FINAL REPORT FOR IHRB TR-719

DEVELOPMENT OF SELF-CLEANING BOX CULVERTS

Phase III




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16. Abstract
The overall goal of this research is to find solutions that permanently solve the sedimentation at culvert problem by using the self-cleaning concept. This concept relies entirely on the use of the stream's hydraulic power for passing downstream the culvert the suspended and bed loads carried by the stream. During more than 10 years of research in this area, our team identified three possible candidates for reducing or completely eliminating the formation of sediment deposits at culverts: a) filled-based (Design A); upstream curtain wall (Design B), and downstream weir (Design C). Funding provided by this study enabled to construct and monitor the performance of Designs A and C following implementation to actual culvert sites. Using a set of innovative research tools for observing and analyzing in-situ the culverts, this study led to useful observations and quantitative correlations between the variables describing the culvert-stream relationship that are difficult to be captured and understood using analytical or laboratory studies. The evidence garnered through this study demonstrates the good performance of the self-cleaning based Designs A and C to mitigate sedimentation initiation and development. Besides mitigating sediment deposition, the tested structures "streamline" the flow through the culvert in a way that secures the safety of the structure at high and normal flows without significant disturbance of the stream behavior.

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Abstract

Sedimentation at multi-barrel culverts is an ongoing maintenance and design issue across many of the nation's erosion-prone watersheds. Sediment deposits may develop quickly, leading to immediate impairing of the culvert capacity to convey design flows which will further result in damages to both the transportation infrastructure and upstream landowners. Typical culvert design protocols are based on hydrologic and hydraulic analyses of the site, with little attention given to the potential for sedimentation. Hence, in many cases, these omissions result in costly and labor intensive cleanup operations. Currently, the information and knowledge for assessing the complex erosion and transport processes leading to culvert sedimentation is still limited.

Building on the outcomes of a series of research projects funded by IIHRB since 2006, the present study aims at developing solutions to mitigate the initiation and subsequent development of sediment deposits at multi-barrel culverts. The backbone of the previous studies was finding solutions that permanently solve the sedimentation problem by using the self-cleaning concept. This concept relies entirely on the use of the stream's hydraulic power for passing downstream the culvert the suspended and bed loads carried by the stream. During more than 10 years of research, our team identified three possible candidates for reducing or completely eliminating the formation of sediment deposits at culverts: a) filled-based (Design A); upstream curtain wall (Design B), and downstream weir (Design C). Up to this study, the Design A had been fully investigated through laboratory and numerical studies and it was implemented at the inlet of a culvert in 2013. Design B has been adopted in several Iowa Counties and Cities guided only by engineering intuition. Design C has been found by our research team at a few Iowa culvert sites (mostly as beaver dams) and was found to perform well in terms of sedimentation mitigation.

The main objective of the present study is to fully implement and test the in-situ performance of Designs A and C. For this purpose, two 3-barrel culverts located within 1.5 miles over the same stream (e.g., Willow Creek in Iowa City, Iowa) were retrofitted according to Design A and C specifications. Coincidentally, the stream reach contains two other 3-barrel culverts: one fitted with Design B at the construction time and another one with typical culvert design. Using a set of innovative research tools for observing and analyzing in-situ the culverts has led to inferring useful correlations between the variables describing the culvert-stream-drainage area triplet that are difficult to be captured and understood using analytical or laboratory studies.

The evidence garnered through this study demonstrates the good performance of the self-cleaning based Designs A and C. Besides mitigating sediment deposition, the tested structures "streamline" the flow through the culvert in a way that secures the safety of the structure at high and normal flows without significance disturbance of stream behavior. The self-cleaning designs maintain a clean and clear area upstream the culvert and keep a healthy flow through one or more barrels, offering hydraulic and aquatic habitats similar to those in undisturbed stream reaches. Aside from proving the good behavior of the self-cleaning designs, the study offers details on the in-situ monitoring and analysis protocols that have fully proved their efficiency and utility. It is hoped that the insights into the sedimentation process highlighted in this study will benefit designers and researchers by providing factual information that can be fed back into the analytical formulations that guide the culvert design. We are committed to share the project findings and recommendations with other Midwestern states that are also facing this chronic problem.

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1. Introduction

1.1 Background

Culvert sedimentation overview. Since U.S. Midwestern secondary roads often rely on culverts to allow streams to pass under roadways, culverts play a major role in our transportation infrastructure. Various culvert types are used depending on the culvert site and the characteristics of its drainage area. In general, larger flows and road embankment heights entail the use of multi-barrel (a.k.a. multi-box) culverts. Multi-box culverts require less headwater and are more economical than one larger, single-box culvert. Box culverts are typically designed to handle events with a 50-year return period; hence, in many areas of Iowa and indeed elsewhere, the amount of water flow through a typical box culvert is relatively low throughout most of the year. While culverts are commonly sized to accommodate specific return flows (i.e., 25, 50, or 100 years), evidence suggests that culvert failures are rarely related to the exceedance of some level of flood flow (Cafferata et al., 2017). Instead, accumulations of debris and sediment at the culvert inlet that partially block the culverts are more often than not the underlying cause of failure.

Review of Processes Leading to Culvert Sedimentation. Developing solutions for mitigating sedimentation at culverts requires a sound and holistic understanding of the physical processes involved. Conceptually, the processes associated with culvert sedimentation may be grouped into three major categories as illustrated in Figure 1: (1) soil detachment (i.e., erosion, sediment supply, and sediment production), (2) sediment transport (overland and in-stream), and (3) sediment deposition (settling at culvert structure and stabilization due to vegetation growth). The three categories of sediment processes are tightly related in an end-to-end spatial continuum that connects the sedimentation sources (in drainage basins) with the transport pathways (through watersheds and stream networks) and deposit locations (at culverts) (Haan, 1994; Schumm, 1977; Merritt et al., 2003, and Lord et al., 2009). In order to understand the origin, structure, and the local processes involved in the formation of sediment deposits at culverts, we review below the relevant features for all the aforementioned processes.

a) b)

Figure 1. End-to-end culvert sedimentation processes: a) soil detachment (sediment production and overland transport) in the culvert drainage area; b) in-stream sediment transport to culvert vicinity and deposition processes in the vicinity of the culvert (Muste and Xu, 2017).

Sediment Production. The detachment of soil particles within culvert drainage basins is considered to be the primary source for sediment which, through downstream transport, eventually leads to sediment deposits near culvert structures. This process has been differently labeled as “erosion,” “sediment generation,” or “sediment production” in previous studies. In principle, soil detachment is driven primarily by raindrop impact and overland flow (Hudson, 1975; Loch and Silburn, 1996) as a two-phase process that entails the detachment of individual soil particles and their transport by erosive agents (Morgan, 2005). Although soil detachment is a natural process that causes mobilization through off-site transport of soil particles in undisturbed landscapes, acceleration of the soil erosion rates is usually and typically associated with human activities in the watersheds, such as agriculture, urbanization, and mining (Fernández-Raga et al., 2017). These anthropogenic activities do not only alter the pristine hydrologic watershed behavior, but also reshape the landscape surface and natural drainage waterways, causing stream instability and the degradation of the entire area.

For regions such as Iowa, one of the land management challenges is the considerable increase of agricultural land in use, which involves the removal and/or alteration of the native ground cover, resulting in changes in the roughness of the landscape surface through tilling and other practices (Muste and Xu, 2017). Recent studies have revealed that streams in Iowa used to carry a larger sediment load in the early twentieth century, followed by a drop and stabilization in loads during recent times that is merely the reflection of the alterations brought about in Iowa’s natural landscape (Jones and Schilling, 2011). These trends are associated with the widespread agricultural adaptation of conservation farming practices (i.e. changing crop rotations, artificial drainage, and buffer strips). The formation and rate of accumulation of sediment deposits at culver sites relate not only to the changes in the stream-reach approaching the culvert, but also to the incoming flows. As a result, changes do occur both in the pathways and in the amounts of the runoff triggered by the same precipitation volume. Additional factors contributing to sedimentation at culverts include local topography, soil types, and the intensity of the storms occurring at the site.

Another source of sediment mobility is today’s continuous urbanization. This process is associated with extensive construction projects (a major source of sedimentation if they are not properly regulated) that involve the installation of impervious surfaces and alterations of the natural slopes and flow paths by moving ditches, swales, and other open channels outside the perimeter of development. The combined effect of these changes is a surge in the peak flow for the same storm event and in the velocity of the flow through the streams. This increase is a major driver for the increased erosion of the stream banks and their stability over time.

Finally, another aggravating factor of sediment-increased erosion within the drainage area of the culverts is the change in rainfall patterns. Recent studies have suggested that major rainfalls are projected to become even more extreme, consistent with the redistribution toward more intense rainfalls as described in the observational records over the recent past (Villarini et al., 2013). The changes in rainfall intensity and frequency are decisive factors that influence sediment deposition in a culvert. The predicted increase in the frequency and intensity of rainfall indicates that the problem of sedimentation at culvert sites will continue -- and perhaps even increase in intensity.

Depending on their mechanism and location in the drainage basin, the erosion processes can be further categorized into six major types: splash, sheet and rill, gully, in-stream erosion, landslides, and construction site washouts (Emmett, 1978; Foster, 1982; Hairsine & Rose, 1992; Merritt et al., 2013). These processes may occur in isolation or may be linked through a splash–sheet–rill–gully erosion sequence (illustrated in Figure 2). According to Merritt et al. (2013), the potential of occurrence for different types of erosion is related to both landscape and rainfall characteristics. Production of sediment within the watersheds will occur due to:

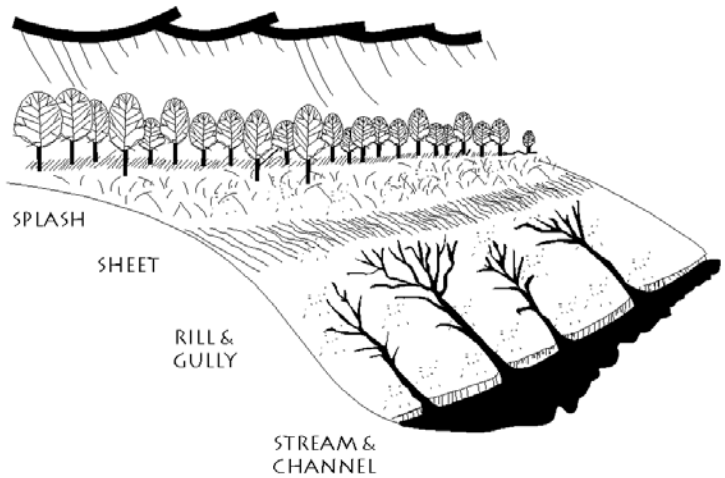


Figure 2. Major types of soil erosion (UNEP, 1998)

1. Splash erosion refers to the dislocation of the bare soil surface by raindrops falling on the ground. The raindrop impact destroys the soil structure and causes particles to be transported over a short distance (Angulo-Martínez et al., 2012). The process is recognized as the first phase in the soil erosion, causing soil detachment and disintegration so that individual soil particles will be eventually transported by erosive agents (Fernández-Raga et al., 2017).
2. Sheet and rill erosion is defined as the uniform detachment and removal of sediment particles by overland flow or raindrop impact that are evenly distributed across a slope, followed by the formation of soil surface flows along preferential pathways (Hairsine & Rose, 1992; Rose, 1993). According to Merritt et al. (2013), sheet and rill erosion are often classified as 'overland flow' erosion and are significant in agricultural watersheds.
3. Gully erosion refers to the formation of channels of concentrated flow that are too deep to be obliterated by cultivation (Rose, 1993; Loch and Silburn, 1996). In general, gully erosion forms deeper channels and its flow also differs from sheet and rill flows, since raindrop impact is not a critical factor for sediment particle detachment (Bennett, 1974). According to Carey (2006), gully erosion is a significant sediment supplier for culvert and road sedimentation and its occurrence is affected by land cover (e.g., the presence of vegetation prevent gully formation) and topography (e.g., steepness of channel).
4. In-stream erosion involves the direct removal of sediment from the stream banks (lateral erosion) or the stream bed (Merritt et al., 2013). The process is usually reflected by the widening and deepening of the stream channel and is not acknowledged as a problem unless the channel stability is compromised owing to excessive erosion rate. However, certain human activities (e.g., stream channelization) that involve the straightening of the natural course of a channel will considerably jeopardize the channel's stability and may lead to excessive rates of streambank erosion. Lord et al. (2009) suggest that the degrees of in-stream erosion may be indirectly evaluated through vital signs of stream channels (longitudinal profile and planform) monitored via the examination of historic aerial photographs and maps.
5. Landslide and construction site erosion are localized processes that dislocate the sediment by exposing the disturbed land to both direct raindrop impact and transport. These processes are not relevant to sedimentation in Iowa, as the overall local topography is mild and the state is not heavily urbanized (Muste and Xu, 2017). These factors are not considered herein.

Overland and In-stream Sediment Transport. Following the production of free sediment, the dislocated material is transported over the watershed surface and -- even much more efficiently-- through the stream network. Most of the sediment materials generated from soil erosion processes are trapped during overland and in-stream transport and are thus unable to reach far downstream. Conventionally, sediment yield is related to several stream and watershed characteristics, including the drainage density, slope-length factors (topography), land use/land cover, and soil texture. Another useful indicator for characterizing the propagation of the sediment materials through the watershed is the drainage density (a.k.a. channel density). This indicator is defined as the total length of all the streams in a drainage basin divided by the total area of the drainage basin (USGS, 1963). This indicator reflects the average distance that the dislocated sediment travels within a watershed. A higher drainage density implies that the overland sediment transport distance is relatively short, therefore the dislocated particles are more likely to enter the drainage networks before getting trapped. Finally, the changes of land use/ land cover have considerably impacted the overland sediment transport mechanisms. The changes in the land use/ land cover have altered the natural permeability, surface roughness, and the cover condition of a watershed, therefore directly influencing both overland and in-stream sediment transport (Muste and Xu, 2017).

In-stream sediment transport is defined as the movement of solid, non-dissolved particles through the stream network. The main driver for the in-stream transport is the channel slope. Conventionally, this process is characterized by two major transport modes, namely suspended load and bed load (Karim, 1981). Only a portion of the soil particles dislocated in the headwaters enters the drainage network as suspended load and is subsequently delivered to downstream locations (Da and Bartholic, 1997). Bonniwell et al. (1999) and Matisoff et al. (2001) have demonstrated that fine-grained sediments (e.g. clay and silt) produced from gully and streambank erosion may potentially travel a longer distance along a stream as suspended loads. In principle, coarse-grained sediments, such as sand and gravel particles, normally require a higher stream power to be transported as bed load, so they are typically prone to deposition and trapping.

Because multi-barrel culverts are usually placed on relatively large streams, the amount of bed load is small as compared with suspended load, making up only 5-10% of the total sediment load (Richardson et al., 1990). Site inspections conducted at culverts have confirmed this aspect, finding most of the sediment in deposits as fine-grained soils that are not present in the bed load material. Irrespective of the type of transport, the culvert design discharge and sediment transport rate display a positive correlation (Howley, 2004; UDOT, 2017). The underlying mechanism of this correlation is explained by the equilibrium between sediment load and stream power (Lord et al., 2009). According to Howley (2004), flood discharge and sediment transport rate are also positively correlated, i.e., larger design discharges normally imply larger sediment loads. Furthermore, culverts that require a large design discharge are susceptible to oversizing.

Sediment Deposition at Culverts. The in-stream transport processes described above are valid for channels that are in their natural (undisturbed) configuration. A stable channel (i.e., one that maintains a quasi-uniform geometry in its streamwise direction) is expected to balance erosion and sedimentation over time (i.e., self-cleaning regime). In contrast, the stream's geometry is considerably altered at the location of culverts where the local hydrodynamic processes are dominated by the structure-stream interaction. The critical factor leading to sedimentation is the degree of natural channel disturbance that is well reflected by the Stream-to-Culvert Width (SCW) ratio. In addition to this main factor, the type of culvert flow control (i.e., inlet or outlet) and stream ecology are also involved in defining the sediment deposition processes. Culvert structures that are well-aligned with the natural channel and are non-vegetated are not expected to develop a sedimentation problem. However, 95% of the three-box culverts in Iowa are severely silted, as illustrated in many of our previous studies (e.g., Ho et al., 2013).

The SCW ratio is defined by the needed culvert cross section to pass the designed discharges associated with flood flows of various return periods. A culvert associated with SCW > 1 requires transition areas in its vicinity which comprise an expansion upstream from the culvert and a contraction downstream from the culvert (Ho, 2010; Charbeneau et al., 2006) as illustrated in Figure 3a. These transitions produce a flow non-uniformity characterized by the divergence/converge of the streamlines for all flow regimes and, eventually, flow areas of widely different velocities. The low-velocity areas are prone to sedimentation as they favor the sediment deposition on a continuous basis. Most of the time the culverts are conveying only a fraction of the designed flow passing through the structure as a non-uniform steady flow. Even in these extreme cases, flow recirculation procedures are developed as illustrated in Figures 3b (conceptual sketch) and 3c1 (laboratory experiments conducted by Ho et al., 2013). However, the most energetic sedimentation events ensue during the propagation of unsteady flows following the storms occurring in the culvert drainage area, since the flow complexity increases after such situations.

One of the complexity factors is the passing of unsteady flow carrying sediment. The flow during the propagation of a storm hydrograph acts differently on the rising and falling limbs of the hydrograph, a.k.a. hysteresis (see Figure 3c2). Hysteresis is currently unaccounted for in flow monitoring, hence it is also neglected in the design and analyses of river structures such as culverts. The unsteady flow associated with the storms occurring in the culvert drainage area entrains the sediment in suspension and activates the bed load transport. The sedimentation at culverts occurs on the falling stage of the hydrographs, when the stream power diminishes. The rising phase of the hydrograph is characterized by a dynamic sediment transport phase followed by a falling stage when the sediment rates return to normal transport regimes, as shown in Figure 3c3. Specifically, the maximum total sediment load passing through a section during a storm event is uncoupled from the peak flow as it precedes it, irrespective of the discharge magnitude.

The flow's non-uniformity combined with its inherent dynamics during the transitions decides where and when the sediment settling in the culvert vicinity will occur. Currently, there are considerable gaps in theory regarding the non-uniform, unsteady, sediment-laden flows developing in three-dimensional culvert geometry. Lack of understanding of the complexities of this combination of local processes preclude making accurate predictions without proper analytical tools. Given the complexity of the local processes and the nature of the transported materials, only a handful of studies have focused on the stream and structural attributes that will affect sediment deposition at culverts (Cafferata et al., 2017; Ho et al., 2013; Howley, 2004).

