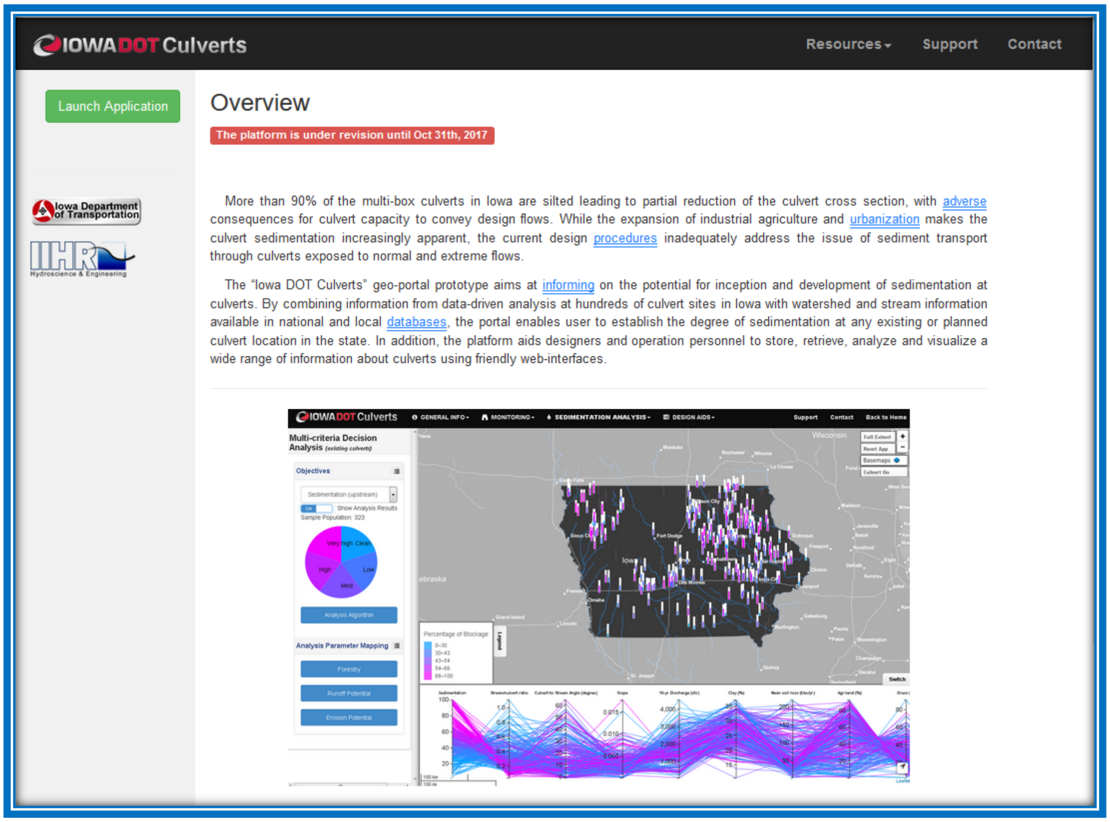
FINAL REPORT FOR IHRB TR-665

MITIGATION OF SEDIMENTATION AT MULTI-BOX CULVERTS



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Investigators:
M. Muste, H. Xu
IIHR-Hydroscience & Engineering, The University of Iowa
Iowa City, IA 52242-1585

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We study the sedimentation problem with a data-driven approach embedded in a web-based problem-solving environment that can provide the critical information needed for designing and maintaining culverts operational and free of sedimentation. At the core of the study is a Multiple-Criteria Decision Analysis (MCDA) software that systematically identifies the likelihood of culvert sedimentation as a function of stream and culvert geometry, along with landscape characteristics, in the culvert drainage area. The MCDA works atop of a variety of data sources (time series, statistical analyses, maps, and other site-specific characteristics) that are stored in various formats in multiple data provider repositories. To make the data easily accessible, we designed a web-based geo-portal that assembles in one place pre- and post-construction data and information, irrespective of their provenance. User-friendly portal interfaces allow users to prepare a systematic plan for culvert monitoring, and offer means for quantitative assessment of the potential for sediment deposit formation.</td></tr>
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Abstract

Culverts are common means to convey flow through the roadway system for small streams. Box culverts are generally designed to handle events with a 50-year return period, and therefore convey considerably lower flows much of the time. While there are no issues with conveying high flows, many multi-box culverts in Iowa have a significant problem with formation of sediment deposits at culverts. The highly erosive Iowa soils can easily cause silt-in and barrels can become partially filled with sediment in just a few years. Silting can considerably reduce the capacity of the culvert to handle larger flow events.

