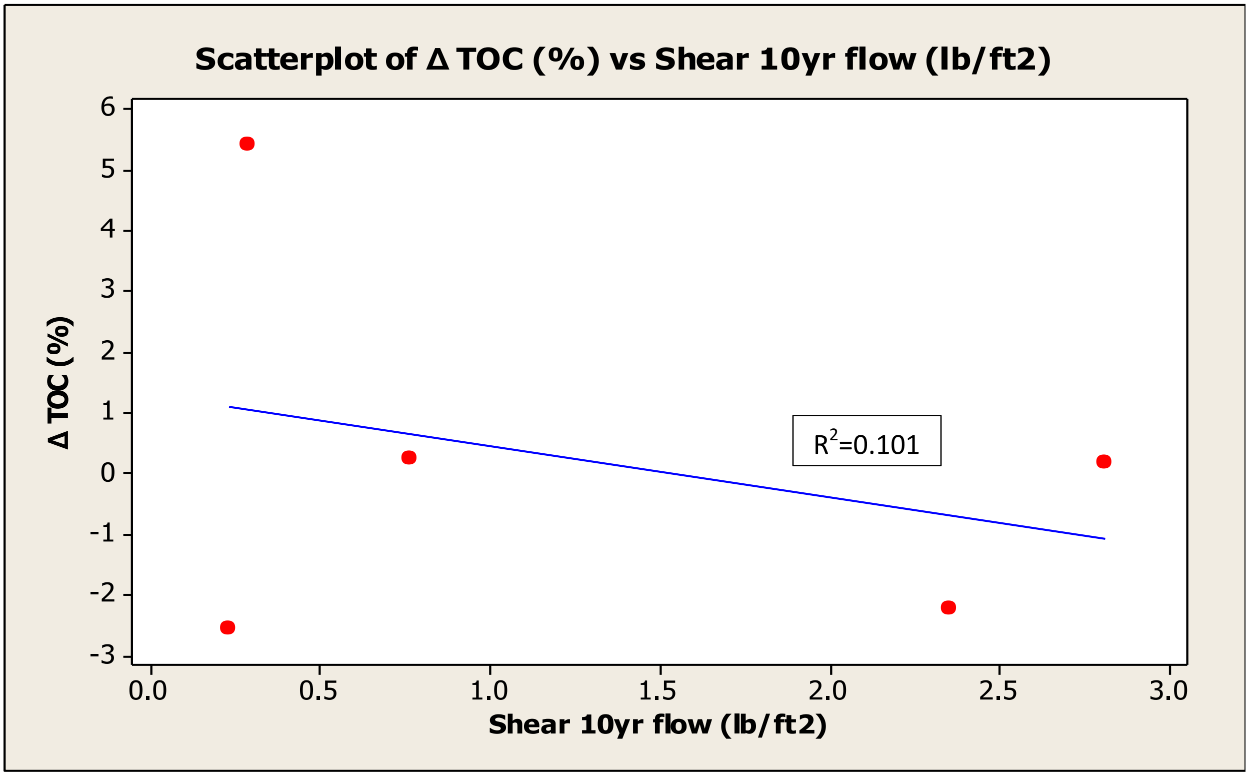


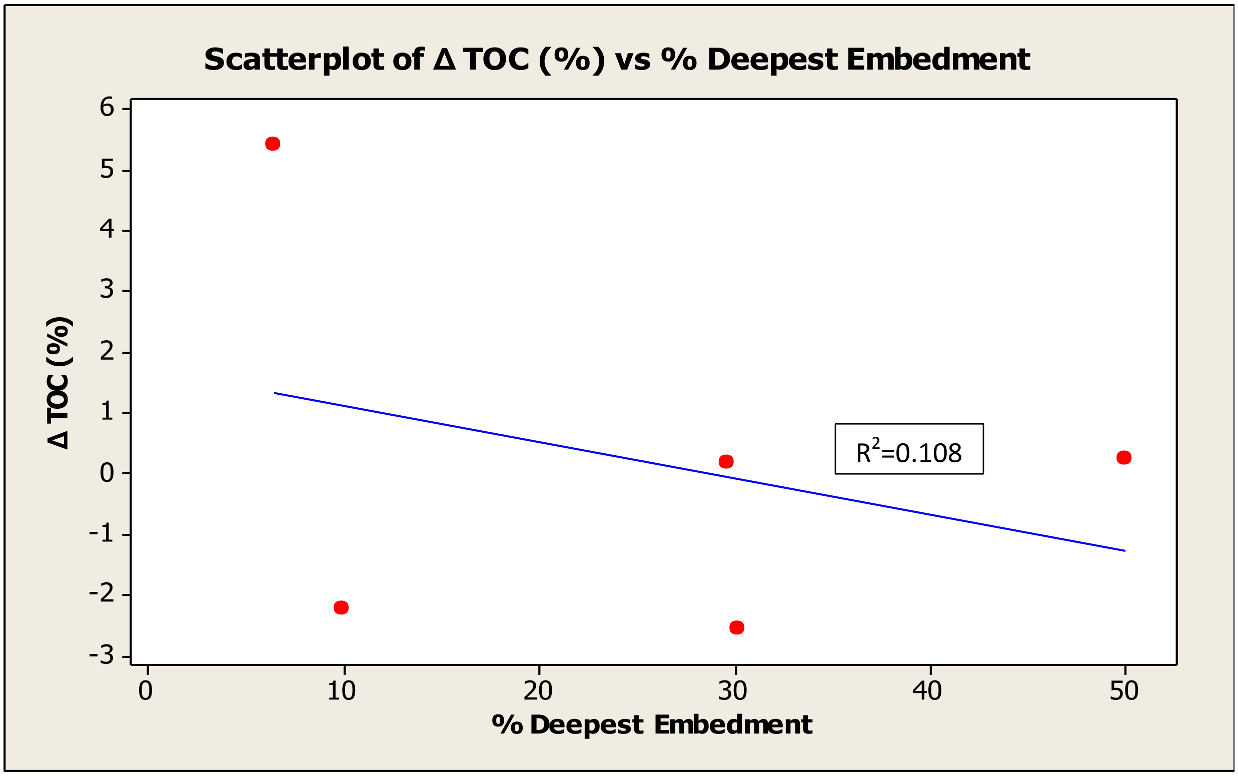


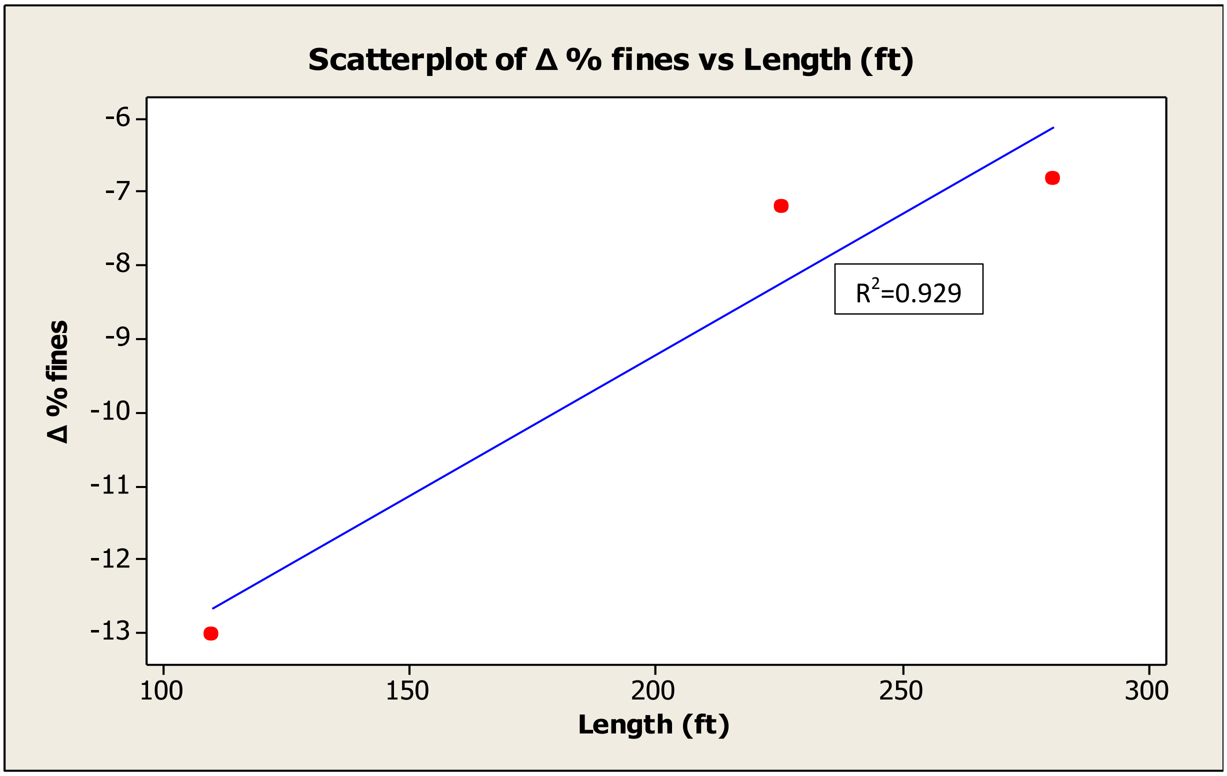

Scatterplot of Δ TOC (%) vs Diameter (ft)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R^2=0.045
5
6
7
8
9
10
11
Diameter (ft)