Finally, stream ecology is another factor that is considerably involved in sediment accumulation at culverts (Ho et al., 2013). The presence of vegetated or forested zones in the culvert drainage area is beneficial for the present context, as riparian vegetation or forested stream vicinities prevent the sediment from reaching the stream (Pearce et al., 1998). However, the presence of vegetation developed within culvert transitions also leads to the increase in culvert sediment deposits (Muste and Xu, 2017). Our focus herein is only on the latter vegetation-related aspect. The vegetation growth over the newly formed sediment deposits occurs between storms when the sediment islands reach a height that exceeds the water surface at low flow conditions. Terrestrial vegetation, such as cattail and weed, grows quickly in the fertile soil provided by the sediment deposits. The grown vegetation acts as additional roughness against the high flows loaded with sediment and further exacerbates the rates of sediment deposition (Brock and Jefferson, 2013; Cotton et al., 2006; and Box et al., 2019). Field observations conducted by Muste and Xu (2017) have revealed that after a 4 to 5-year deposition cycle, the vegetated sediment deposits stabilize and consolidate so that subsequent storms cannot wash away the deposited material. Where the vegetation growth is limited by the absence of light, such as the area within the culvert boxes, the deposited material is much less than that outside the culvert (both at the inlet and outlet).

a) b)

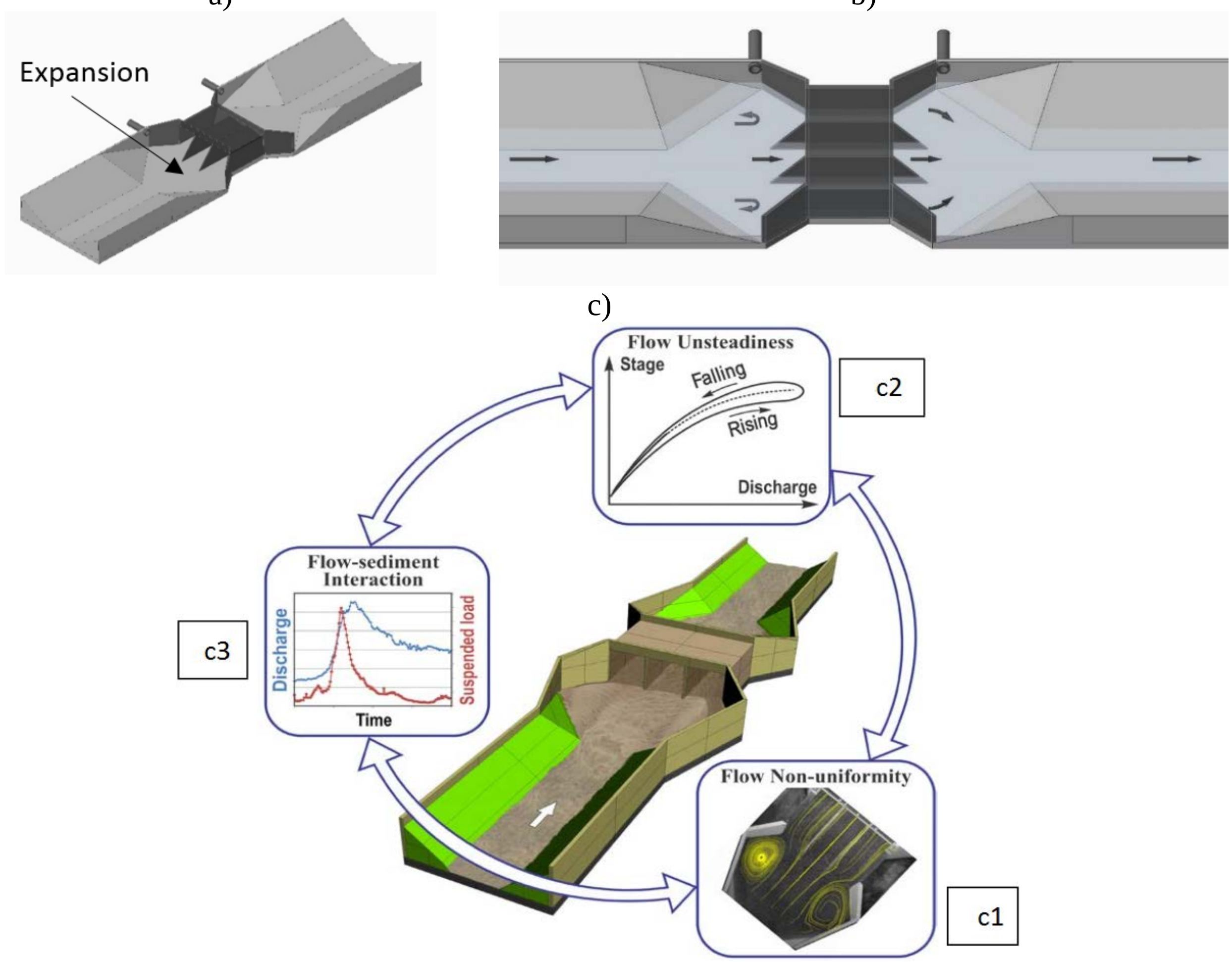


Figure 3. Flow configuration at culvert sites: a) stream-to-culvert transition; b) flow patterns in the vicinity of culvert (patterns vary with the streamflow magnitude); c) flow complexities due to flow unsteadiness (Muste and Ho, 2013)

1.2. State of knowledge on culvert sedimentation.

Sediment transport through culvert structures has been recognized as a problem for many years (Haight, 1912). The variety and complexity of the problem posed by sediment passing continues to be a challenge at stream crossings provided with culverts. In general, current knowledge of sedimentation processes at culverts is fragmented and the literature on this topic is scarce. More recently, however, the intensification of land use changes (through intensive agriculture and urbanization) and the impact of climate change reveal how critical this area of research is.

Conventionally, sedimentation problems in a watershed may be analyzed and evaluated by using soil erosion models (Nearing et al., 2005). Over the past two decades, different types of models, such as empirical (lumped parameter), conceptual (comprehensive, partly empirical/mixed), and physically-based (spatially distributed) ones, have been developed for identifying the areas within a watershed that contribute to significant loads of sediment, impacting water quality and sedimentation within watersheds (Jha & Paudel, 2010; Merritt et al., 2003; Sorokine et al., 2006). Most soil erosion models (e.g. WEPP, SedNet) have been developed to simulate natural channel flows that are uniform, under steady conditions, as well as free from disturbances by human-made structures (EPA, 2017; Nearing et al., 2005; Papanicolaou & Abaci, 2008; Prosser, 2001).

Culvert sedimentation cannot be properly addressed through soil erosion modeling alone because of the high number of unknowns and knowledge gaps. Therefore, there are very few (if any) research studies tackling transport processes that lead to sedimentation at culverts, as an end-to-end process. Even in their simplest forms, investigations of these erosion and transport processes are bound to be complex, as they must track sediment sources dislocated from a watershed, their overland movement, and their delivery into the streams. Then they must resolve the hydrodynamic processes occurring in streams and at the location of the culverts as well. Their complexity is further increased by the continuous change of the erosion process drivers that is dependent in turn on natural and anthropogenic activities in upstream drainage areas. This interactive chain of processes is a relevant example of coupled human–environment systems, an area of investigation insufficiently understood because of the lack of tools to appropriately handle the vast amount of data needed for these inquiries. It comes, therefore, as no surprise that the existing research, textbooks, and guides do not typically provide adequate information on sediment control at box culverts for single or multi-barrel culverts.

More recently, pressed by the mounting evidence of sedimentation at culverts and the adverse impact that it entails, there has been an expansion of investigations in this area, too. The initial studies were based on semi-empirical or piecemeal modeling approaches that adjust exiting water conveyance formulae to sediment presence. Most of the available investigations and practical guidelines related to sedimentation deal with embedded pipe culverts, specifically with the change in the local hydraulics in the presence of bed load passing through this type of culvert. Howley's study (2004) broadened the scope of the research by investigating the relationships among various culvert characteristics and their effect on sediment -- predominantly in suspension -- deposition in culverts. His analysis is mostly focused on culverts contained in storm water systems by combining site specific field data, watershed modeling, culvert modeling, and data interpretation. Goodridge (2009) investigated how alluvial material in sand and gravel sizes occurs in pipe culverts to provide semi-empirical bed load transport equations for predicting sediment yields. A more recent study was aimed at developing design criteria for self-cleansing drainage systems entailing circular as well as other channel cross sections (Safari et al., 2017). Self-cleansing ensures that the sediment deposition is minimized as much as possible.

The closest in scope to our study is the field investigation conducted by Rowley (2014) which aimed to understand how coarse sediments behave near culverts. Rowley investigated embedded-type culverts (bottomless), a culvert type that is promoted for its ability to enable migration of aquatic organisms. He collected data at multiple sites and compiled them to generate a hydraulic numerical model for predicting the deposition of sediments at the entrance of the culverts, sediment replenishment inside the culverts, and lateral fining within the culvert barrel. According to Rowley, this was the first time that deposition of sediments upstream of a culvert and lateral fining within a culvert barrel had been successfully modeled. The distinction between our studies and Rowley's is in the nature of the sediment (Rowley studied coarse sediment whereas we studied fine sediment) and the simplicity of the culvert geometry (pipe culverts). These differences were sufficient to reveal a completely different sedimentation pattern upstream from culverts: Rowley focused on central deposition while we addressed lateral deposition predominantly observed in our field investigation (see also Figure 1). Our present study is also relying on field experiments which are deemed to be the most reliable, albeit more expensive than other investigative approaches.

Given the complexity of investigating the sedimentation at culverts, there are no rigorous design techniques available to size culverts for sediment passage which will predict the loading of sediment. There are, however, strategies based on engineering judgements that may suggest the optimal design of culverts in regard to sedimentation. Most of the available guidelines are developed for pipe culverts that are easier to deal with due to the simpler flows they convey. For example, Cafferata et al. (2017) recommends that engineers should:

- Choose a culvert width as close as possible to the width of the natural channel.
- Keep the headwater depth at the culvert inlet at half-full (no more than two-thirds) of the culvert height for the design flow.
- Install the culverts with a slope close to the natural channel.
- Avoid oblique stream-to-culvert angles by setting the culvert along the channel direction.

Except for the first recommendation, the goal of the above design guidelines is not very different from the considerations required for the hydraulic sizing of the culverts, so it is not exactly clear whether these recommendations assure better sediment conveyance, thereby reducing the risk of structural failure. Additional considerations are available regarding the changes that the sediment induces on the hydraulic gradient and the friction factor for the flow passing through the culvert (UDOT, 2017). The guidelines warn users that these assessments are not thoroughly scientific, therefore engineering judgment is essential in their implementation. Currently, there are no considerations to account for sediment issues in multi-box culvert design. Consequently, it is advisable to utilize culverts that are close to the width of the active channel (Cafferata et al., 2017).

It is apparent that the complexities of the watershed sediment dynamics continuously shaped by anthropogenic impacts exceed the problem-solving capabilities of the available experimental, analytical, or numerical simulation-based investigations. In order to provide watershed managers and structural engineers in charge of sedimentation at culverts with the information needed to make decisions, an alternative end-to-end analysis and associated support tools are proposed in the study of Xu (2019). Specifically, a data-driven approach embedded in a web-based problem-solving environment has been developed to provide the critical information for planning, designing, and maintaining culverts. The proposed method maintains the holistic, systems approach, to problem investigation with low-cost and effective means. The developed framework is modular, compatible with the Contiguous US scale, and may be adapted to other river management (i.e., habitat deterioration, water pollution). This method, however, may only be applied to data-rich watersheds or to areas where surrogates for those data are available. Xu's study (2019) tests the feasibility of the data-driven framework in conjunction with the issue of culvert sedimentation in Iowa.

2. Study Scope and Overall Results

2.1. Problem definition

The view of an ideal culvert operation is indicated by its stable stream geometry in the culvert vicinity as illustrated in Figure 4a. Situations such as those shown in Figure 4a are, however, rare across Iowa's landscape. The surveys conducted by our research team in 2009 and 2013 indicate that about 95% of Iowa culverts are silted (Ho, 2010; Muste & Xu, 2017b). Sedimentation (a.k.a., silting) of culverts will considerably reduce their capability to handle larger flow events, as the partial blockage of their structures may severely impair their hydraulic capacity to convey designed flows. For such conditions, obstruction at the culvert inlet may cause both damage to the transportation structure (due to culvert and road overtopping) and upstream flooding. Culvert sedimentation concerns are widespread in the nation, from California to Pennsylvania and from Wisconsin to Florida (Rowley, 2014), with direct bearing on their ability to maintain normal operation during extreme flows when culverts are essential for the communities they serve.

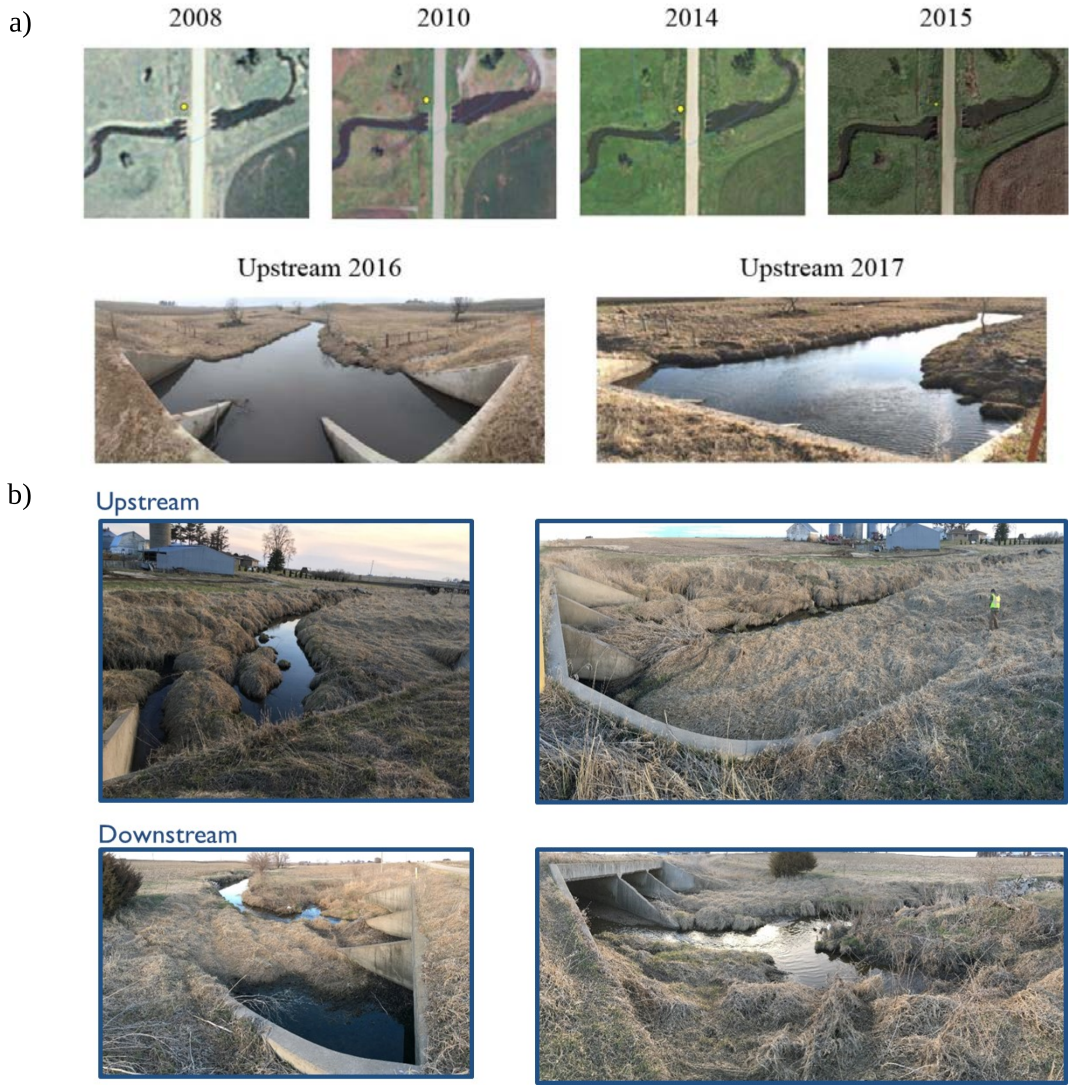


Figure 4. Sample of culverts in Iowa: a) ideal operation (less than 5%); b) silted culvert (about 90%)

Multi-box culverts located within flat, erodible watersheds are especially prone to sediment blockage. This is precisely the case for the highly erosive Iowa landscape where sediment accumulation may quickly fill the culvert cross section. Information assembled during filed visits and by inspecting aerial photographs collected over successive years has revealed that the process of sedimentation at culverts can attain a stable form of sediment deposits in no more than four to five years (Muste & Xu, 2017a), as shown in Figure 5.

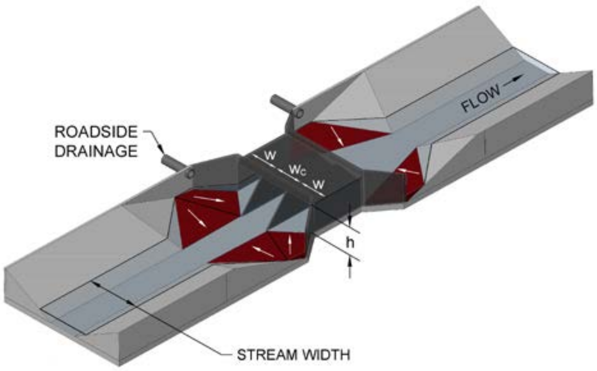
Figure 5. Sedimentation is fast and can quickly reduce a culvert's conveyance capacity.

Given that currently sedimentation at culverts does not benefit from well-established mitigating solutions, the only alternative for DOT maintenance offices is sustained cleaning operations. Culvert cleaning is one of the costliest maintenance problems for Iowa culverts due to the frequency with which culverts need to be cleaned, the range of equipment used, and the labor required for a thorough operation. The socio-economic damages associated with culvert sedimentation are unlikely to diminish, as recent studies predict that the frequency and intensity of storms will continue to increase throughout the contiguous United States (Villarini et al. 2013).

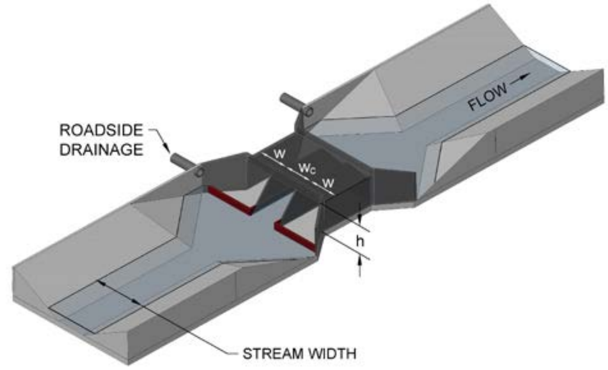
2.2. Potential solutions

The ideal candidates for permanently solving the sedimentation at culverts are grounded in the self-cleaning concept. This concept relies entirely on the use of the stream's hydraulic power for passing downstream the culvert the suspended and bed loads carried by the stream. During more than 10 years of researching various aspects of sedimentation mitigation at multi-barrel culverts, our team identified three possible candidates for reducing or completely eliminating the formation of sediment deposits at culverts (see Figure 6): a) filled-based (Design A); upstream curtain wall (Design B; upward or downward curtain), and downstream weir (Design C).

a)



b)



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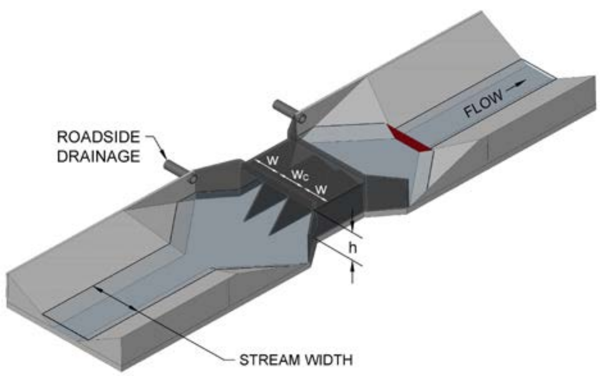


Figure 6. Self-cleaning culvert solutions identified through previous research for 3-barrel culverts: a) Fillet-based, b) upstream curtain wall (upward version), and c) downstream weir

Based on a series of studies and observations of all the above-mentioned culvert designs, the Iowa research team has found that under particular set of geomorphological and hydraulic conditions, all the aforementioned self-cleaning designs perform well. More specifically, Design A has been fully investigated via laboratory and numerical studies and implemented at a culvert site since 2013 (Muste and Xu, 2017a). Design B has been adopted for sedimentation mitigation purposes at culverts in several Iowa Counties and cities. Design B has not been fully investigated by way of hydraulic studies (Muste & Xu, 2017b). Design C has been randomly found at few Iowa culvert sites (mostly as beaver dams) and was implemented in-situ through a recent study.