The overall project objective is to systematically identify the likelihood of culvert sedimentation as a function of stream and culvert geometry, along with landscape characteristics, in the culvert drainage area. The ideal approach for predicting sedimentation is to track sediment sources dislocated from the watershed, their overland movement, and their delivery into the streams using physical-based modeling. However, there are considerable knowledge gaps in addressing the sedimentation at culverts as an end-to-end process, especially in connecting the upland with in-stream processes and simulating the sedimentation at culverts in non-uniform, unsteady flows while also taking into account vegetation growth. It is, therefore, no surprise that existing research, textbooks, and guides do not typically provide adequate information on sediment control at culverts.

We study the sedimentation problem with a data-driven approach embedded in a web-based problem-solving environment that can provide the critical information needed for designing and maintaining culverts operational and free of sedimentation. The proposed method maintains the holistic, systems approach of the problem investigation but it does so with cost-efficient and effective means. The method can best be applied in data-rich watersheds or in areas where surrogates for that data are available. Fortunately, these surrogates are increasingly available through the expansion of remote sensing technologies that survey watershed properties over large scales at a fraction of the cost compared with conventional observational means.

At the core of the study is the Multiple-Criteria Decision Analysis (MCDA), an approach that uses quantitative and qualitative data, along with expert judgment, to develop quantitative relationships between the degree of culvert sedimentation and the key process drivers within the drainage area of the culvert, using the power of machine-learning and visual-analytics techniques. The MCDA works atop of a variety of data sources (time series, statistical analyses, maps, and other site-specific characteristics) that are stored in various formats in multiple data provider repositories. To make the data easily accessible, we designed a web-based geo-portal that assembles in one place pre- and post-construction data and information, irrespective of their provenance. The portal enables four workflows: (1) storage and query of culvert specifications and ancillary information; (2) monitoring of sedimentation at culverts using in-situ or remote sensing technologies; (3) analysis of the sedimentation at culverts; and (4) support of the design of the culvert by forecasting the sedimentation potential for any culvert site. User-friendly portal interfaces allow users to prepare a systematic plan for culvert monitoring, and offer means for quantitative assessment of the potential for sediment deposit formation. The workflows can be applied to existing or potential culvert sites, therefore assisting both operations and design purposes.

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1. Introduction

1.1 Background

Culvert sedimentation overview. U.S. Midwestern secondary roads often rely on culverts to pass streams under roadways, therefore playing an important role in 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 a 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, 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, depending on the structure type), there is evidence 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 the underlying cause of the failures.

For multi-box culverts located in flat, erodible watersheds, the most significant operational problem is sedimentation near the culverts. This is the case for the highly erosive Iowa landscape that can lead to situations whereby some of the barrels can become partially filled with sediment, as illustrated in Figure 1. Surveys of Iowa county and Iowa Department of Transportation (IDOT) engineers conducted by IIHR_Hydroscience & Engineering (IIHR) in 2009 and 2013 suggest that more than 95% of Iowa culverts are silted. The sedimentation concern is widespread in the nation, from California to Pennsylvania and from Wisconsin to Florida (Rowley, 2014).

Figure 1. Sample of silted culvert in North-East Iowa.

Silting can considerably reduce the capability of the culvert to handle larger flow events as the partial blockage of the structure could severely impair the hydraulic capacity to convey design flows. Obstruction of the culvert inlet can cause severe damage to both the transportation structure (e.g. overtopping of road and culvert) and upstream headwater areas (e.g. flooding). Not surprisingly, the occurrence of culvert sedimentation is a major concern for road maintenance authorities in many Midwest areas. Silting situations, such as those illustrated in Figure 1, were encountered at almost all the culvert sites visited by our research team during the lifetime of this project. During the visits, we learned that cleaning sedimentation is one of the costliest problems in culvert operations in Iowa, as the siltation develops quickly—the sedimentation process attains its stable form in no more than four or five years—and might require repeated cleanups, as illustrated in Figure 2. Lack of guidance on how to mitigate sedimentation leaves no alternative other than the costly and labor-intensive mechanical cleaning of sediment whenever it becomes critical. The costs it incurs are compounded because many culverts are small, making cleaning of sediment difficult due to the small space for cleanup vehicles, thus requiring a range of utility vehicles.