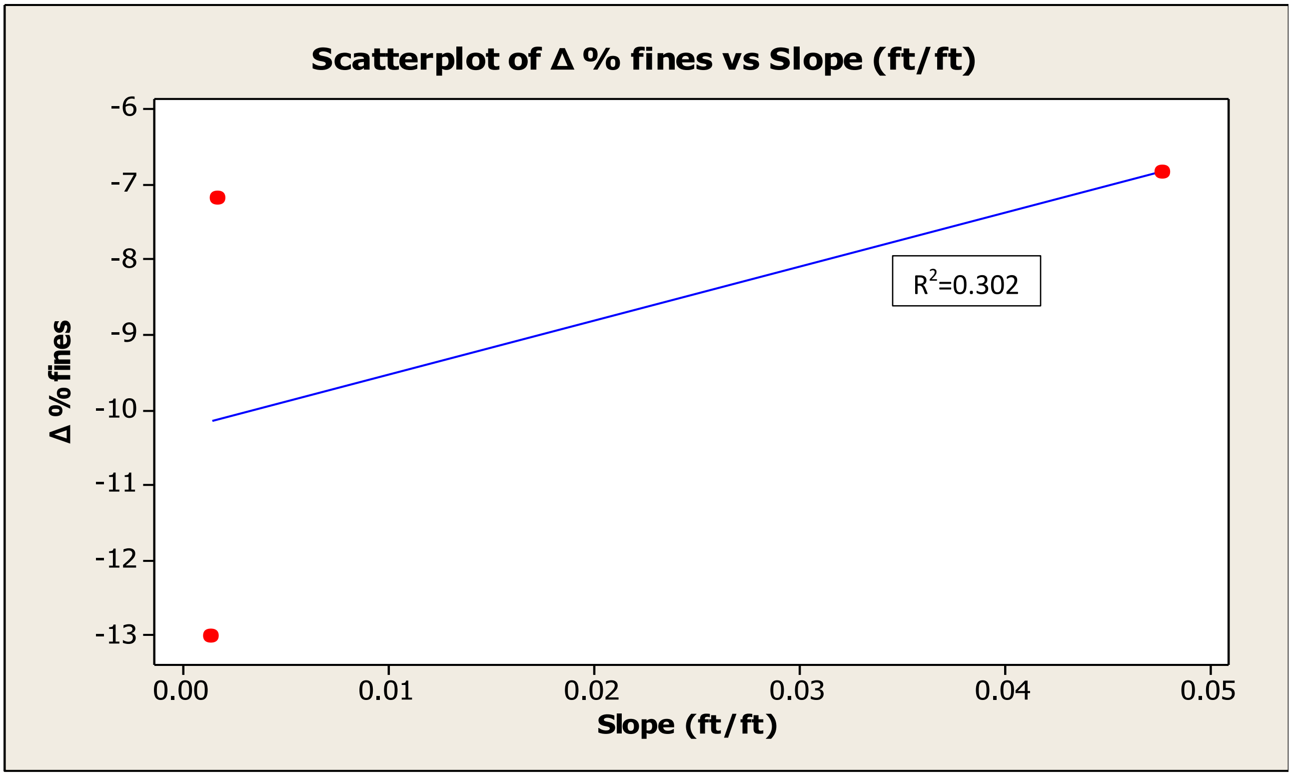

Scatterplot of Δ TOC (%) vs Shear 2yr flow (lb/ft2)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
R^2=0.114
0.0
0.5
1.0
1.5
2.0
2.5
Shear 2yr flow (lb/ft2)


Scatterplot of Δ TOC (%) vs Shear 5yr flow (lb/ft2)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
0.0
0.5
1.0
1.5
2.0
2.5
Shear 5yr flow (lb/ft2)
R²=0.102

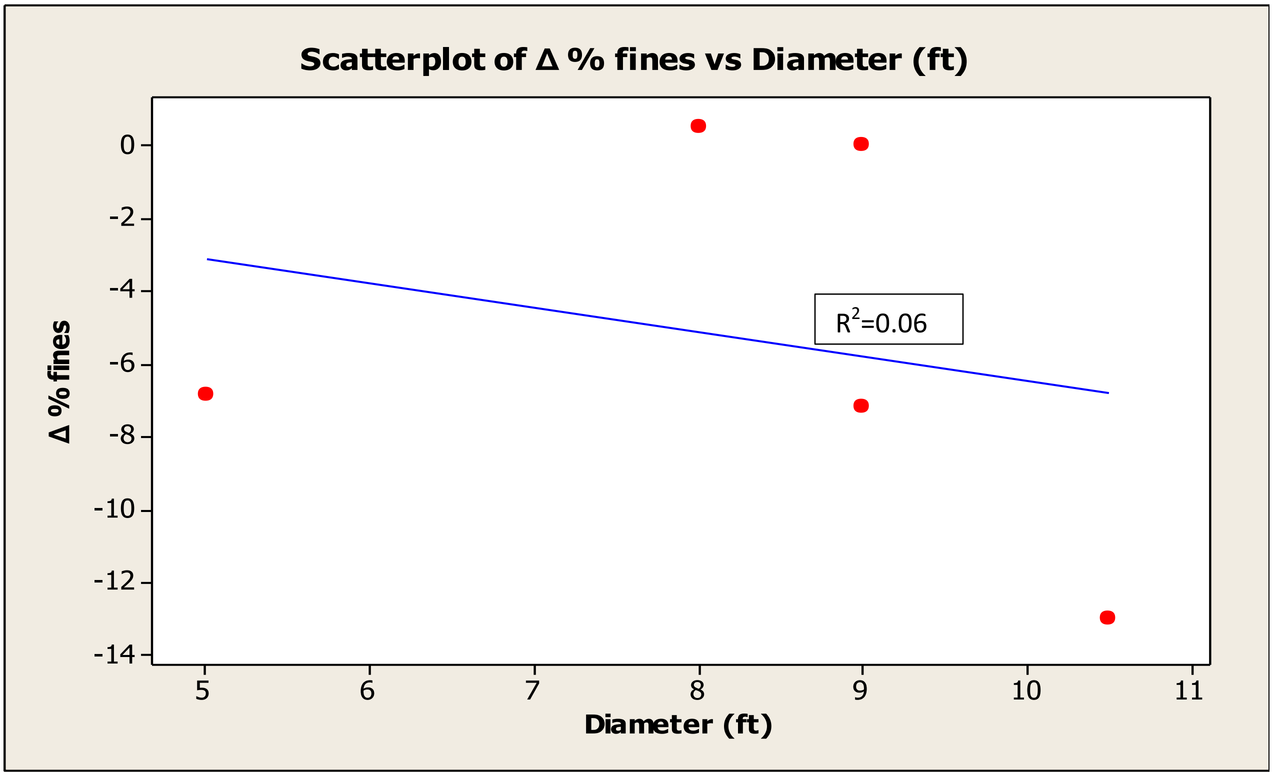

Scatterplot of Δ TOC (%) vs Shear 10yr flow (lb/ft2)
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Shear 10yr flow (lb/ft2)
R²=0.101


Scatterplot of Δ TOC (%) vs % Deepest Embedment
Δ TOC (%)
6
5
4
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
% Deepest Embedment
R^2=0.108