2.3. Study sites and objectives

This study assembles observations and experiments acquired since 2010 on three of the four 3-barrel culverts located within 1.5 miles on the Willow Creek in Iowa City (Iowa). The location of the four culverts is shown in Figure 7. Through this study, Designs A and C located at culvert Site #1 (FHWA #031711) and Site #3 (FHWA # 364790) respectively, were implemented and monitored for their performance between 2017 and 2019. Design B is not part of this study. In between Site #1 and Site #3, there is a 3-box culvert that was not modified since its construction in 2006. This culvert is heavily silted and will be used as a reference for the present study.

a)

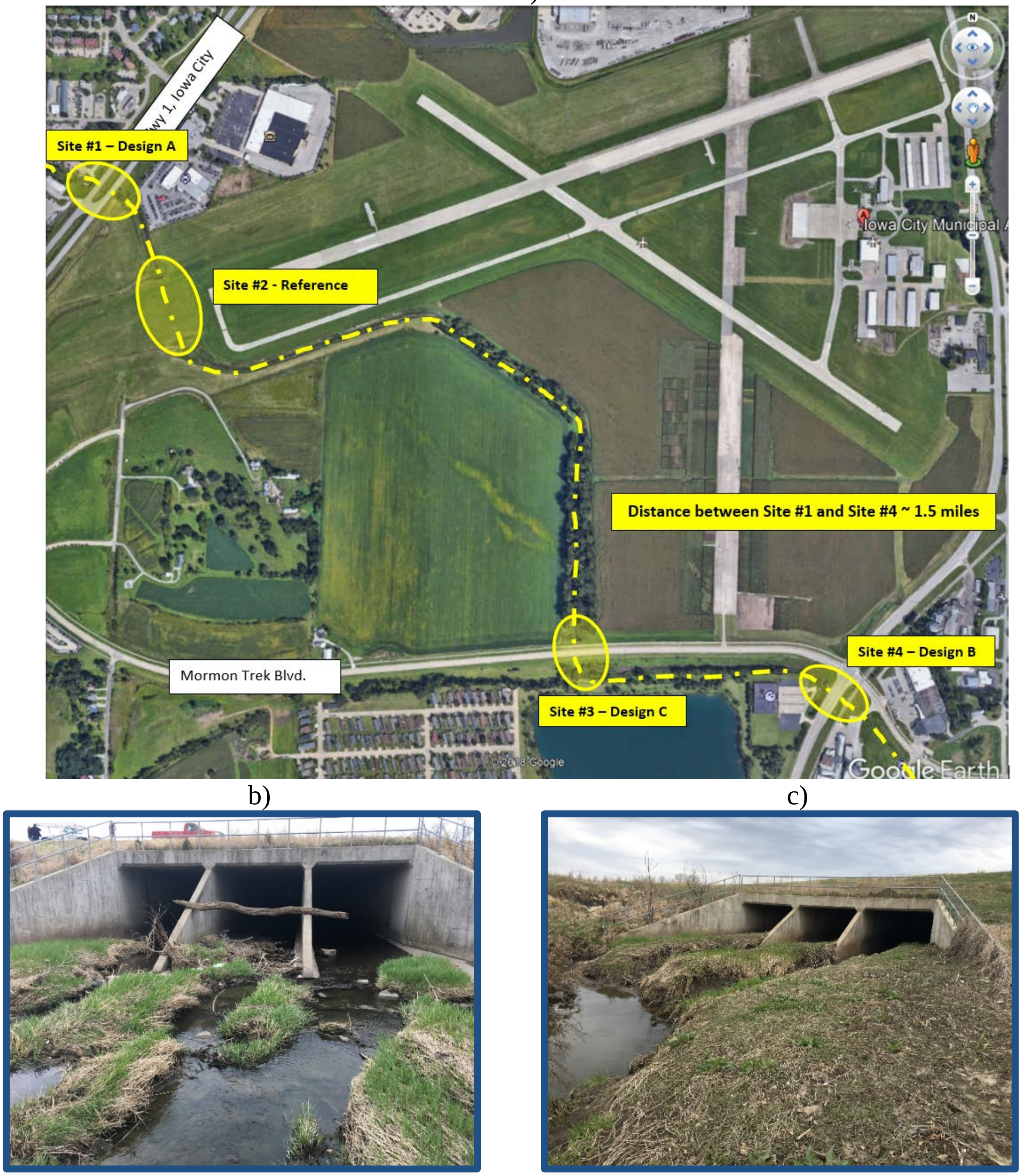


Figure 7. Culvert study location: a) the layout of the four observed culverts, b) view of the reference culvert entrance; c) view of the location of the reference culvert exit

The overall objective of the TR719 Phase III project is to evaluate the performance of new self-cleaning designs for mitigating sedimentation at culverts by deploying observational equipment, gathering data and information, and analyzing and synthesizing the ground-truth observations collected during the culvert monitoring. The specific objectives of this study are:

O.1. Implementation of the self-cleaning Design A in the downstream area of Hwy 1 culvert (FHWA #031711) by using guidelines developed through previous TR 619 research.
O.2. To monitor and asses the overall behavior of the 3-box culvert (FHWA # 364790) located downstream from Hwy 1 culvert, in its close vicinity.
O.3. To design, deploy, and monitor of Design C implemented at FHWA #364790 culvert.
O.4. To synthesize the findings of pre- and post-construction observations on flow and sediment mitigation for the self-cleaning designs as applied at the two culverts.

It should be noted that Site #1 (FHWA #031711) was partially retrofitted through the project TR 619 Phase II by using the Design A concept based on self-cleaning principles (Muste and Xu, 2017a). The retrofitting ensured its successful operation for 5 years following the cleanup and it continues to operate as such to this day. In contrast, the downstream area of a culvert which has not been previously retrofitted, has built up sediment over the same period of time. During the conduct of the FHWA's State Transportation Innovation Councils (STIC) project (Muste and Xu, 2017b), the project's TAC suggested to complete the retrofitting of the downstream part of the culvert in order to observe its performance. A second culvert was suggested for retrofitting, following the site surveys conducted by our research team in the spring of 2016 as part of the TR 619 project. Specifically, we encountered 3 culvert sites in various Iowa regions that were relatively sediment-free in an area where all the neighboring culverts were silted. The common element of the clean culverts was the presence of a pool in the culvert's vicinity. The shallow pools were created by low-head weirs constructed ad-hoc by beavers or by land owners in order to facilitate stream crossing. These observations led to the realization that this type of culvert "retrofitting" might also serve as self-cleaning design and warrants further investigation. The new self-cleaning solution was labeled as Design C (as illustrated in Figure 6c).

2.4. Efficiency of the monitored solutions

A photo-documentary of the study culverts' status before and after their retrofitting with Designs A and C are provided in Figures 8a and 8c, respectively. The culvert retrofitting using Design A specifications was deployed at Site #1 and has performed well throughout the 6-year period of observations. The culvert has been free of sediment following the passing of numerous storms; it has not developed vegetation and has not posed hydraulic problems during any of the year's seasons. The fillets are still in place with the intent to remain as permanent installations. The overall conclusion to Design A is that it represents a robust and definitive solution for sedimentation problems. Similarly, Design C implemented at Site #3 performed well during the 2018-2019 period of observations. In the fall of 2019 (at the end of the present project), the downstream weir was dismantled since the weir construction was intended to be temporary, to begin with. Included in the Figure 8 is also Design B (located at Site #4), meant to provide more context to the present investigation. During the project time, this culvert's design maintained its inlet clean, yet the culvert developed sediment deposits at the outlet (as shown in Figure 8b). The "reference" culvert shown in Figure 7 is a significant benchmark for the cases depicted in Figure 8. This culvert displays "fossilized" sediment deposits that are not expected to grow.

In sum, it can be concluded that the three sediment mitigation solutions are feasible for implementation. Their cost-to-benefit ratios are, however, different. Using analytical estimations and field observations, some preliminary evaluations and ancillary comments of the three self-cleaning designs can be formulated, as illustrated in Table 1. The conclusions are, however, not definitive, as they represent only a subset of the variety of stream-culvert configurations.

Culvert Inlet **Culvert Outlet**

Figure 8. Self-cleaning solutions: a) Design A (fillet-based) applied to a triple 15’-18’-15x12’ ~ 170-ft long culvert; b) Design B (upstream downward curtain) applied to a triple 15’-18-15x12 ~ 800-ft long culvert ; c) Design C (downstream weir) used for a Triple 15’-18-15x12, ~ 200-ft long culvert

Table 1. Comparison of the three self-cleaning culvert designs.

Design concept	Hydraulic principle	Protected area	Sensitive to approach angle	Relative cost*	Relative efficiency**	Applicable
Fillet-based (Design A)	sediment transfer	Upstream, downstream	yes	highest cost	-	anytime
Curtain wall (Design B)	sediment transfer	Upstream	yes	relatively high	relatively limited	anytime
Downstream weir (Design C)	sediment trapping	Upstream, downstream	no	-	Similar (unknown lifetime)	anytime
* Reference: Design C; ** Reference: Design A						

3. Research Methodologies

3.1 Culvert retrofitting phasing

The research on sedimentation at culverts, as well as the development of mitigation measures are relatively new areas of investigation, with little guidance in terms of the construction and monitoring of mitigation structures. From this perspective, this study had to undertake an exploratory research approach, owing to unexpected aspects that surfaced during the investigation and which required immediate attention. One of the tasks of the present study was to cleanup and retrofit the downstream side of the FHWA #031711 culvert. This work was carried out with funds provided by IDOT according to Design A specifications (see Figure 6a). The retrofitting work was delayed for one year (i.e., April, 2019) because of scheduling conflicts in the IDOT workflow planning. This task did not raise any major problems (see Figure 9). The construction of the fillets followed the protocols used for retrofitting the upstream area of the culvert (Muste and Xu, 2017a). The retrofitting material consists of specially woven, double-layered synthetic forms filled with a pumpable, fine aggregate concrete grout in such a way as to form a stable revetment of required thickness, weight, and configuration. The two layers are joined together by narrow perimeters of interwoven texture resulting into a matrix of rectangular compartments, i.e., the concrete articulating bloc (ABM). Multiple factory pre-formed ABMs were assembled to cover the retrofitted area. IDOT had prepared detailed specifications for the development and layout of the formed concrete structure revetment.

a)


c) d)


e)

Figure 9. Aspects of the preparation and installation of the articulated block mat at FHWA #031711 site

Figure 10 provides views of the fully retrofitted culvert following the fillet construction. It also reveals some minor changes made to the previous installed ABM mat. These changes were devised based on observations of the flow patterns in that area, collected during the 2018 monitoring. The downstream area of the culvert was retrofitted with a new design, slightly different from the one on the upstream side. Drawings for the revetments deployed in the culvert vicinity as well as specifications about the make-up and installation of the ABMs are available upon request from the IDOT office of Bridge Design. Lessons learned from the constructing and finishing the ABM mats are summarized in a subsequent section.

a)

b)

Figure 10. Views of the completed retrofitting at the FHWA #031711 culvert site: a) culvert inlet, b) culvert outlet

In contrast with the situation at FHWA #031711 site, the retrofitting conducted at the culvert FHWA #364790 site posed multiple construction and maintenance problems. They are mostly related to the downstream weir associated with the self-cleaning Design C. The original plans for retrofitting this site were based on in-kind contributions from the City of Iowa City. Typically, such funds are relatively limited, as they depend on an unpredictable timeline. Despite these constraints, the City of Iowa City accomplished all tasks associated with the project. The cleanup of the culvert area was made through a hired contractor in two phases: December18-22, 2017 and February 1, 2018 (see Figure 11). Following the cleanup, the site was also provided with vegetation mats as shown in Figure 12.

In subsequent stages, the City of Iowa City made considerable efforts to accommodate the schedule of the weir construction, as their routine program permitted. For a better control of the project advancement, IIHR-Hydroscience & Engineering (IIHR) shop staff took over the work of setting in place the downstream temporary weir (made of wood). IIHR decided to construct a temporary weir in order to ensure timely implementation of the design. This weir was constructed by the IIHR shop staff under the close supervision of the Project PI.

Culvert inlet

Culvert outlet

Culvert inlet at the end of cleanup

Culvert outlet at the end of cleanup

Figure 11. Views of the culvert site during the site cleanup (compare with Figure 8c)

The weir's construction has been completed in three phases by gradually raising its level and observing the hydraulics of the ponded area with dedicated instrumentation. The phases of the temporary weir construction are shown in Figure 12. Given that the foundation of the weir was formed by large boulders (already existent at the site since the culvert's construction 10 years before), setting the wood-made upper structure for tight holding of the flow had met with difficulties at the interface between the boulder base and the wood structure. As the weir level was elevated with each phase, the water pressure increased which led to the formation of under-weir leaks. While the construction and setting of the wooden part of the weir was a straightforward job, the stoppage of the leaks under the weir required substantial efforts of the IIHR staff. Since the costs for the weir setting were not included in the original TR 719 phase III proposal, IDOT provided extra funds to cover the time associated with the weir construction by the IIHR shop.

The fragility of the weir was an issue, since its monitoring was tenuous and required extra effort in order to check for the stability and water-proofing of the structure. The efforts carried out with the modest resources available at the IIHR shop were barely enough to keep the project fairly close to, yet short of reaching the optimum stage required by the Design C specifications. Similarly, the evaluation of the performance of the proposed mitigating solution for FHWA # 364790 required a constant consultation with the project TAC and subsequent interventions over the course of its completion. In spite of these difficulties, the project was finalized and delivered as planned.

a) b)

Figure 12.

c) d) e)

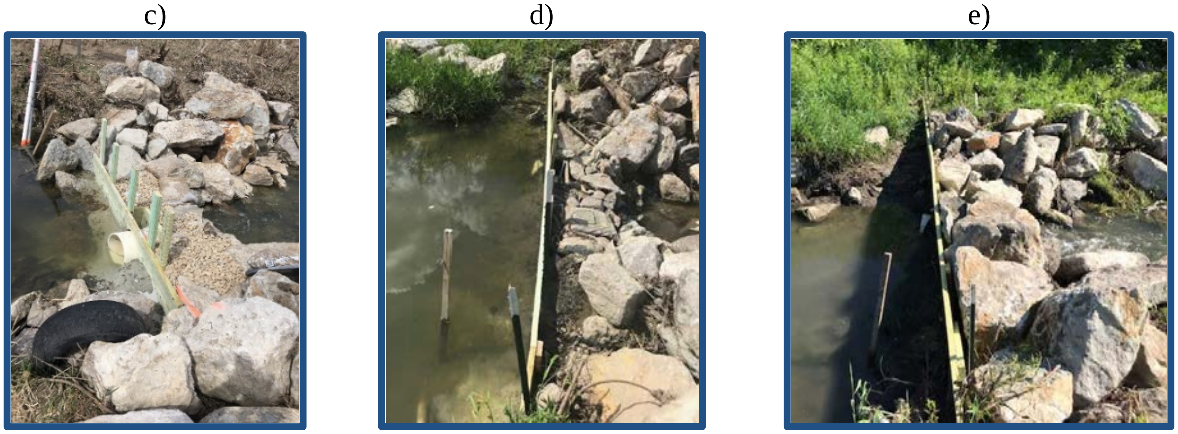


Figure 12: The FHWA #36490 culvert after cleanup and retrofitting: a) upstream area; b) downstream area. Phases of the temporary weir construction FHWA #36490 culvert: c) Level I (May 1, 2018); d) Level II (May 16, 2018); e) Level III (June 28, 2018)

3.2. Research activities

The end-to-end process for developing the self-cleaning solutions associated with Designs A and C entails a combination of experimental, data-driven and physical modeling analyses, along with the formulation of design specifications and in-situ, post-construction monitoring. These activities started in 2006 and were carried out in their logical sequence, thanks to a succession of funds available throughout the years. The funding of the present TR-719 is aimed at testing the feasibility of the identified solutions through continuous monitoring over the span of two and a half years of retrofitted culvert operations. In order to highlight the context for the full cycle of the solution development from design to construction, a summary of the essential research aspects is provided below.

3.2.1 Laboratory and numerical modeling

During the 2006 to 2012 period, extensive laboratory experiments have been conducted at IIHR for modeling the sedimentation patterns observed in-situ and for testing alternative self-cleaning concepts applied to culverts. The major tasks for the initial laboratory model study were to replicate accurately the dynamics of sedimentation process in relation to the culvert and to provide benchmark data for its numerical validation. Multiple facilities and modeling scales were used through a succession of laboratory studies (Muste et al., 2009; Ho, 2010; Muste et al., 2010; Muste & Ho, 2012). The common denominator of these studies was the use of the three-barrel culvert with angled wingwalls in the hydraulic model. Moreover, the channel approaching the culvert was set at a normal angle and the model accounted for expansion and contraction in the culvert's vicinity, as these areas strongly affect the non-uniformity of the flow that further drives sedimentation.

Sediment deposits at culverts are influenced by many factors, including the size and characteristics of the materials which compose the channel, the hydraulic characteristics generated by different hydrologic events, the geometry of the culvert and channel transitions, and the type and age of the vegetation in the culvert's vicinity. The multitude of combinations produced by this set of variables has turned the investigation of practical situations into a complex undertaking. Whereas most the hydraulic manuals do provide design specifications obtained from experiments with clear water moving over beds of sediment, our studies investigated separately the difference in pattern for suspended and bed loads continuously fed into the mode. Consequently, we have come to conclude that employing the bed load experiments was sufficient for tracking the sedimentation aspects of interest in order to develop and test design approaches for sedimentation mitigation (Muste & Ho, 2012). In the same study, the modeling of the hydrologic events was approached using a "stepped" methodology, whereby flows were sequentially maintained until they reached a state of equilibrium for transport before moving to another point on the hydrographs. We chose this modeling approach to simulate more closely the real situations where the rates of flow and sediment loads are changing during the passing of a storm over the culvert area.