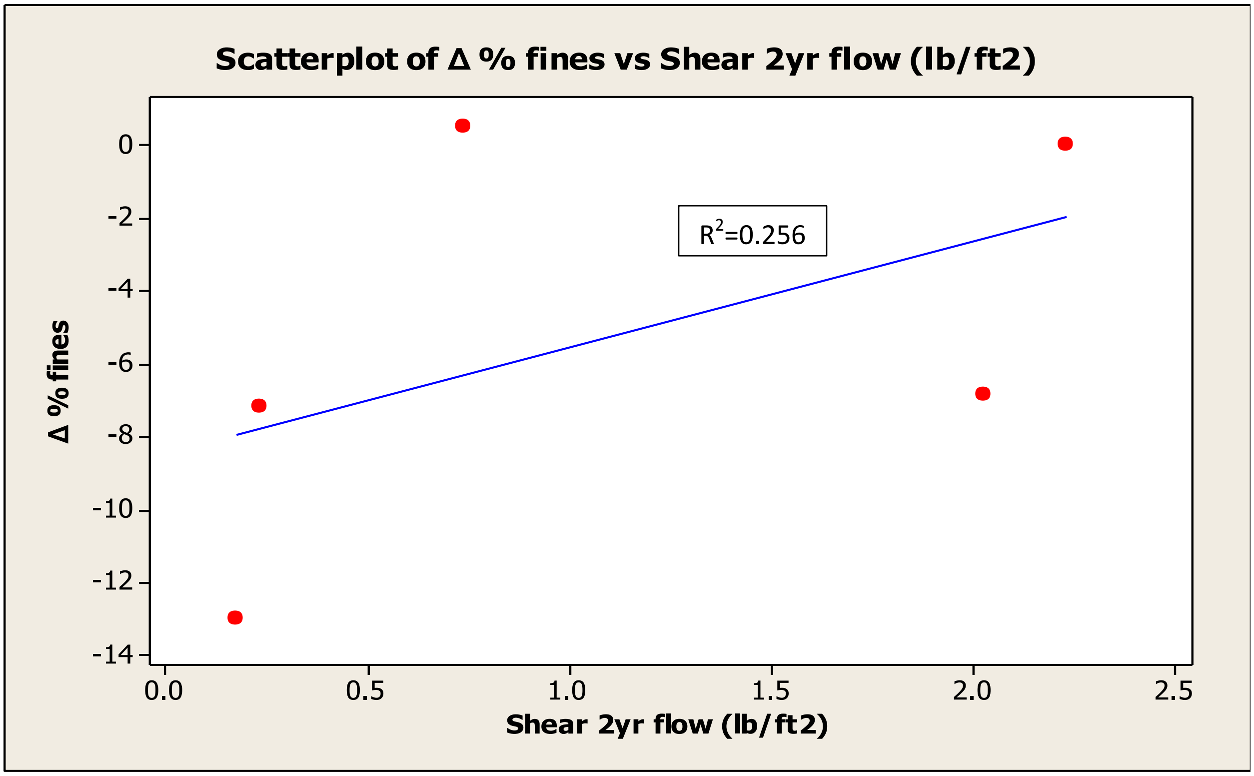

Scatterplot of Δ % fines vs Length (ft)
Δ % fines
-6
-7
-8
-9
-10
-11
-12
-13
100
150
200
250
300
Length (ft)
R^2=0.929

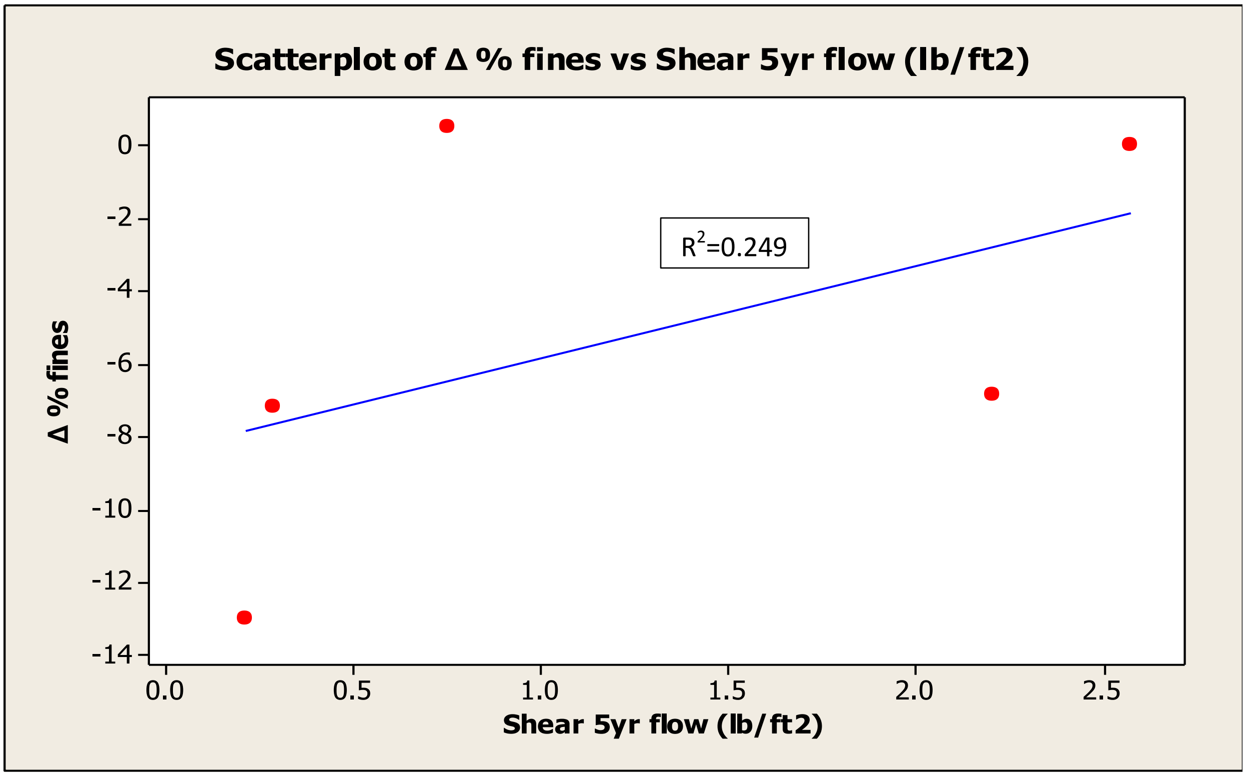


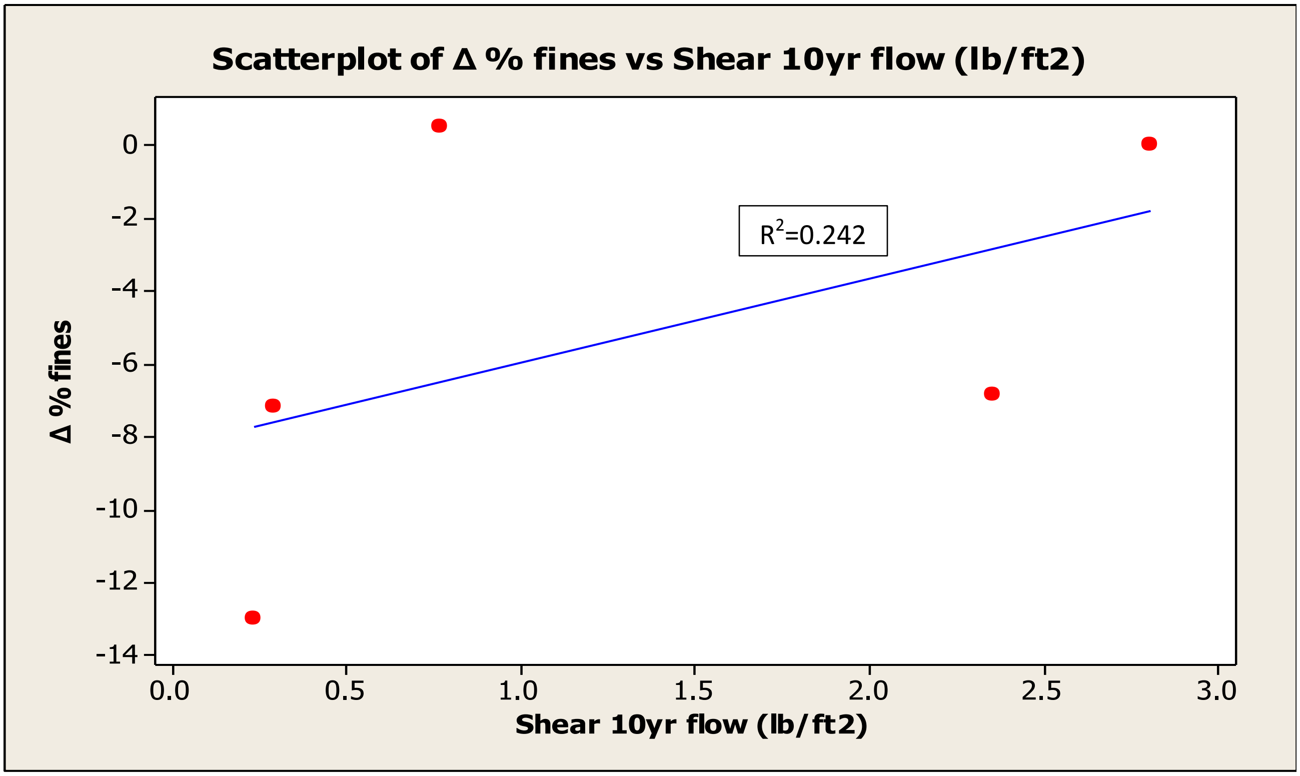
Scatterplot of Δ % fines vs Slope (ft/ft)
Δ % fines
-6
-7
-8
-9
-10
-11
-12
-13
0.00
0.01
0.02
0.03
0.04
0.05
Slope (ft/ft)
R²=0.302