The general strategy for retrofitting the culverts is driven by the self-cleaning principle applied to them without modifying their structure geometry. By following this principle, it is ensured that the developed solutions are valid for both new and existing culverts, since no structural changes to the culvert geometry are required. For example, the development of a self-cleaning solution leading to Design A is aimed at:

1. Increasing the flow capacity in the central barrel (or the one best aligned with the stream)

to ensure that most of the sediment transport is conveyed through this culvert area;

2. Reducing the sedimentation in the other barrels at a level that does not deteriorate the capability of the culvert to flush the sediment;
3. Enhancing the turbulence level in the low velocity areas in order to keep the sediment in suspension during the flow-sediment movement through the culvert;
4. Avoiding formation of sediment deposits at levels that are below the stages corresponding to the minimum flow passing through the culvert, especially in the contraction and expansion areas where the growth of vegetation will accelerate the sediment deposition rates;
5. Testing the effectiveness of the self-cleaning solutions over a range of flows commensurate with those used in the hydraulic design of the culverts.

A complete series of baseline and screening tests were conducted through an IHRB project on a small scale model (1:20) followed by performance tests on a larger scale model (1:5). This sequence of tests led uncompromisingly to the filled-based solution (Design A) that showed good capabilities for totally eliminating the formation of sediment deposits at 3-barrel culverts, as illustrated in Figure 13a. The numerical simulations conducted with FLUENT confirmed the experimental findings, as illustrated in Figure 13b.

a) b)

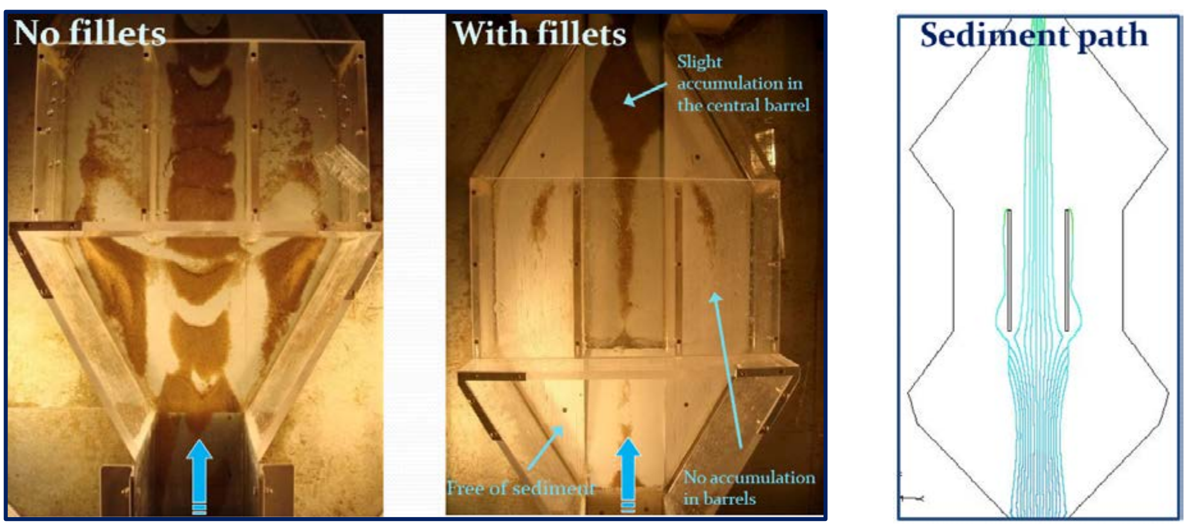


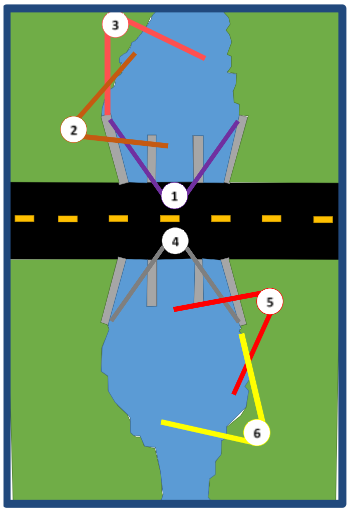
Figure 13. Results from laboratory and numerical modeling: a) experiments with sediment on culvert Design A; b) numerical simulations with FLUENT for culvert Design A (Muste et al., 2009)

3.2.2. Field monitoring

The monitoring activities for this project stem from continuous improvements brought to our in-house methodologies through a series of culvert projects, for monitoring these structures in field conditions. The methods were developed in order to both understand and document the process of sedimentation at culverts, as well as to observe the efficiency of self-cleaning solutions implemented at several culvert sites. The methods and ancillary instruments along with the raw information collected during the monitoring activities are described below.

In-situ terrestrial synoptic surveys. The most comprehensive visual evidence of the sedimentation processes has been obtained with photo-documentation (see Figure 14). These surveys are most effective if they are conducted in early March and April (before the spring vegetation begins to grow) using a uniform experimental protocol illustrated in Figure 14a. The close-up images recorded at the sites provide detailed information about the sediment deposit layout, structure, and -- if continuously acquired over time -- they will give substantial information to understand the underlying mechanism for sedimentation patterns and their evolution. This is the only type of survey that provides critical information about the status and the effects of vegetation on the deposit formation.

a)



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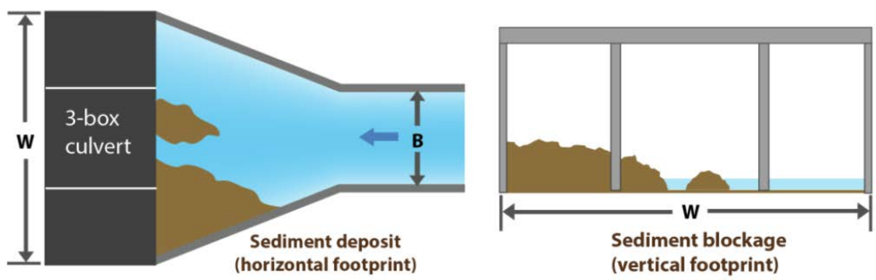


c)

Figure 14. Field measurement protocols: a) positioning of the photo camera during the photo survey; b) illustration of the measurement acquired for the degree of sedimentation blockage; and c) illustration of the photo-documentation acquired at the culvert site.

The main variables tracked through this survey are the stream-to-culvert width ratio (SCW), the areal degree of sedimentation, and the blockage at the culvert entrance (see Figure 14b for the schematic definitions). The degree of the sedimentation -- a critical parameter for the present study -- defines the ratio between the area occupied by sediment deposits at any given time and that of the original clearance between the inlet and outlet in relation to the natural stream at the time of the culvert construction. The degree of blockage is related to the reduction of the culvert's inlet cross section that, in turn, is directly related to its capacity to convey high flows. The outcomes of the terrestrial surveys include the following information (see Figures 14a and 14c):

- The degree of sedimentation at the culvert inlet (photo-documentation);
- The degree of blockage at the culvert entrance cross section (survey);
- Critical features characterizing relationships between the culvert and the associated stream, as well as specifications on sediment deposits (notes).

For sites where the quantitative estimation of the sedimentation was essential, an in-situ survey with Real Time Kinetic (RTK) GPS instrumentation was used (see Figure 15). The resultant survey of the sediment deposits allows to quantify efficiently both the degree of culvert sedimentation and the blockage at the culvert inlet and outlet. These indicators define the most important parameters of the functional relationship outlining the outcomes of the sedimentation process, hence their estimation and accuracy are critical. However, the in-situ deployment of the equipment and personnel for acquiring the needed RTK data is time and cost consuming, so only relatively few such surveys have been conducted. The role of the detailed RTK in-situ surveys was to compare or supplement the aerial photographs obtained, as described next.

a)

b)

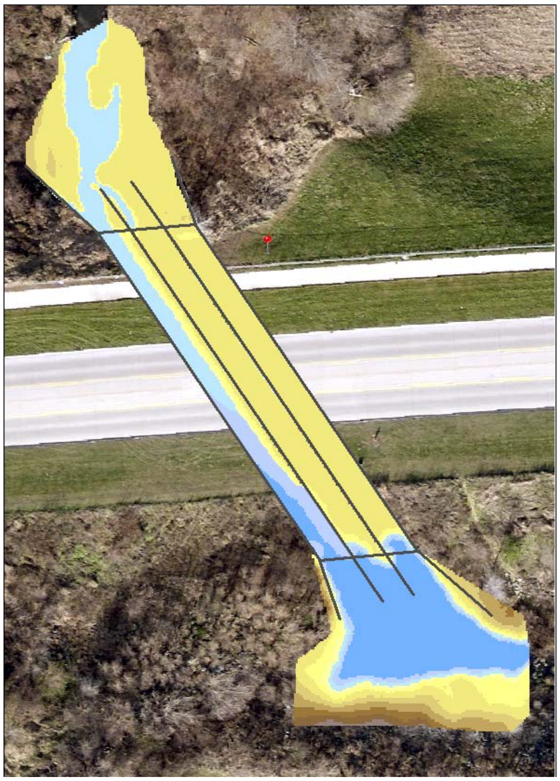


Figure 15. Three-dimensional mapping obtained with RTK at the Mormon Trek Blvd. on Clear Creek in Iowa City (FHWA #364790): a) RTK components; b) RTK mapping of the elevation in the vicinity of the culvert (the sediment deposits inside the culvert was mapped with staff gauges)

Aerial photograph & drone-based surveys. An efficient alternative to the in-situ surveys for estimating the degree of sedimentation is the processing of aerial photographs obtained from several data sources (see Figure 16a). In order to expedite the quantitative estimation of the degree of sedimentation at the visited culverts, a geo-processing tool has been developed that allows to map the contours of the sediment deposit directly on an aerial image (Xu, 2019). The outcomes of the on-screen measurements (i.e., segment lengths and polygon areas) are displayed in real time.

Drone-based surveys entail low-altitude flights with continuous image recordings followed by post-processing of the images using Structure from Motion (SFM) processing in conjunction with specialized photogrammetry software (Agisoft Photoscan Software). The software applies photogrammetric principles to the drone-acquired images to reconstruct the landscape as 3D digital photos or elevation maps. This modern type of survey has become increasingly popular due to its low cost and simple deployment. As most civil drones are equipped with digital cameras with continuously increased resolution and positioning accuracy, they have become reliable substitutes for aerial photo surveys. A sample drone-based survey obtained through a previous research project is illustrated in Figure 16b (Muste & Xu, 2017a) to fully demonstrate capabilities of the technique. Similar results for the FHWA # 364790 culvert investigated in this study will be presented in a subsequent section. Given the absence of sediment formation at the other culvert studies through the project (FHWA #031711), this type of survey was not engaged.

a)

2010 **2011** **2013**

b)

2016

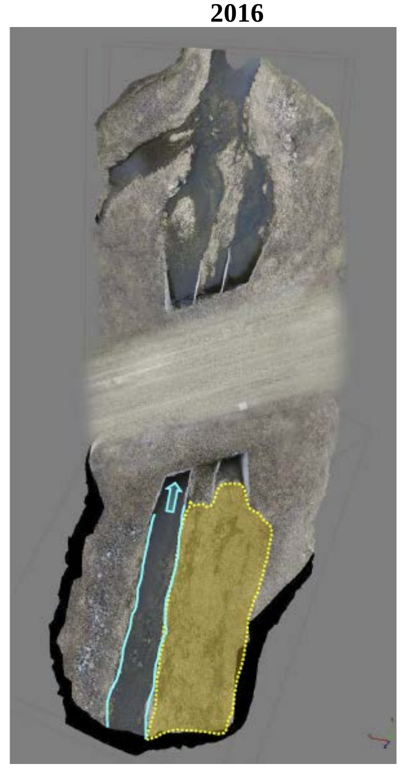


Figure 16. Illustration of rapid sedimentation at a 3-box culvert (FHWA #152811, on the Dibble Creek, Iowa). Following the culvert cleanup in 2010, the sediment deposit increased continously (first by lateral expansion, then by increased layer thickness): a) Aerial Imagery (with Bing, ESRI, and Google maps, respectively); b) IIHR-drone survey at the same site

Continuous monitoring methods. Following the implementation of the self-cleaning solutions initiated in Iowa in 2013, the culverts that were retrofitted (i.e., see Sites #1 and #3 in Figure 7a) have been continuously monitored for different purposes and with different methods. Figure 17 summarizes the methods and the outcomes for each type of monitoring.

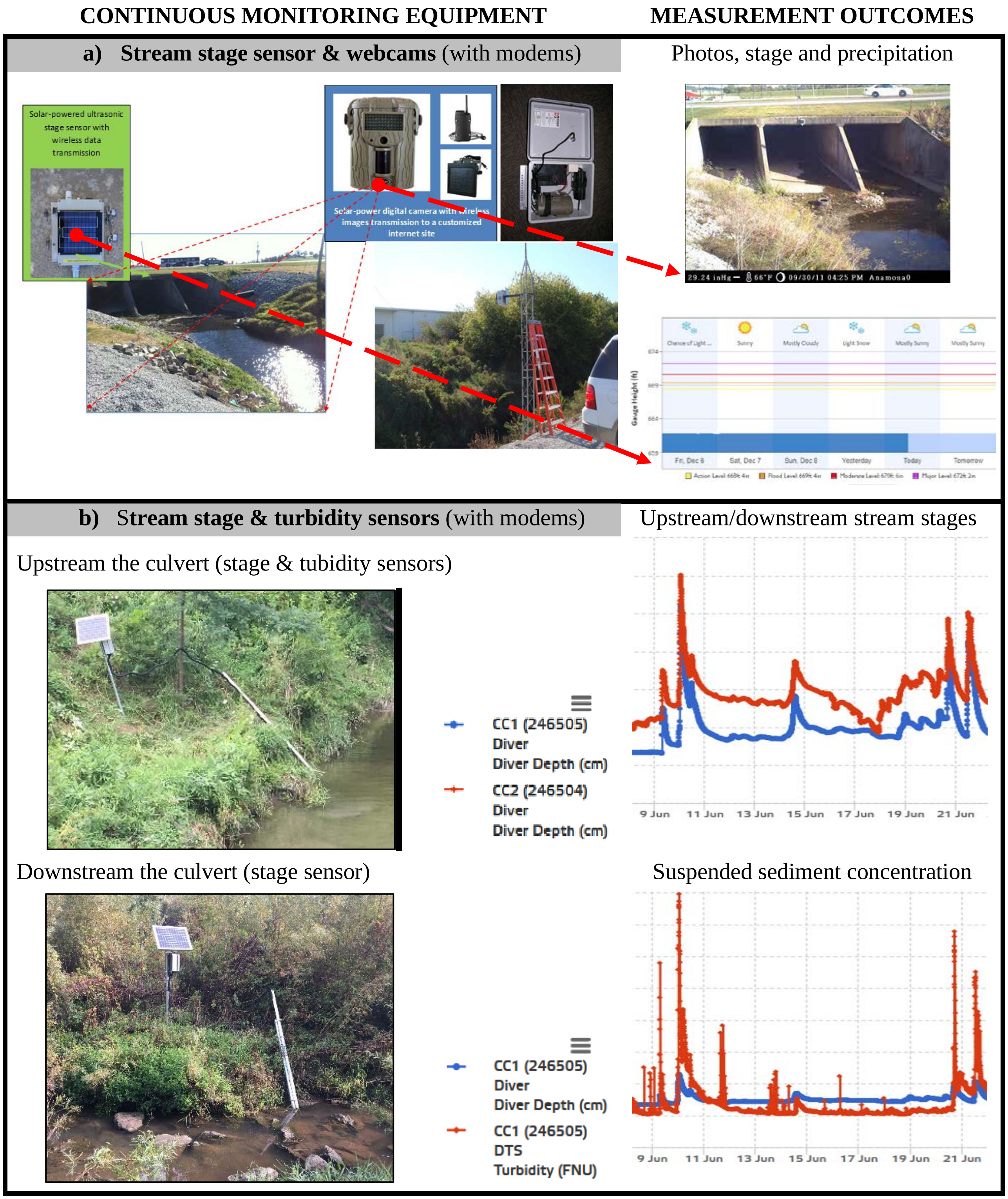


Figure 17. Deployment of continuous monitoring sensors for quantification of the hydrologic/hydraulic and morphological variables at the study sites: a) Hwy 1 on Clear Creek in Iowa City (FHWA #31711); b) Mormon Trek Blvd. on Clear Creek in Iowa City (FHWA #364790)

The overall goal of these monitoring activities was to document the effects of single and multiple storms propagating through the culvert, with special attention given to the impact on sedimentation on the culvert in various stages of project implementation, i.e., before or after retrofitting. Another important role of continuous monitoring is to observe the process as it evolves, for gaining a better understanding of how and where sedimentation occurs and progresses, as it is scaled over time: from an individual storm event level to a seasonal one (which is important for the understanding of the role vegetation growth plays) and eventually an annual one (that is used for design purposes). Lastly, the continuous monitoring has allowed us to observe the performance of the sediment mitigation measures in order to reveal possible corrections to their design.

3.2.3. Analysis and synthesis activities

Sedimentation process conceptualization. While the focus of this study has been to assess the performance of self-cleaning sediment mitigation solutions at culverts, the monitoring activities carried out during the projects have produced results that provide useful insights into the sedimentation as it occurs prior to retrofitting of the sites with mitigation designs. The description of the processes associated with culvert sedimentation in natural streams are outlined in Section 1.1 of this report. A major outcome of surveying the end-to-end chain of sediment transport phases is that sedimentation at culverts is not a local process, as it depends on a variety of regional geomorphological and hydrological conditions. Tracking the sediment dynamics as an end-to-end cycle includes the identification of the sedimentation sources in drainage basins and of the sediment transport pathways through watersheds and stream networks up to the location of the culvert (Xu, 2019). It is known that in absence of stream perturbations generated by hydraulic structures or by other natural factors, a stable channel is expected to balance erosion and sedimentation over time (i.e., the stream is in a perpetual self-cleaning regime). Similarly, culverts which are located on, and aligned with natural channels—unless they are heavily covered with vegetation-- are not expected to develop sedimentation problems, as illustrated in Figure 4.a.

The high degree of sedimentation encountered at the Iowa culverts requires a sound understanding of the sedimentation process as a whole and its manifestation on specific locations. An initial glimpse into the process can be obtained from observations made from third-party aerial photographs of the culvert sites acquired over longer time intervals (a decade or more). Aerial photographs are available for direct observations from freely-accessible digital repositories residing with various agencies (e.g., IDNR, USDA, Google, etc.). They are invaluable source of information from many respects. Appendix A assembles the historical appearance of four monitored culverts since their construction, as documented by annual aerial surveys that were conducted over the State of Iowa by EagleView (https://www.eagleview.com). The availability of these high-resolution images in digital format allows for not only general qualitative inferences, but also for more refined quantitative analyses that may be linked to morphological interpretation of the stream-structure interaction. One common feature of the historical records contained in Appendix A is the confirmation of a feature observed at many other culvert locations in Iowa: i.e., the formation of the sediment deposits takes place at a fast rate and stabilizes to a final form in about five years after the culvert construction.