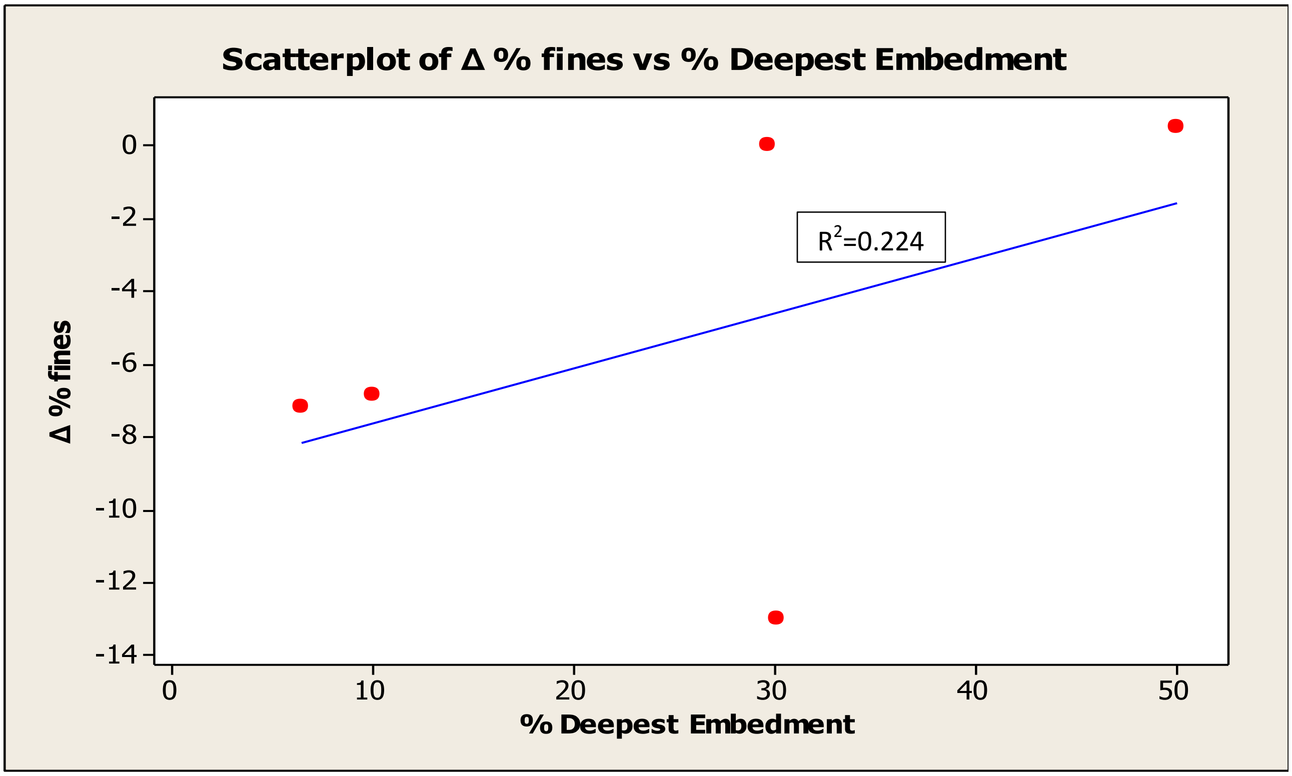


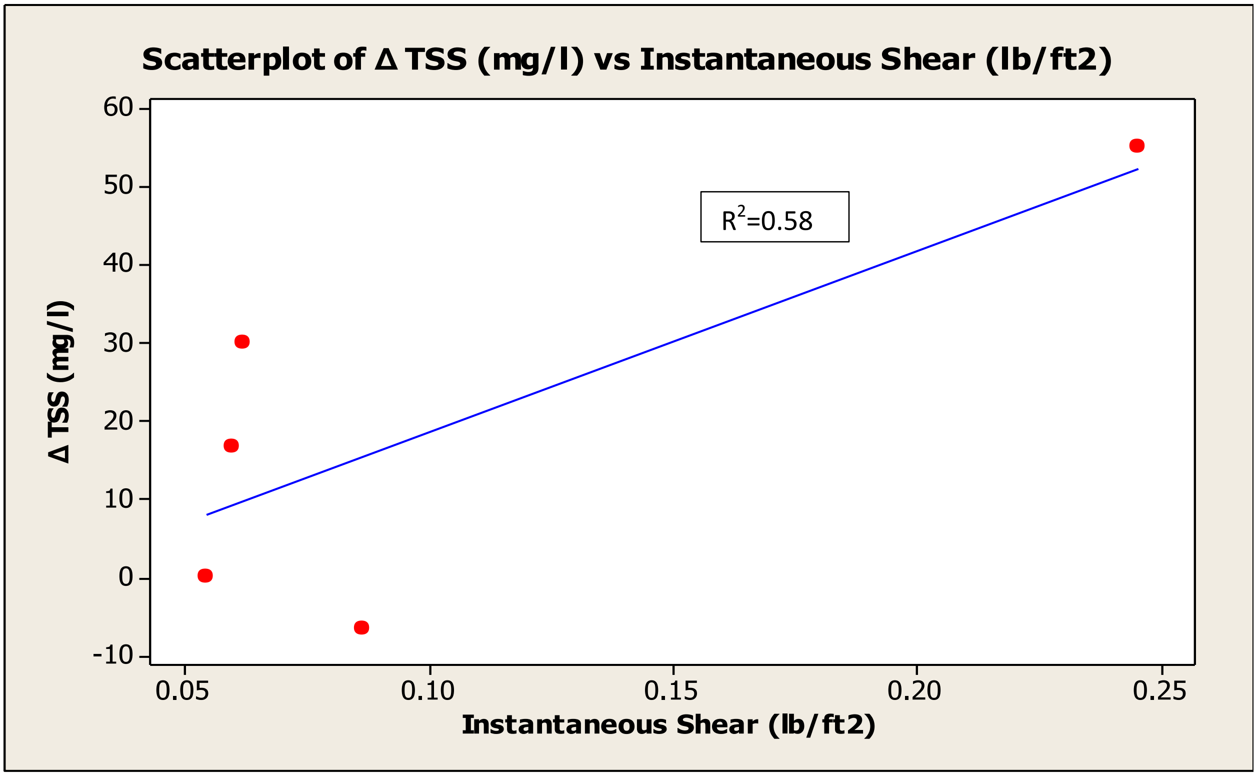
Scatterplot of Δ % fines vs Diameter (ft)
Δ % fines
0
-2
-4
-6
-8
-10
-12
-14
5
6
7
8
9
10
11
Diameter (ft)
R²=0.06