The analysis of the results produced by the continuous in-situ monitoring applied to culvert FHWA # 364790 enables one to pinpoint details involved in the sedimentation processes. The organization of the analysis has to be built around the variables driving the process. A summary of these variables along with relevant data sources are provided in Table 2. Review of the literature indicates that the most important factor of all those involved in the sediment movement is the flow-sediment interaction within the culvert vicinity. Our previous work found that the most important local factors leading to sedimentation at culverts are the Stream-to-Culvert Width (SCW) ratio, the type of culvert flow control (i.e., inlet or outlet), and the stream geo-morphological and ecological aspects at culvert location (Ho, 2010). This section reviews various analyses undertaken through this study for improving the understanding of sedimentation processes.

Table 2. Hydro-geomorphologic variables driving accumulation of sediment at culverts

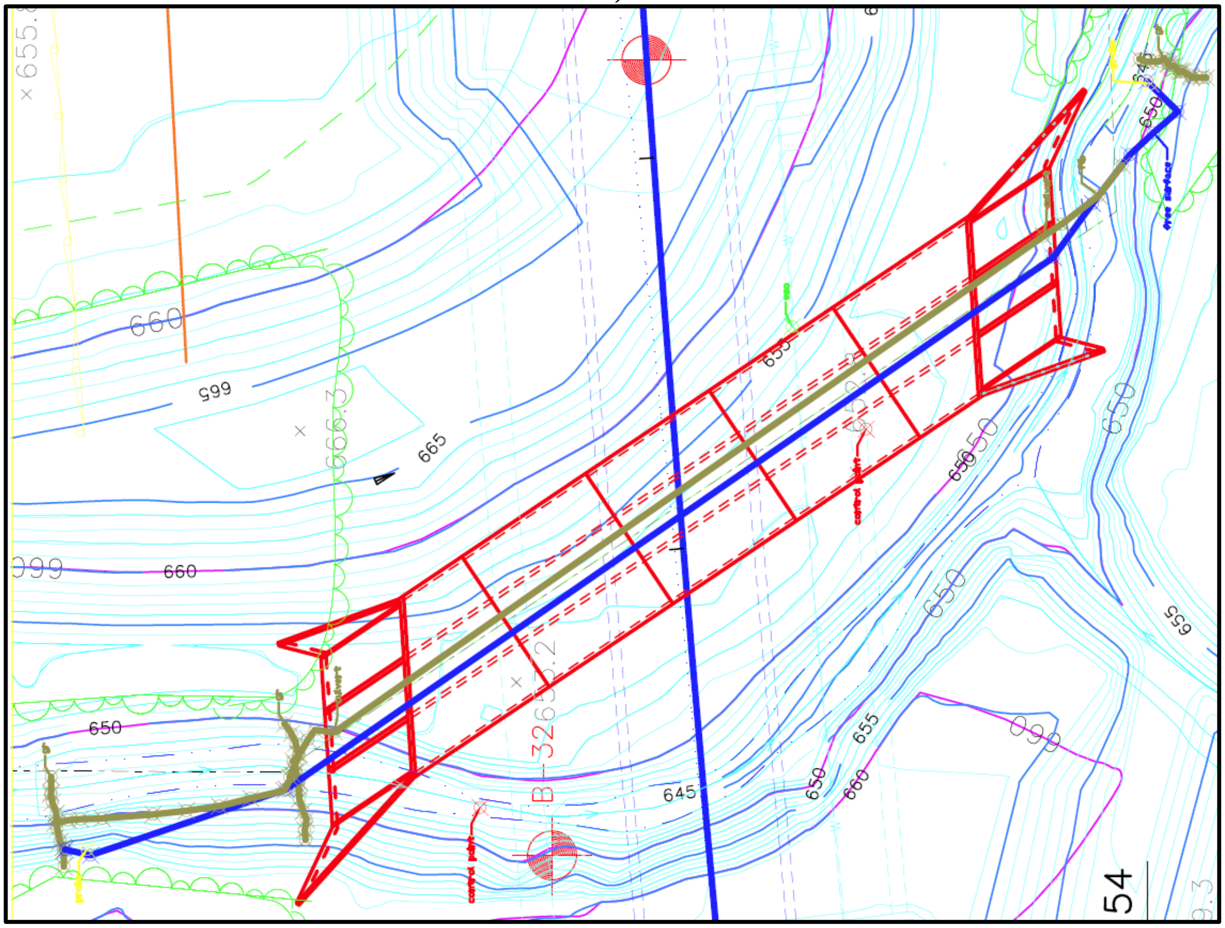
Parameter	Data source(s)
Stream-to-culvert width ratio	SIIMS, aerial imagery
Angle of stream incidence	Aerial imagery
Culvert flow controls	SIIMS (hydraulic design data)
Local geomorphology	Coring, local surveys, bed and free-surface flow slopes
Vegetation presence	Aerial and local imagery (acquired during vegetation growth)
Hydrologic regimes	Meteorological stations, USGS StreamStats, RUSLE
Upstream riparian corridor	SSURGO, NHDplus, StreamCAT

Local hydrologic-hydraulic and morphologic characterization. The characterization of the type of sediment accumulations with respect to geometry and structure requires local monitoring of the hydrologic/hydraulic variables passing through the site, as the movement of the water over the terrain and in the stream itself is the prime factor in sediment movement. In our study, we designed and deployed customized monitoring systems for this purpose. The system entailed data acquisition equipment for the following variables and visual information:

- stage at the culvert inlet and webcam images at culvert inlet and outlet for the FHWA #031711culvert site (see Figure 17a).
- stage and webcam images upstream and downstream the culvert, along with suspended sediment concentration (linked to direct measurements of the turbidity) sampled in the upstream area of the FHWA #364790 culvert site (see Figure 17b).

The morphological characterization for the FHWA #364790 culvert site was accomplished by a total station survey conducted by the City of Iowa City personnel prior to the downstream retrofitting which followed the deployment of the hydraulic observation system. Results of the topographic survey are shown in Figure 18. The survey of stage sensors deployed at the FHWA #364790 allowed for the estimation of the free-surface slope through the culvert area needed to quantify the degree of disturbance produced by the downstream weir in comparison with the stream geometry with just the culvert in place. A good configuration for any of the self-cleaning designs should not considerably change the energy losses through the retrofitted culvert in comparison to an as–constructed culvert. The change in the water level drop after the weir installation was less than one foot (specifically, between 1.3 ft to 0.45 ft), as illustrated in Figure 19a. The aforementioned local variables were complemented with precipitation records from a neighboring weather station located within the airport, along with local turbidity measurements (see Figure 19b). The quantitative and qualitative observations made on the development of the sediment deposits may be subsequently corroborated with measurements of water stages and slopes, along with those of precipitations during each storm. Rates of suspended sediments could be obtained from hydrologic variables coupled with sediment concentration measurements. This comprehensive characterization is helpful for assessing the relationship between sediment deposition rates and the factors driving flow and sedimentation processes at the culvert site.

a)



b)

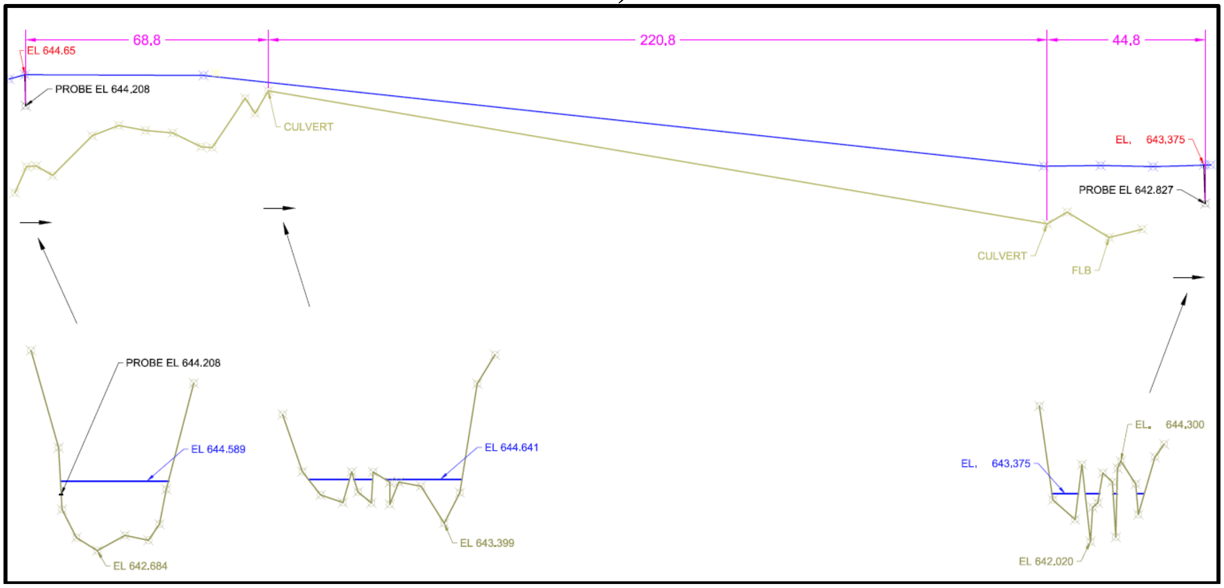


Figure 18. Topographic survey for the FHWA #364790 culvert site: a) plan view, b) cross section

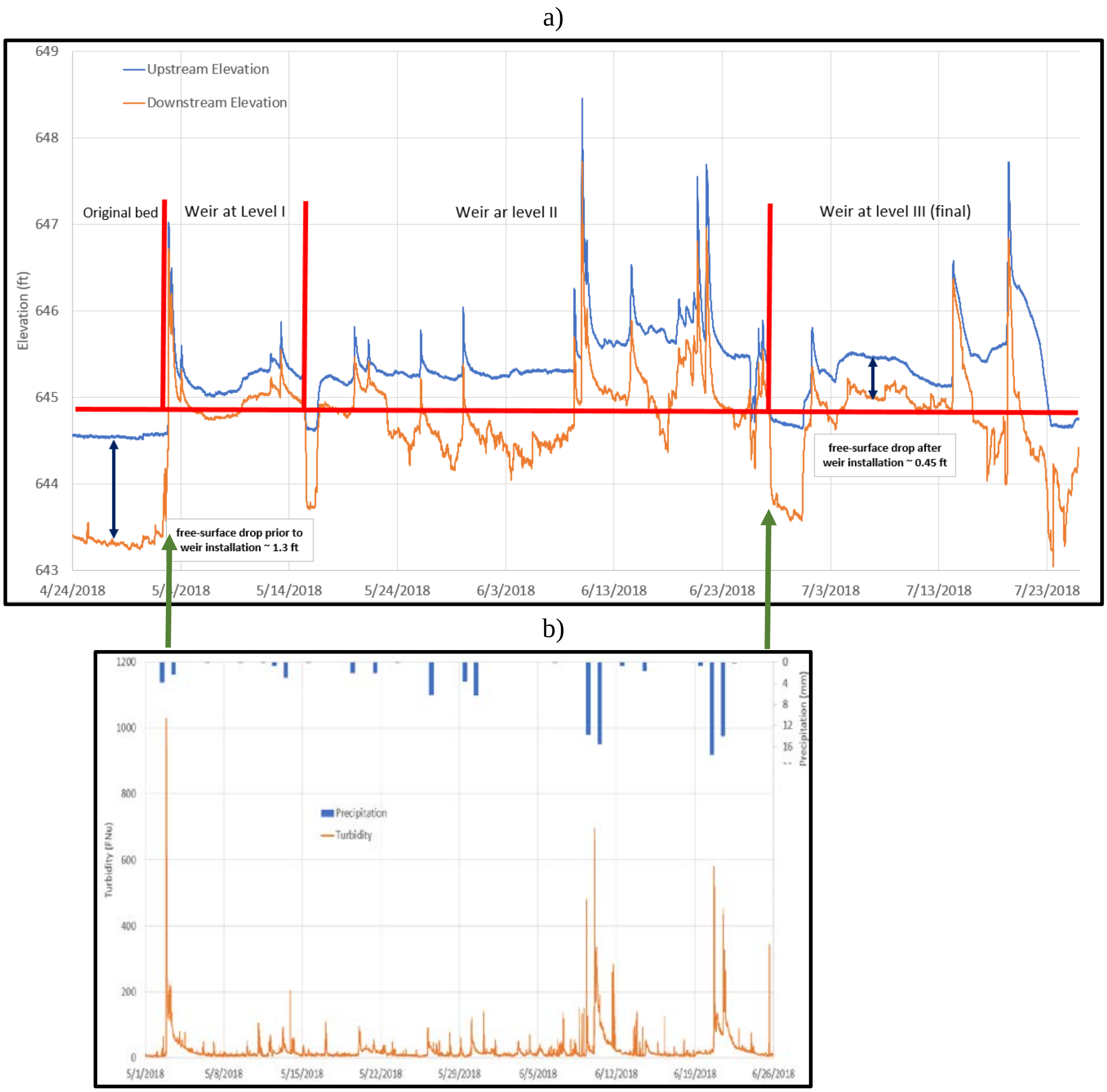


Figure 19. Hydrologic/hydraulic variables along with turbidity measurements acquired at the FHWA #364790 culvert site: a) water surface stage variation during downstream weir construction; b) precipitation measurements and turbidity sampled upstream the culvert. Note: the two plots were scaled to cover the same time interval for allowing inferences.

The aforementioned hydraulic measurements made possible associating the qualitative visual information of the flow through the culvert with direct stage measurements, as illustrated in Figure 20 for the FHWA #031711 site. The description of the dynamics of the suspended and bed load movement through the culvert exceeds the scope of the present study. However, in order to highlight the potential value of the complementary measurements of water hydrodynamics to sediment transport for evaluating the performance of culvert operations (with or without retrofitting installations), we illustrate the measurements of local variables recorded for the FHWA #364790 culvert site in Figure 21.

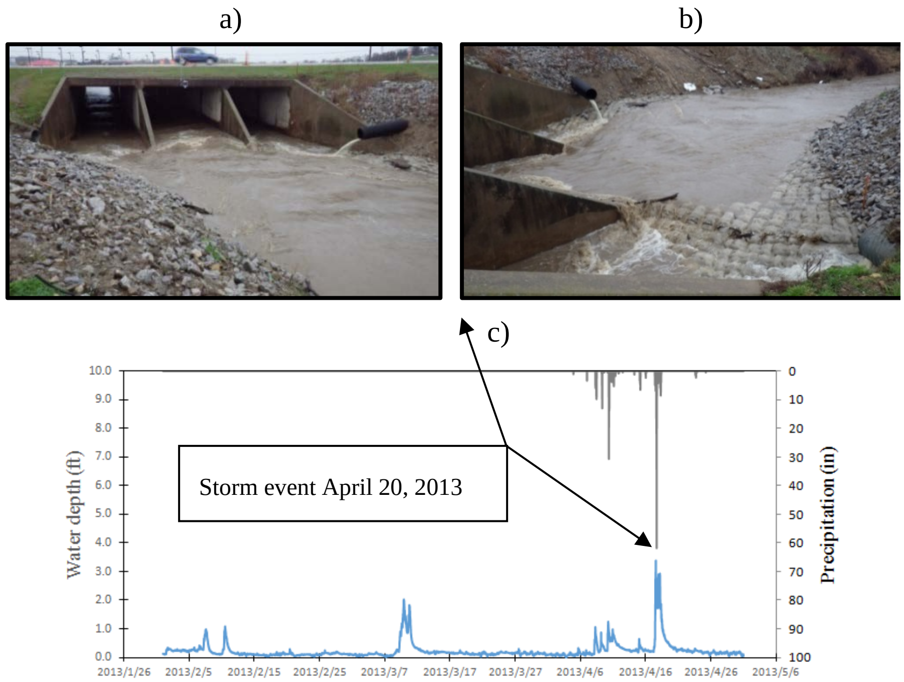


Figure 20. Documentation of the culvert performance during a storm event at FHWA #031711: a) and b) views of the flow through culvert during a storm; c) precipitation and stage hydrograph at the culvert location for the same storm.

Notes:

1) the stream stage is measured with the IFC stream gage sensor shown in Figure 15a.
2) the comparison is extracted from a prior study as during the current one the stage sensor was removed due to construction work in the culvert area.

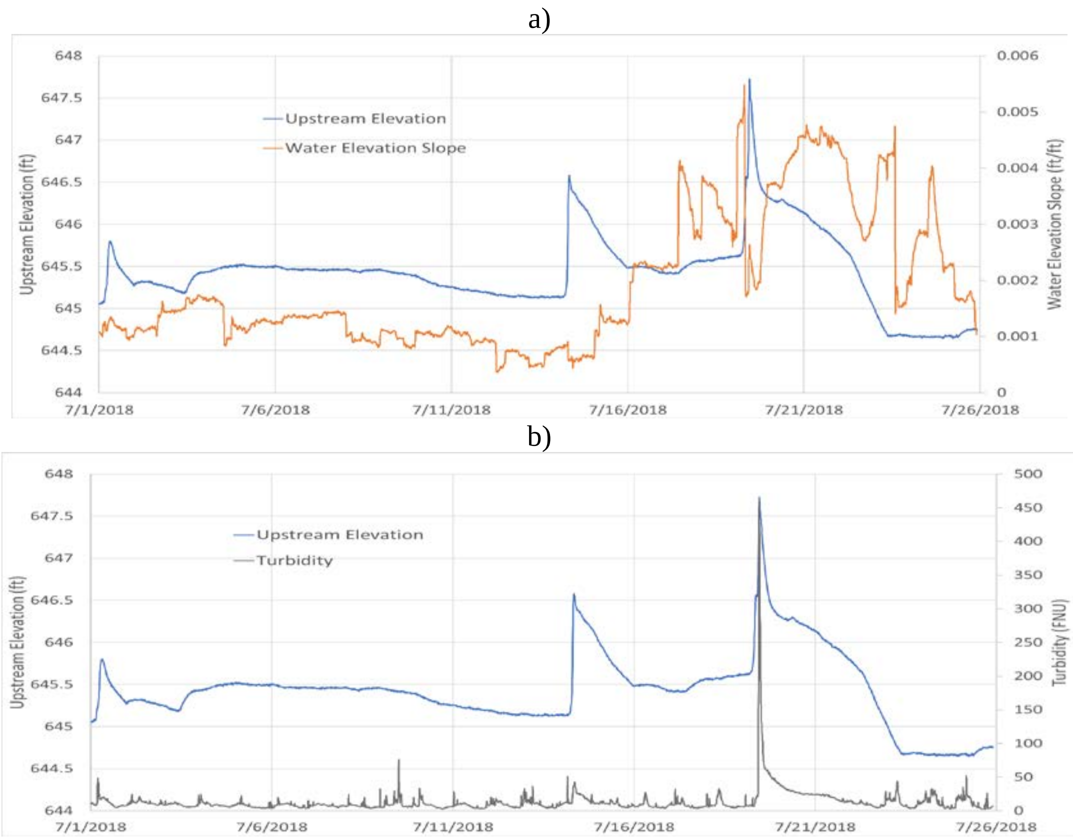


Figure 21. Recordings of water stages and turbidity at the retrofitted culvert for FHWA #364790 site: a) upstream stage and free-surface slope, b) stage and turbidity recording at the inlet of the culvert

A complementary monitoring activity for local hydrologic-hydraulic and morphologic characterization was accomplished by the continuous image acquisition with webcameras. Figure 22 provides sample images at the two retrofitted sites, acquired with the Moultrie real-time communication web-cam systems, as illustrated in Figure 17a. Regrettably, webcams are, however, not fully reliable and we have had numerous downtimes during project monitoring. Thanks to the proximity of the sites, we have been able to visit them after each storm in order to document the situation photographically. Over the 2.5 years while the project lasted, we checked the two sites 97 times. Visits were made regardless of the webcams' status in order to ensure good records of the project's evolution.

a) **FHWA #031711 culvert site**

Upstream webcam

Downstream webcam

b) **FHWA #364790 culvert site**

Upstream webcam

Downstream webcam

Figure 22. Snapshots provided by the pairs of webcams installed for each of the study sites.

Qualitative sediment deposit mapping and surface-structure analysis. The quantitative investigation of the deposit growth was guided by a continuous photo documentation of the sites. This was especially important for the FHWA #364790 culvert site that has not be subjected to any prior investigations. The documentation of the sediment growth was made through multiple visits using the photo-documentation protocol described in Figure 14. The inspection of the underwater sediment deposit formation was facilitated by a vane set on a pipe segment, as illustrated in Figures 23a, and 23b. The pipe segment was embedded in the downstream weir (see Figures 23c and 23d). By opening the valve, the pool created by the weir could be drained whenever a special site inspection was needed (i.e., after large storm events, at the beginning and the end of the seasons, for fixing the leaks at the weir). This arrangement enabled a good illustration of the growth of the underwater sediment deposits in the upstream area of the culvert providing a good understanding of the hydrodynamic processes and of the nature of the materials in the deposits.

a) b)

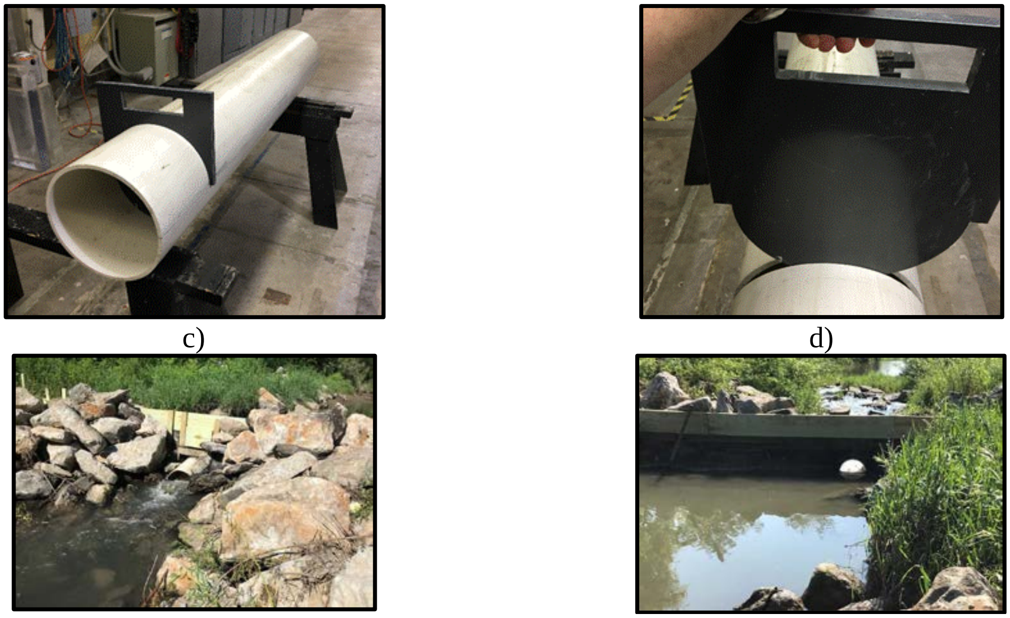


Figure 23. Draining pipe set in the downstream weir at the FHWA #364790: a, b) views of the pipe segment and vane, c, d) downstream and upstream views of the pipe segment during draining.

Field inspections carried out at 257 culverts located on Iowa streams (Muste and Xu, 2017a) revealed that most of the sediment deposits developed at culverts are made of fine sediments delivered as the suspended load. The preferential location of the depositional areas coincides with the location of the area of flow recirculation in the culvert vicinity, as illustrated in Figure 24. Analysis of the soils obtained by coring support these statements (Ho et al., 2013). These deposits develop quickly, sometimes within the yearly hydro-meteorological cycle. Carey (2006) also confirms that the suspended sediments, made of fine and colloidal particles, are major causes of siltation at fence lines, waterways, and road culverts. Figure 25 illustrates the gradual buildup of the underwater sediment deposits during the lifetime of the monitoring program.

a) b)

Figure 24. Preferential sedimentation of the sediment transport in the upstream area of the FHWA #364790 culvert during the first 12 months of culvert operation from the total cleanup: a) culvert after cleanup in February, 2018; b) sediment deposits in October, 2018. Yellow arrow: streamflow dominant direction; dotted white line: culvert orientation.

a) 2 months after weir installation (June 15, 2018)

b) 7 months after weir installation (November 8, 2018)

c) 12 months after weir installation (April, 1, 2019)

Figure continued

d) 18 months after the weir installation (July 26, 2019)

e) 24 months after the weir installation December 1, 2019) and 4 months after weir removal.

Figure 25. Development of the underwater sediment deposits in the upstream area of FHWA #364790 culvert site over the period of study. Note: the draining pipe shown in Figures 23 was used to empty the pooled area. The culvert downstream area is not shown as it remained submersed after pipe opening.

Another important capability of the close-up photos was to document the growth of vegetation that is another important factor in the sediment deposit formation and stabilization. The assumption that sediment in the stream deposit in normal flow conditions and then is flushed out during storm events prevails, despite that there is few evidence for this process. The statement can be valid for areas where the material in the deposits consists of coarse sediments without considerable fine soil fraction. For situations where the deposits consists of mostly fine fraction of fertile soil, the vegetation plays an important role in accelerating the sediment retention. Such a situation is prevalent in the Iowa landscape where unstratified silt (i.e., loess) is a large portion of the deposition at culverts. For such situations, the vegetation is quickly developing on the sediment islands exposed to air (between storm events) especially that the storms occur mostly in spring during the optimum conditions for vegetation growth. Terrestrial vegetation finds a fertile ground and abundant moisture to develop even faster than in the uphill areas.

The fast pace of vegetation growth could be observed during the monitoring of the FHWA #364790 culvert site after the weir removal in August 2019. Figure 26 contains images recorded on the upstream deposits at this culvert illustrating well the vegetation growth despite that it was late summer when the images were taken. The grown vegetation act as a sediment attractor leading in short time the deposits that are reinforced by the vegetation roots. The increase of the island is however limited, as after a certain growth of their high they become less frequently covered by the storm flows. Prior observations on Iowa culverts led to the conclusion that the sediment deposits "stabilizes" in no more than five years.

1 week of exposure

2 weeks of exposure

3 weeks of exposure

Figure 26. Illustration of the fast pace of vegetation growth on sediment deposits exposed to air at culvert FHWA #31711 culvert site

Another illustrative example of the pace of vegetation growth is provided by an opportunistic situation occurred at FHWA #031711 culvert site during the previous retrofitting of the upstream area. Specifically, during the installation of the ABM in the upstream area of the culvert (December, 2013), the contractor miss positioned one of the ABM mats on the left side of the culvert entrance, as illustrated in Figure 27a. This barely perceivable depression led in subsequent seasons to a sedimentation problem that could compromise the performance of the entire retrofitting structure. Specifically, this depression developed in time a "patch" of vegetation that continue to growth even if the layer of the soil had no communication with the stream bed as the sediment island was sitting on the top of the mat. The abundant water and sediment supply provided by the stream during normal and higher flows led to a continuous development of the island as shown in Figures 27 b, c, d. e, and f. The area was retrofitted to this project and, similarly to the right fillet area, did not show favorable conditions for vegetation development during the current monitoring phase.

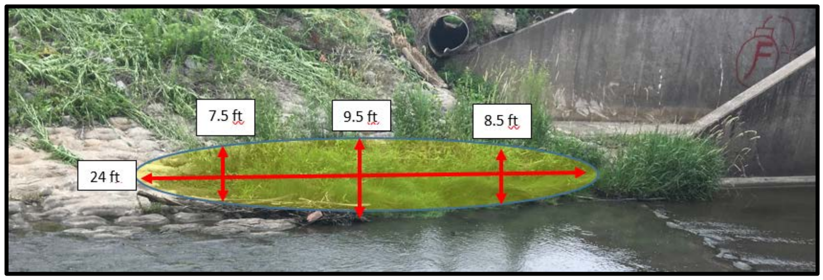
a) May, 2014

b) November, 2014

c) May, 2015

d) June 2016

e) June, 2017



f) Septembe5, 2018

Figure 27. Illustration of the fast pace of vegetation growth on sediment deposits exposed to air at culvert FHWA #364790 culvert site

Quantitative sediment deposit mapping and structure analysis. Complementary to the short-time qualitative monitoring associated with passing of individual storms, quantitative analyses applied to the periodic in-situ surveys offered by aerial photographs or drone surveys can offer useful information on the sedimentation evolution over seasonal or annual scales. The power of this analysis is self-evident in the series of photos taken in successive years for the culverts in the study area, as illustrated in Appendix A. These images can be explored quantitatively to inform on the patterns of sediment development, rates of evolution over time, and formulation of the correlations between stream geometry, culvert geometry and the nature of the drainage area upstream from the culvert site using, for example, the IDOT Culverts web-platform developed by the authors through a previous study (Demir et al., 2019). A more precise quantification of the extent of sediment deposits can be obtained from local drone surveys. The drone surveys carried out after culvert retrofitting are illustrated in Figures 28a and 28c along with the other culverts in the study area.

UPSTREAM DOWNSTREAM

a) b)

Figure continued

g) h)

Figure 28. Drone surveys of the culverts monitored through the present study (see Figure 7a for locating the culverts on the map): a) and b) upstream and downstream areas of FHWA #31711 culvert Site #1 (Design A), respectively; c) and d) upstream and downstream areas of the 3-box culvert Site #2 (reference), respectively; e) and f) upstream and downstream areas of FHWA #364790 culvert Site #3 (Design C); and g) and h) upstream and downstream areas of the 3-box culvert Site #4 (Design B).

The photo documentation carried out with drone-based surveys can be subsequently processed in conjunction with image processing software to provide the three-dimensional (3-D) characterization of the areas of interest. This contemporary type of digital elevation survey is increasingly popular due to its low cost and simple deployment. As most civil drones are equipped with digital cameras (with continuously increased resolution and positioning accuracy), they become reliable substitutes for aerial photo surveys. The sequence of steps leading to 3-D quantitative maps entails the following steps (see also Figure 29):

- Acquire an extensive set of drone images by hovering over the area of interest such that each acquired image to overlap with the neighboring one with a prescribed ratio (see Figures 29a and 29b)
- Assemble the acquired images with a specialized software (i.e., Structure from Motion – SFM) to obtained a digital coverage of the whole area of interest (as illustrated in Figure 29b and 29c).
- Transfer the SFM digital images to another specialized photogrammetric software (Agisoft was used for our study). Using the optical characteristics of the camera and the drone altitude of the drone (recorded by the navigation software) the software carries several steps to create the ortho-rectified images of the site.

The drone surveys are most efficient if conducted during dormant vegetation time and in conjunction with ground surveys collected with Real Time Kinetic (RTK) GPS instrumentation. The such-obtained 3-D maps allow to efficiently quantify both the degree of culvert sedimentation (defined as the area of the original inlet and outlet clearance occupied by sediment deposits) and the blockage at the culvert inlet and outlet. These indicators define the most important parameters of the investigated functional relationship, hence their accuracy is critical. However, the in-situ deployment of the equipment and personnel for acquiring the needed data is time and cost extensive, so only a limited number of such surveys have been conducted. The role of the in-situ surveys was to compare the sediment deposits growth over the season, as described next.

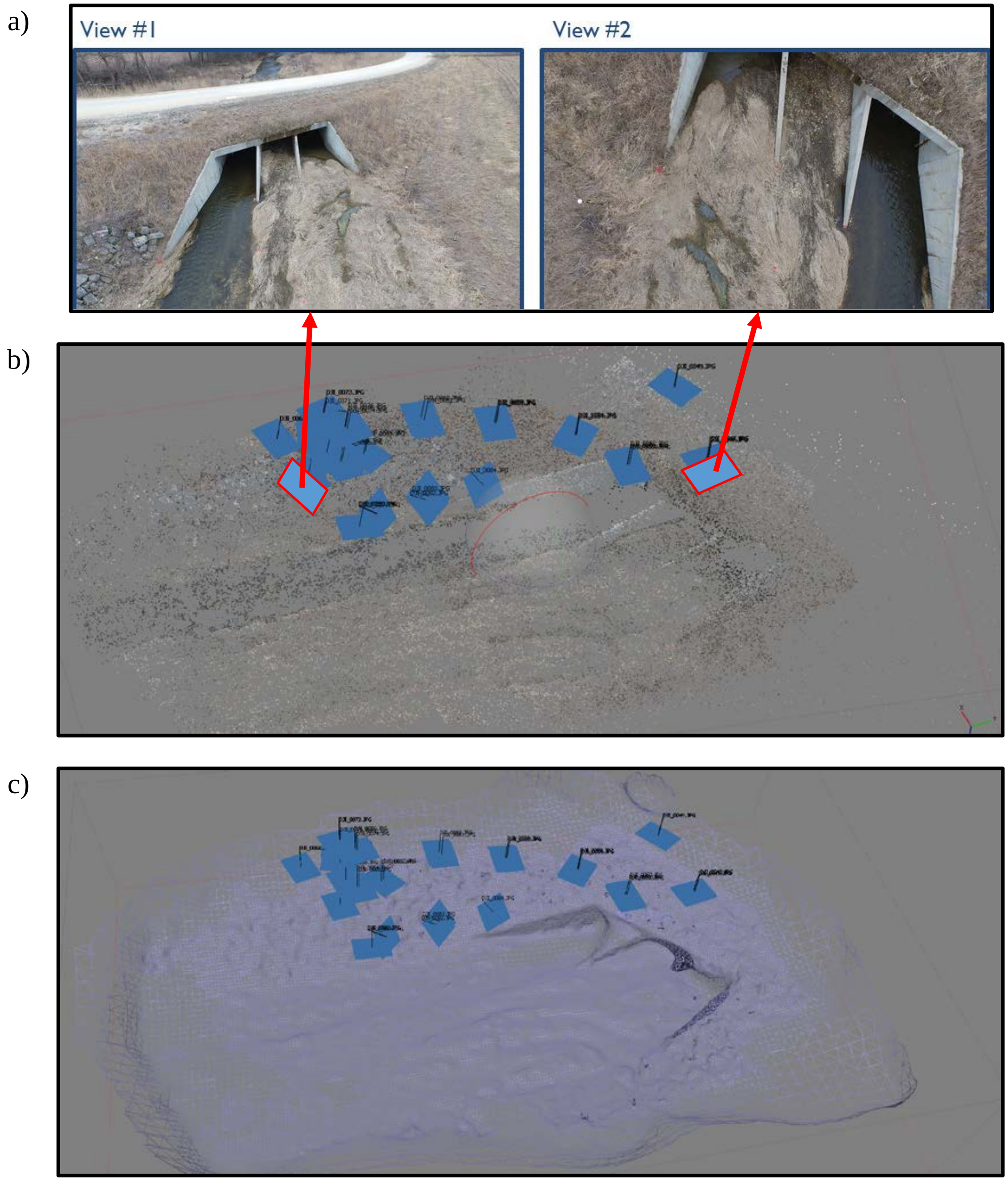


Figure 29. Image reconstruction using Structure From Motion software (Muste & Xu, 2017a): a) drone images; b) image stitching using tie points; and c) addition of the terrain texture.

During the project duration, we executed four photogrammetric surveys: a pair of surveys were made before and after cleanup and the other two were conducted at the end of each monitoring year. The such-obtained digital maps are shown in Figure 30. The quantitative nature of these surveys allowed to estimate the sediment deposit growth. The numerical values of the volumes for the digital elevations mapped in Figure 30 are listed in Table 3.

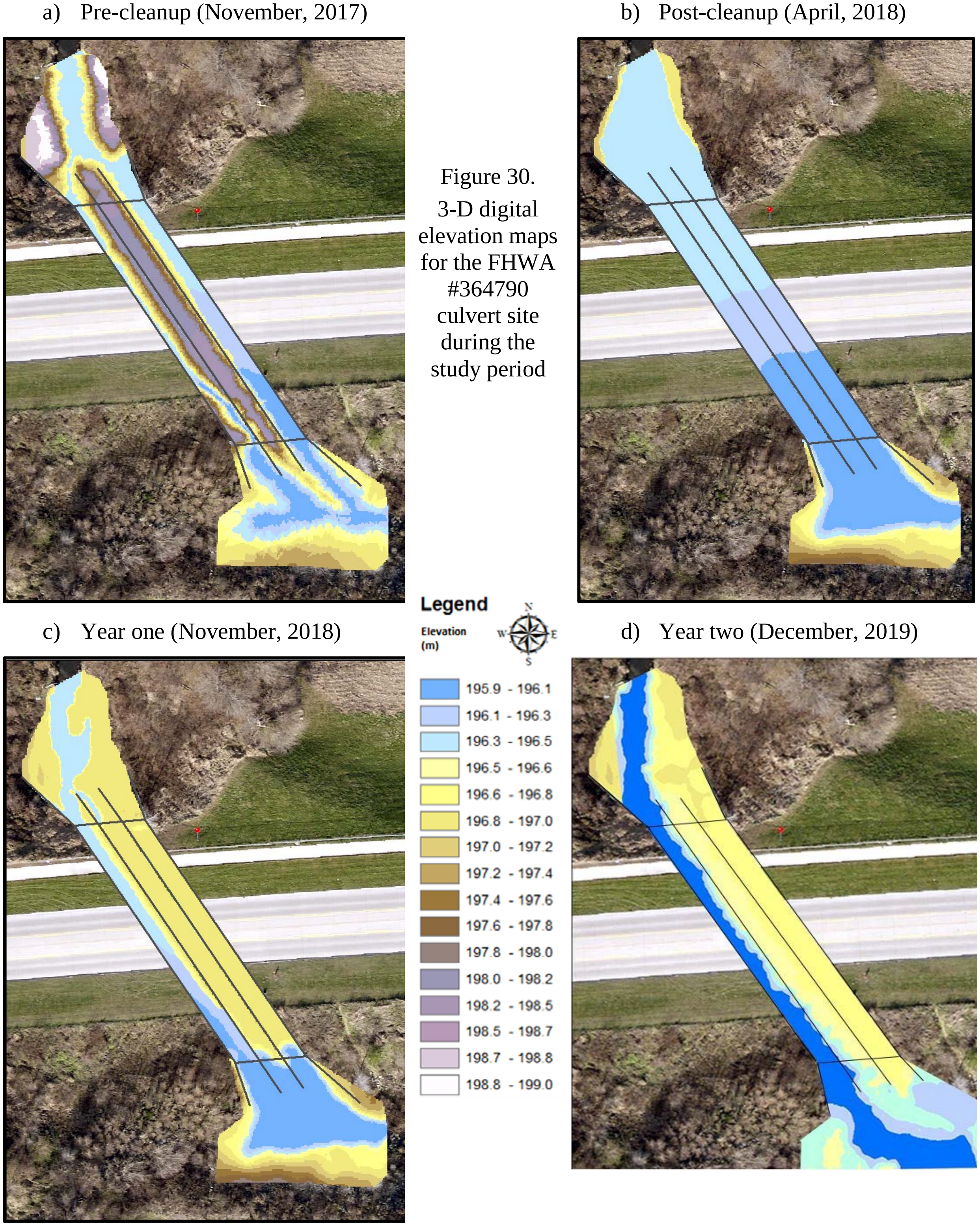
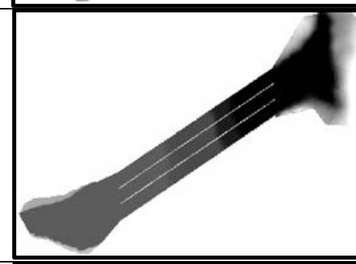
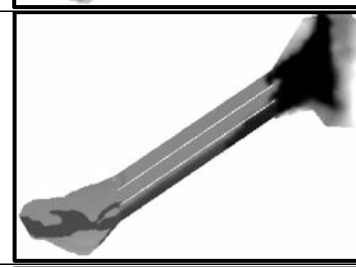


Figure 30. 3-D digital elevation maps for the FHWA #364790 culvert site during the study period

Table 3. Quantitative assessment of the sediment deposits at FHWA #364790 culvert site

	Sediment volume (m^3)	Sediment area (m^2)	Visual display
Pre-cleanup (November, 2017)	972	1721	
Post-cleanup (April, 2018)	0	0	
Post-cleanup 1st year (November, 2018)	183	1566	
Post-cleanup 2nd year (December, 2019)	386	1598	

Finally, another important analysis for understanding of the sedimentation process or evaluating the effectiveness of a mitigation solutions is the investigation of the sediment deposits formed at the culvert. Of interest in this analysis is both content and stratification in the deposits. For this purpose we sampled cores from representative areas of the deposits (i.e., upstream, downstream, inside and outside the channel, and within the covered area by culvert). The cores were analyzed for capturing the layering in the deposits and to estimate the particle size distribution in the samples. The analysis of the coring data for the FHWA #364790 culvert site prior to cleanup (November, 2017) is provided in Figure 31. As expected, the cores visualized in Figure 31b reveal that most of the sediment in the deposit is of the silty-loam nature and that there is are alternating layers through the culvert length that requires more detailed analysis to lead to robust conclusions. This layering was observed in the coring analysis conducted after one year of retrofitting and was related to the passage of coarse materials carried in the culvert during extreme storm events.