Scatterplot of Δ % fines vs Shear 2yr flow (lb/ft2)
Δ % fines
0
-2
-4
-6
-8
-10
-12
-14
R^2=0.256
0.0
0.5
1.0
1.5
2.0
2.5
Shear 2yr flow (lb/ft2)

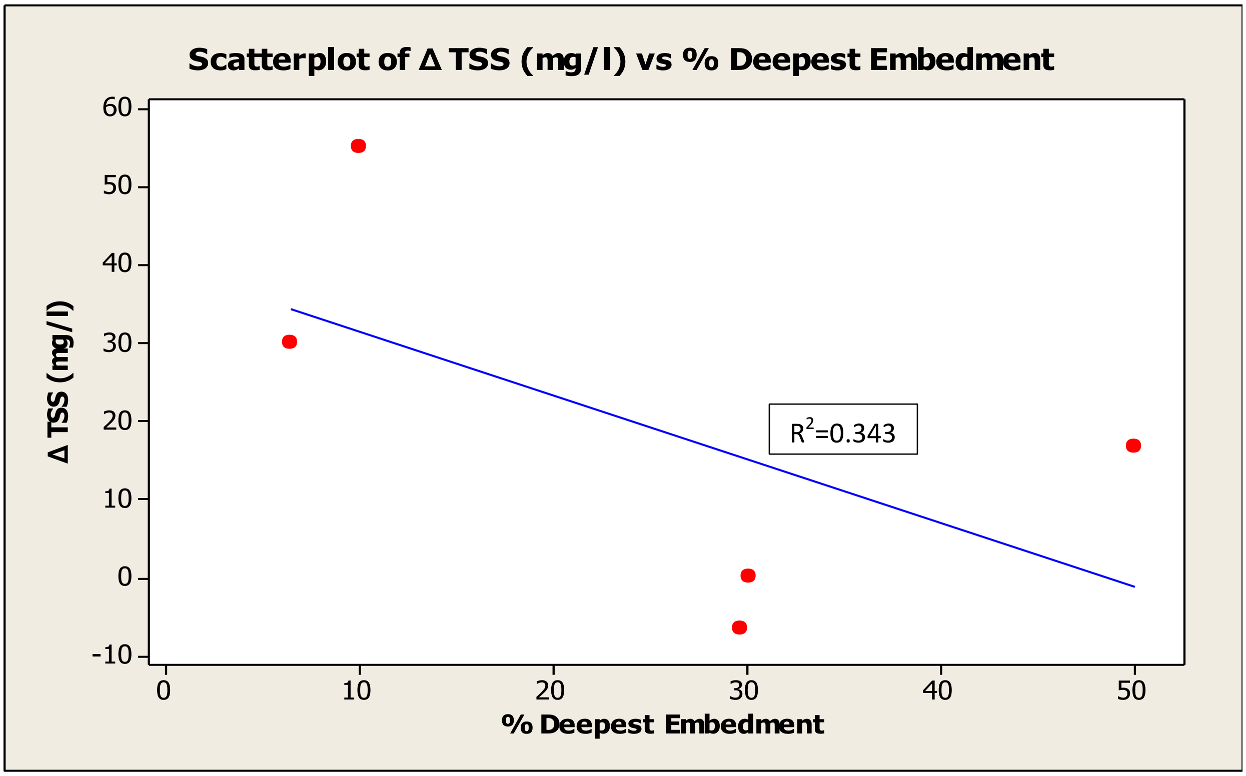

Scatterplot of Δ % fines vs Shear 5yr flow (lb/ft2)
Δ % fines
0
-2
-4
-6
-8
-10
-12
-14
R^2=0.249
0.0
0.5
1.0
1.5
2.0
2.5
Shear 5yr flow (lb/ft2)


Scatterplot of Δ % fines vs Shear 10yr flow (lb/ft2)
Δ % fines
0
-2
-4
-6
-8
-10
-12
-14
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Shear 10yr flow (lb/ft2)
R²=0.242