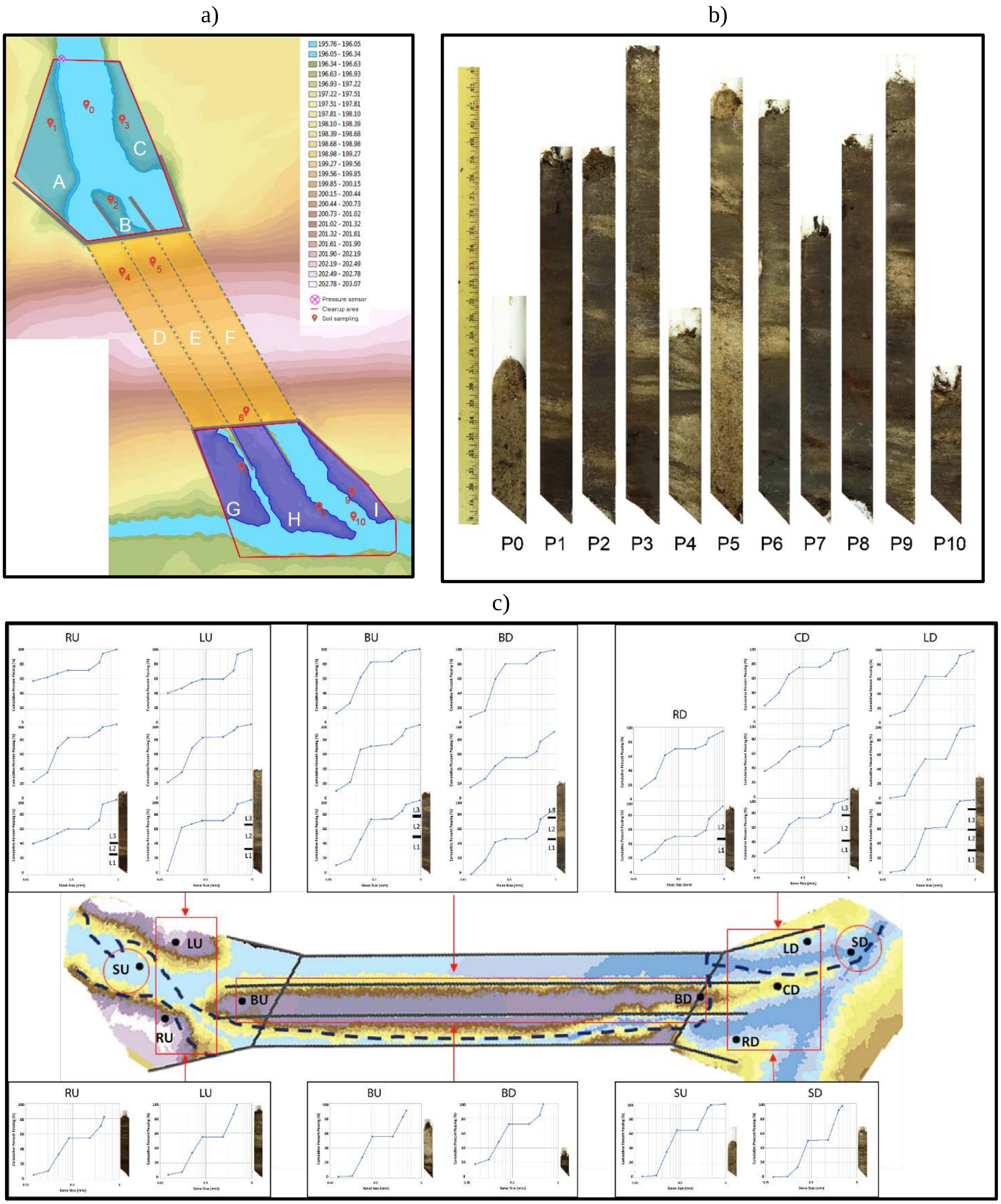


Figure 31. Analysis of the soil cores collected at the FHWA #364790 culvert site prior to retrofitting (original sediment deposits): a) coring locations, b) view of the of the cores, c) synthetic view of the coring analysis including sediment granulometry analysis

4. Research Outcomes

Given that the in-situ investigations of sediment deposition at multi-barrel culverts is an area that is scarcely covered by information in the specialized literature, design standards and specifications, or research literature, the present study employed a variety of exploratory methods and analysis. The research tools proposed for this study allow to infer useful correlations between variables describing the culvert-stream-drainage area triplet that are difficult to be captured and understood using analytical or laboratory studies. The tools could also uniquely serve the strategy for monitoring the mitigation structures after their deployment. The combination of the short- and long-term monitoring during the pre- and post-construction phases of the culvert retrofitting investigated through this study reveals that the self-cleaning Designs A performs very well. Design C is performing relatively well in line with the original expectations, i.e., with sedimentation rates considerably decreased. The main outcomes of the study are summarized below.

Design A: fillet-based solution. Designs A has been fully investigated through laboratory and numerical studies as well as with in-situ monitoring programs. The fundamental principle for this type of mitigation solution has been described though several previous studies and published papers (e.g., Muste and Xu, 2017a; Muste and Xu, 2017b). Design A was applied only in the upstream area of the FHWA #31711 in 2013 and was maintained under observations since then (Muste and Xu, 2017a). The final retrofitting was finalized in 2019. The outcomes of all these studies converge to the conclusion that this solution is highly efficient by completely eliminating the sedimentation in the culvert area. The photographic and field observations collected after full retrofitting of the culvert show no signs of sediment deposition inception in the vicinity of the culvert at any time of the extensive monitoring conducted period conducted at this site. Practically, following more than 7 years of observations of this culvert there were no signs of any deposition in the areas previously covered by sediment and vegetation. From hydraulic perspectives, the retrofitting seems to not influence the culvert conveyance capacity for any flow situation or across seasons, as illustrated in Figure 32.

The current study shows that the articulating block mat (ABM) layer provides a good protection against vegetation growth such that the covered area is free of vegetation up to now. However, during the retrofitting carried out through this study, a series of shortcomings for this type of fillet revetments were noted. Specifically, the use of ABM mats are not recommended as first choice for revetment on low slopes such as is the case for FHWA #31711 culvert site as the texture of their surface increase the stream bed shear. This is a direct result of the “pillow-like” finish of the ABM mats that are not avoidable due to the design of the mat geometry. Moreover, the uneven ABM surface inherently creates small pockets that are prone to sediment retention. Furthermore, if a larger area revetment area is improperly positioned (as described in Figure 27) they favor development of soil islands that are quickly growing. For low-slope revetments, the use of a thin layer of concrete applied to grouted rip-rap substrate is recommended instead. ABMs are highly recommended only for revetments applied on high slopes.

Another important finding observed through this study is related to the design of long culverts. It was observed that given the low slope of the culvert invert at FHWA #31711 site, the deposition of the sediment occurs at the lower end of the culvert barrels due to the friction losses developing along the culvert length. For long culverts it is recommended that the fillets placed at the culvert outlet to be set lower than elevation of the culvert invert in that area. This arrangement will avoid creation of backflow that will further increase sedimentation in the culvert barrels.

UPSTREAM DOWNSTREAM

a) b)

c) d)

Figure 32. Design A at FHWA #31711 culvert site: a), b) during normal flow; c), d) during storm

Design C: downstream weir. This design was implemented by the construction of a low-head weir downstream of the FHWA #364790 culvert site. It should be noted that this solution was inspired by the clean appearance of a few 3-barrel culverts visited throughout Iowa, as shown in Figure 4a. The views of the retrofitted culvert shown in Figures 28e and 28f provide a striking resemblance with the view of the clean culverts observed in the previous study. While the latter culvert sites have not been investigated for the status of the submersed sediment deposits, it is assumed herein that the sedimentation layers are similar to those reported in Figure 25. The plots in this figure show that the path of the flow and sediment are following a natural (i.e., streamlined) course whereby the sediment deposits are initiated in the side areas of the expansion and contraction toward the culvert where the water velocities are lower. The deposits continue to grow in elevation on the initial footprint.

Over time, an "equilibrium" is expected to be reached between the bed morphology and the flow hydrodynamics that is favorable to both flow events of various magnitudes and for conveying a large amount of suspended sediment downstream. This state of "equilibrium" is also suggested by the photogrammetric mapping illustrated in Figure 30 and Table 3. These quantitative estimations suggest that there has been no significant development of the lateral extent of the sediment deposits following the initial sedimentation phase. While the footprint of the deposits was maintained practically constant over the first two years of monitoring at this culvert, there has been only a slight increase in the height of the deposits. This increase in sediment deposits is not necessarily detrimental to the flow passage, as long as the sediment islands remain submersed so as to preclude the development of vegetation atop of them. Overall, it can be concluded that while the sediment deposits have developed quite considerably over the two years of monitoring, the pace of the sedimentation growth was considerably reduced. Streamflow conveyance through the culvert for various flow stages was constantly satisfactory as illustrated in Figure 33.

A notable feature of the sedimentation pattern during this study is the fact that the sediment deposition does occur in the left and central barrels, as illustrated in Figure 30d. This pattern is consistent with the “natural” course of the flow through a bend, as flow velocities in the outer bend area are typically higher, preventing the deposition of sediments. An identical flow pattern was also observed in the historical photographs of this site in the first years after the culvert construction (see Appendix A). However, 3 years after the culvert construction, a massive accumulation of debris blocked the flow passage through the right barrel and the flow was diverted toward the left barrel. From this moment onwards, the flow through the right and central barrels was slowed down, leading to sedimentation on the right side of the culvert behind the debris curtain. In time, the sediment deposited in these barrels became “fossilized,” forcing the stream to choose the left barrel as a free way. The culvert was found in this status prior to its 2017 retrofitting (as illustrated in Figure 30a).

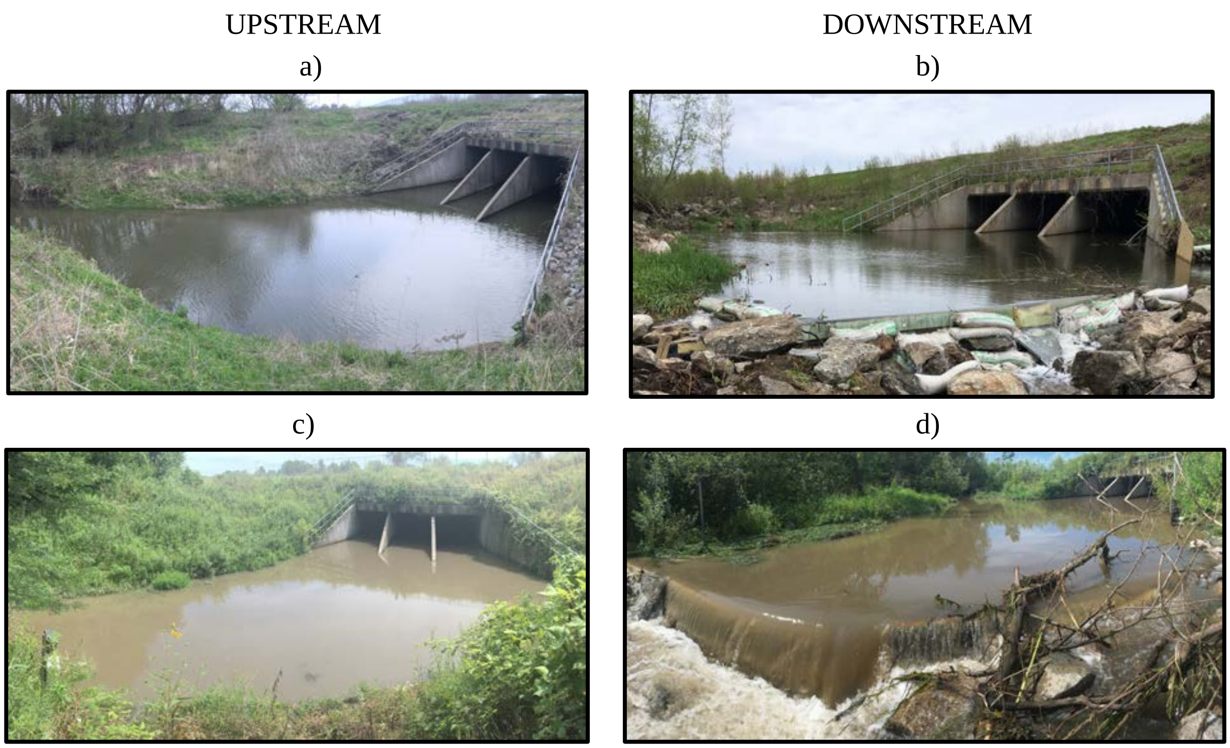


Figure 33. Design C at FHWA #364790 culvert site: a) , b) during normal flow; c), d) during storm

In closing, it is imperative to mention that the outcomes of this study should be regarded as indicative rather than confirmative as there are at least two cautionary notes to mention:

- The present conclusions are based on the analysis of a limited datasets from observations on retrofitted culverts located in geomorphological and hydraulic conditions specific to Iowa landscape.
- The observation period for both solutions was relatively short (i.e., 7 years for FHWA #31711 culvert site and 2 years for FHWA #364790 culvert site)., as compared to the lifetime of the culvert structures

Finally, we share below a set of practical recommendations for culvert design that stem from the knowledge accumulated from the long-term series of studies in this area. They are meant to account for the sedimentation aspects that currently are not part of the culvert design. There are two notable features to mention upfront. First, it should be remembered that streams carry a sediment load that tends to deposit whenever/wherever their velocities decrease. Second, the sedimentation degree at culverts is dependent not only on the stream characteristics and culvert design specifications (orientation w.r.t to stream, width, slope, roughness, offsets – if applied), but also on the drainage area characteristics (i.e., magnitude of the design discharge, soil, land use and practices in the channel and watershed). Currently, the knowledge base for designing sedimentation mitigation measures is in its infancy, as the involved processes are difficult to anticipate, since they depend on multiple stream and watershed characteristics on top of culvert design specifications. The investigations conducted so far corroborated by similar (however, few) studies lead to the following practical considerations:

- Cautiously approach the culvert design with a thorough knowledge of stream flow regime (i.e., high & low flows) and bed-bank and watershed characteristics (sedimentation will likely occur at low flow while culvert sizing is based on high flows, leading to a tendency of oversizing).
- Align the culvert with the direction of the upstream channel (oblique stream entering the culvert affects sedimentation processes, regardless of its type: scouring or deposition)
- Setting the culvert width to less or equal size as that of the channel bankfull width is not expected to inhibit sedimentation at culvert.
- Erosion and sedimentation do not balance over time at culverts located in Iowa streams, even if the channel outside the culvert area is stable (i.e., increased velocities during storm events do not cleanse culverts)
- Sedimentation is initiated and dominant in the upstream culvert area. Therefore, the focus should be on mitigating this area first.
- Vegetation plays a critical role in sedimentation (i.e., as flows recede, vegetation starts growing which leads to increased roughness and consequently enhance sedimentation during the next flood event).
- While solving the hydraulics and sedimentation problems, one should not overlook environmental aspects (i.e., maintaining the natural-stream capabilities to pass fish and other aquatic organisms).
- Sediment mitigation designs introduce additional head losses (checks should be in place during design to verify if damaging backwater levels upstream the culvert are not formed by the implementation of sediment mitigation solutions).
- Recent advancement in construction technology, including 3-D concrete printing, offer good reasons to reconsider culvert design approaches from the bottom.