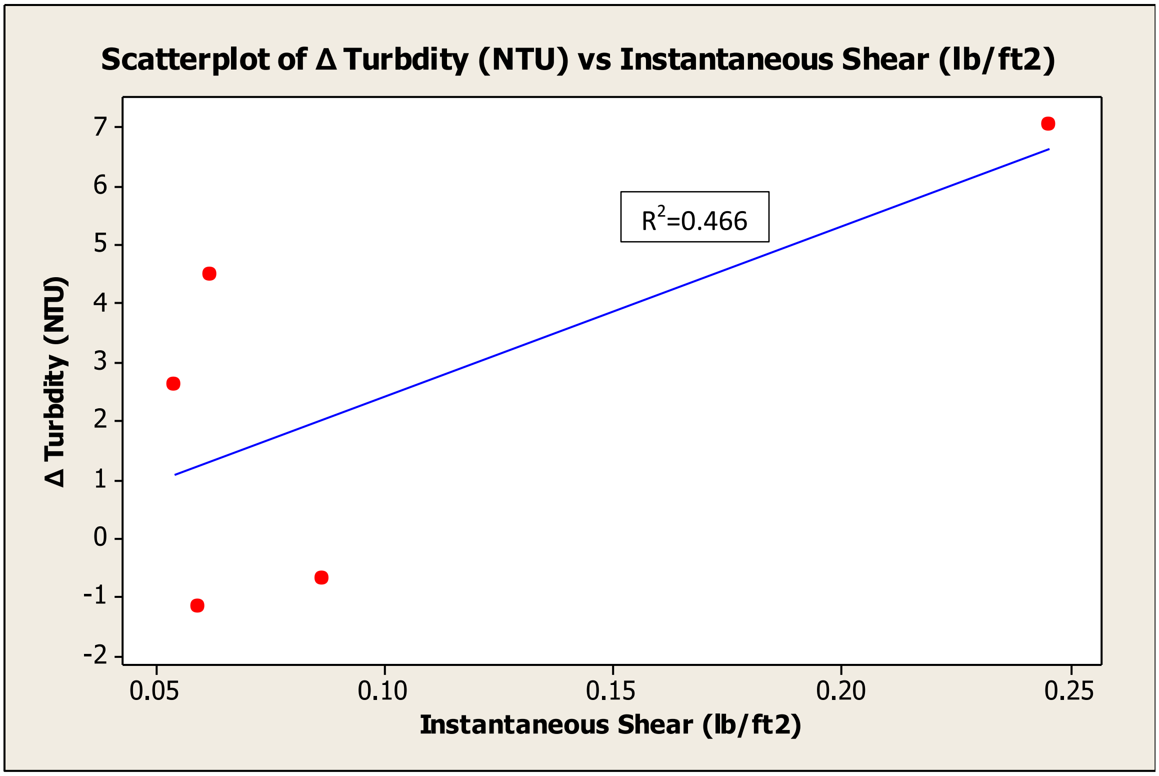

Scatterplot of Δ % fines vs % Deepest Embedment
Δ % fines
0
-2
-4
-6
-8
-10
-12
-14
0
10
20
30
40
50
% Deepest Embedment
R²=0.224

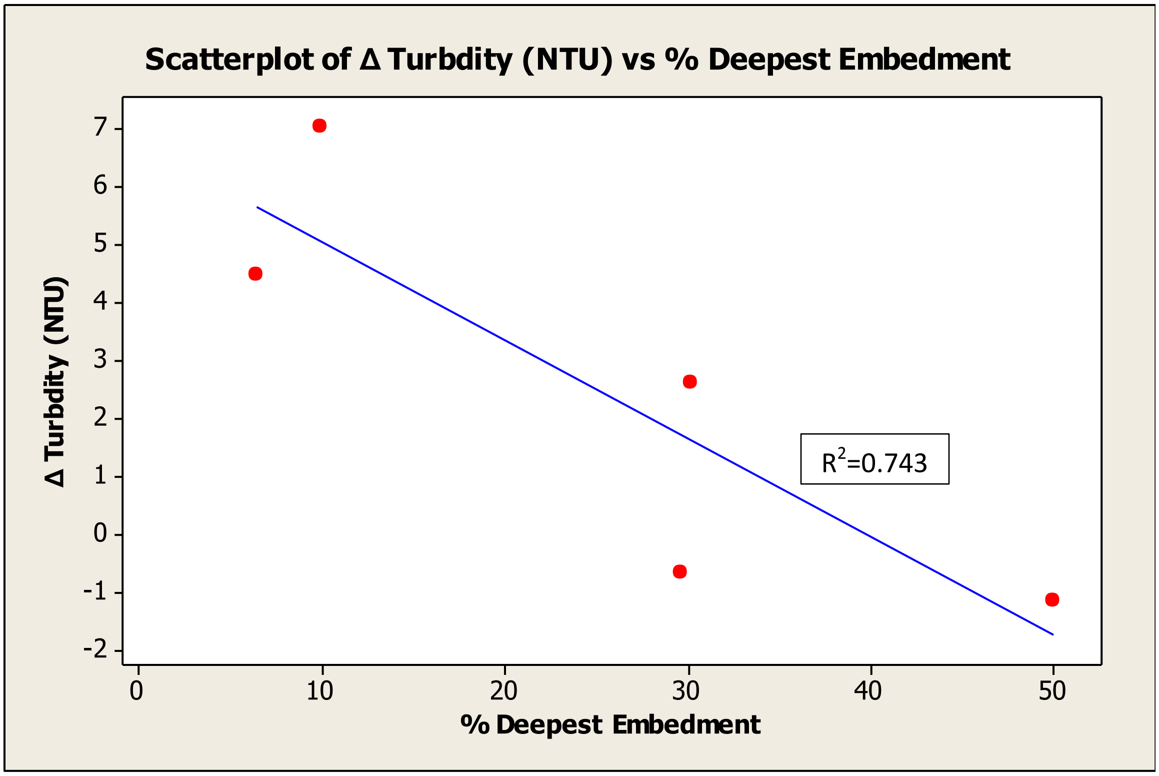


Scatterplot of Δ TSS (mg/l) vs Instantaneous Shear (lb/ft2)
Δ TSS (mg/l)
60
50
40
30
20
10
0
-10
0.05
0.10
0.15
0.20
0.25
Instantaneous Shear (lb/ft2)
R^2=0.58



Scatterplot of Δ TSS (mg/l) vs % Deepest Embedment
Δ TSS (mg/l)
60
50
40
30
20
10
0
-10
0
10
20
30
40
50
% Deepest Embedment
R^2=0.343


Scatterplot of Δ Turbdity (NTU) vs Instantaneous Shear (lb/ft2)
Δ Turbdity (NTU)
7
6
5
4
3
2
1
0
-1
-2
0.05
0.10
0.15
0.20
0.25
Instantaneous Shear (lb/ft2)
R2=0.466


Scatterplot of Δ Turbdity (NTU) vs % Deepest Embedment
Δ Turbdity (NTU)
7
6
5
4
3
2
1
0
-1
-2
0
10
20
30
40
50
% Deepest Embedment
R2=0.743

APPENDIX F

PARTICLE SIZE DISTRIBUTIONS

(SEE ATTACHED COMPACT DISC)