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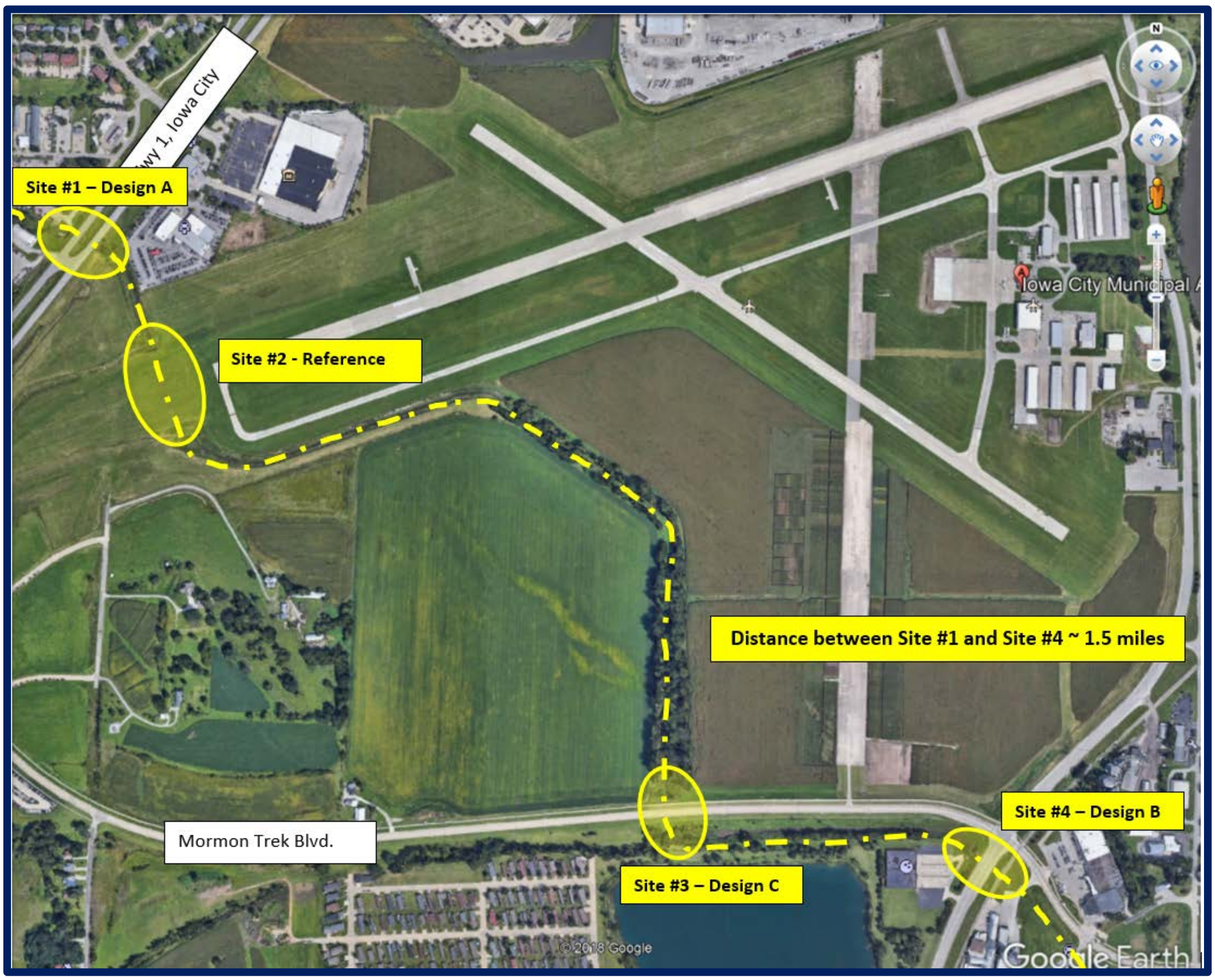
Appendix A

Chronological evolution of the investigated culvert sites (see also Figure 7a).



FHWA #31711, Site #1

41.640250771846326, -91.56038045883179

2007 Nov

2008 June

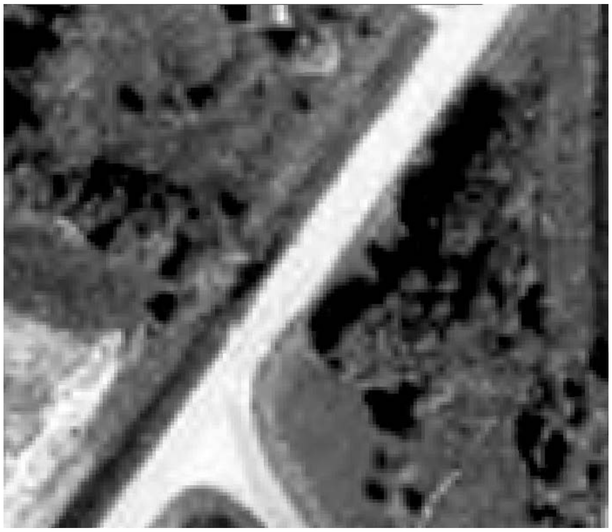
2009 Mar

Apr 2011

Dec 2012

Nov 2017

1970s



1990s

2003

2006

2011

2011 after cleaning

2013

2013

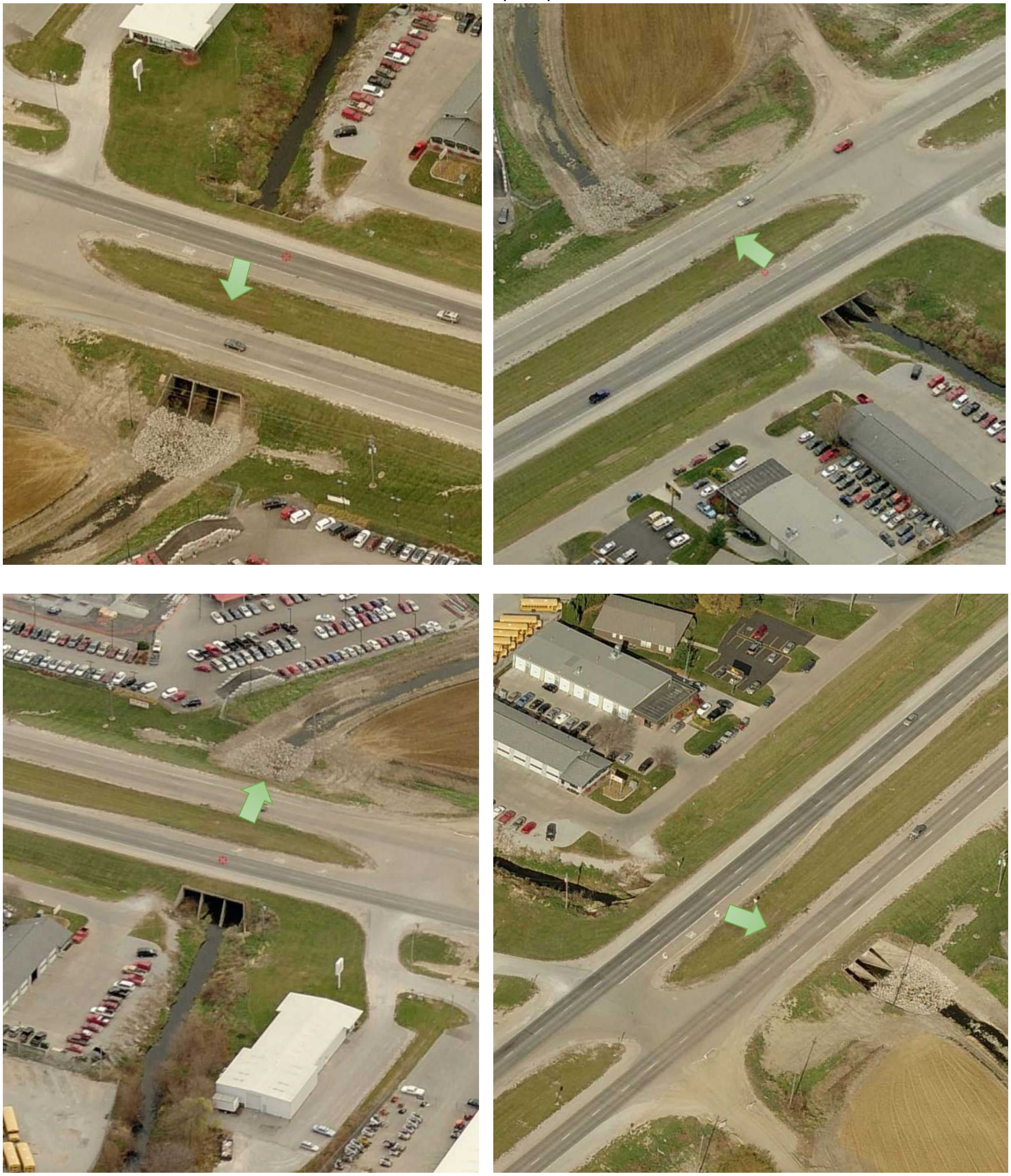
2014

2016

2016

2017

2007 (Nov)



2012 (Nov)

2017 (Nov)

Runway Culvert, Iowa City Airport, Site #2

41.638001684424594, -91.55885696411133

Nov 2007

Jun 2008

Apr 2009

May 2011

Nov 2012

Nov 2017

2003

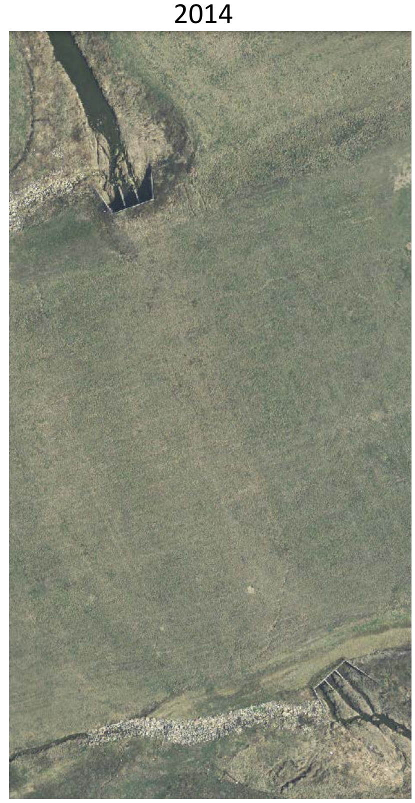
2006

2008

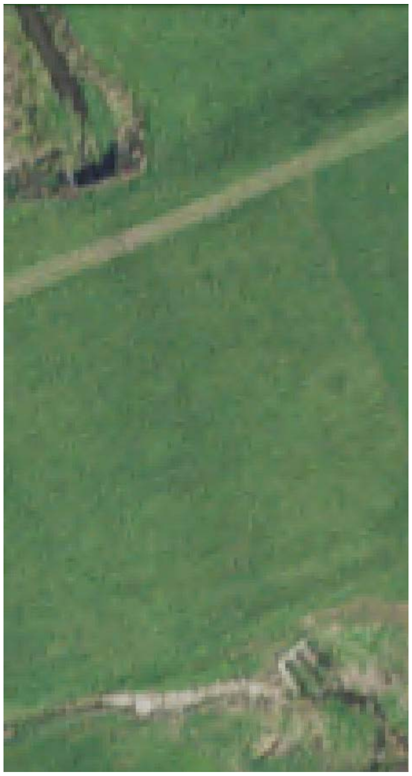
2011

2012

2014



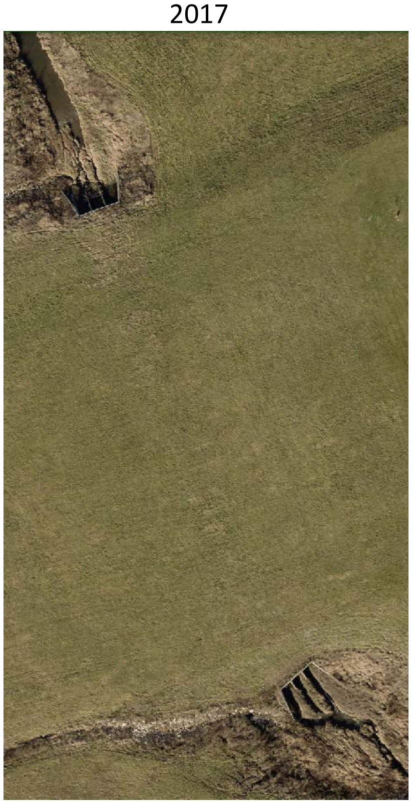
2015



2016

2016

2017



2007 (Nov)

2012 (Nov)

2017 (Nov)

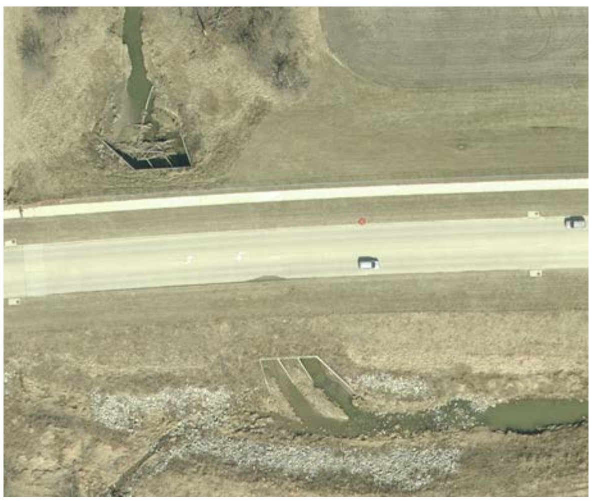
FHWA #364790, Site #3

41.63180325834524, -91.54860019683838

Nov 2007

June 2008

Mar 2009



Apr 2011

Nov 2012

2003 Preconstruction

Nov 2017

2006

2008 - Flood

2008

2011

2012

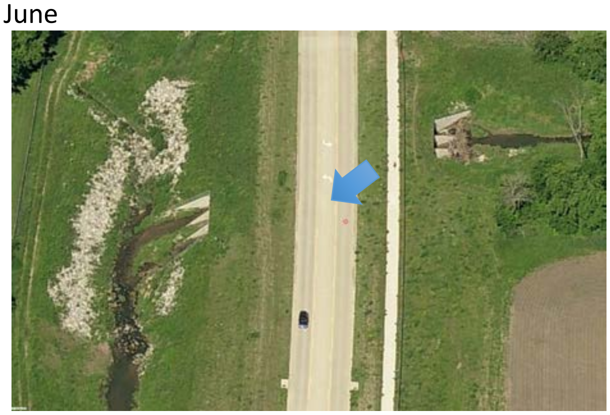
2013 Flood

2013

2015

2007 Nov

2008 June

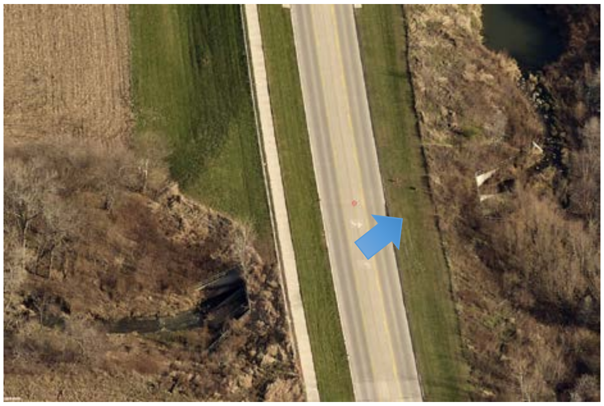


2012 Nov




2017 Nov



FHWA #504835, Site #4

41.6302916500702, -91.54180347919464

2007 Nov

2009 Mar

Apr 2011

Nov 2012

2017 Nov

2008 Jun

2003

2006

2008

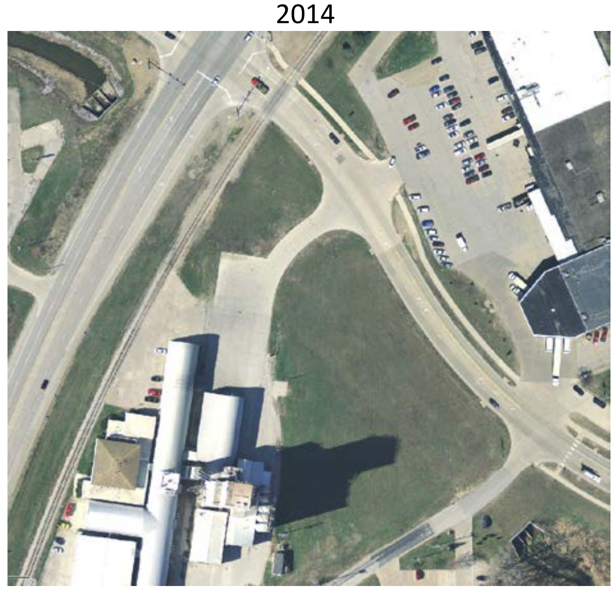
2008 - Flood

2011

2012

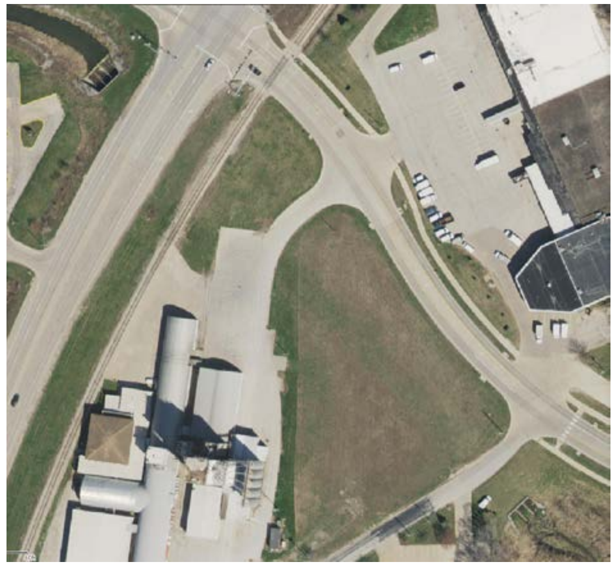
2013 - Flood

2014



2016

2016

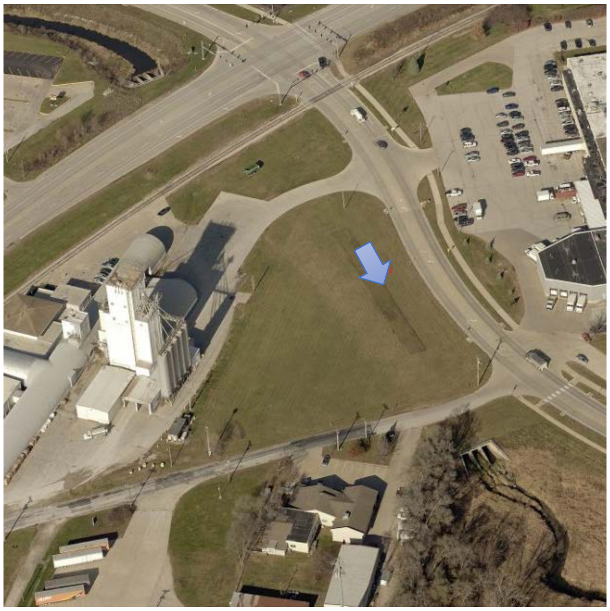


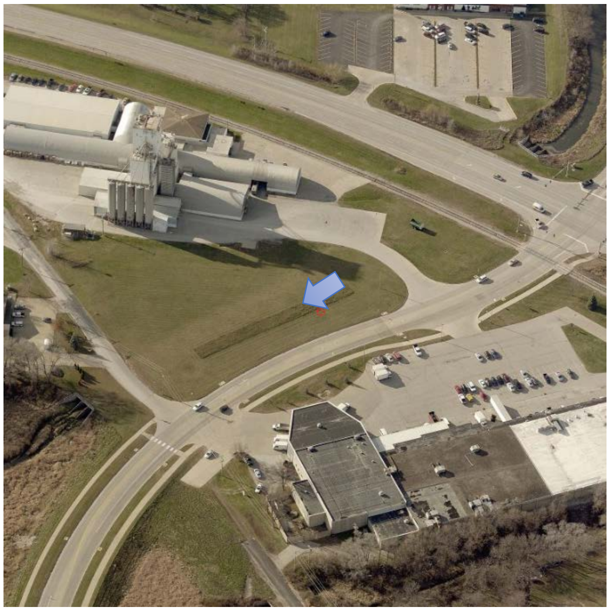
2017

2007 (Nov)

2012 (Nov)

2017 (Nov)





Inlet only

2017 Nov

2012 Nov

2008 June flood

2007 Nov