Figure 2. Sedimentation is fast and can quickly reduce a culvert’s conveyance capacity.

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 of sediment passing continues to be a challenge at stream crossings provided with culverts. In general, current knowledge on sedimentation processes at culverts is fragmented and the literature on this topic is scarce (see a succinct description of the processes in Section 2.2). More recently, however, the intensification of land use changes (through intense agriculture and urbanization) and the impact of climate change makes this a critical area of research.

Agricultural land use challenges include the removal and/or alteration of the native ground cover that change the roughness of the landscape surfaces (through tilling and other practices). Recent studies show that Iowa streams carried a much greater sediment load in the early twentieth century, followed by a drop and stabilization in loads during the recent times (Jones and Schilling 2011). The trend is 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 culverts relate not only to the changes in the stream-reach approaching the culvert, but also to the incoming flows. As a result, changes in the pathways and amounts of runoff triggered by the same precipitation amount occur. Additional factors contributing to sedimentation at culverts include local topography and soil types, and the absolute magnitude of the forces and energy of the hydrologic events 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 an increase 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 suggest that extreme rainfalls are projected to become more extreme, consistent with the redistribution toward more intense rainfall described in the observational record over the recent past (Villarini et al., 2013). The changes in rainfall intensity and frequency are decisive factors influencing 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).

Conventionally, sedimentation problems in a watershed can be analyzed and evaluated 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) models, 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) are developed to simulate natural channel flows that are uniform, under steady conditions, and free from disturbances by human-made structures (EPA, 2017; Nearing et al., 2005; Papanicolaou & Abaci, 2008; Prosser, 2001).

Culvert sedimentation cannot be well addressed through soil erosion modeling alone because of the number of unknowns and knowledge gaps. Therefore, there are very few (if any) research studies tackling transport processes leading to sedimentation at culverts as an end-to-end process. Even in their simplest forms, the investigation of these erosion and transport processes are complex, as it 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. The complexity is further increased by the continuous change of the erosion process drivers that is dependent on the natural and anthropogenic activities in upstream drainage areas. This interactive chain of processes is a good example of coupled human–environment systems, an area of investigation not well understood because of the lack of tools to appropriately handle the vast amount of data needed for the investigations. It is, therefore, no surprise that 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 mounting evidence of the sedimentation at culverts and the adverse impacts that they produce, there has been an expansion of investigations in this area. The initial studies have been based on semi-empirical or piece-meal modeling approaches that adjust exiting water conveyance formula for sediment presence. Most of the available investigations and practical guidelines related to sedimentation deal with embedded pipe culverts, specifically with the change in the culvert hydraulics in the presence of bed load passing through this type of culvert. Howley's (2004) study broadens the scope of the research by investigating the relationships among various culvert characteristics and the effect of sediment (predominantly in suspension) deposition in culverts. The 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) investigates 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 recent study aims at developing design criteria for self-cleansing drainage systems entailing circular and other channel cross-sections (Safari et al, 2017). Self-cleansing ensures that the sediment deposition is minimized at its maximum extent.

The closest in scope to our study is Rowley's (2014) work which aims to understand how coarse sediments behave near culverts. Rowley investigated embedded-type culverts (bottomless), a culvert type that is promoted for the ability to enable migration of aquatic organisms. He collected data at multiple sites and compiled them to inform 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. This is the first time, according to Rowley, that deposition of sediments upstream of a culvert and lateral fining within a culvert barrel have been successfully modeled. The distinction between our studies and Rowley's is in the nature of the sediment (Rowley studied coarse sediment while we studied fine sediment) and the simplicity of the culvert geometry (pipe culverts). These differences were sufficient to induce 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).

Given the complexity of investigating the sedimentation at culverts, there are no rigorous design techniques available to size culverts for sediment passage and predict the loading of sediment. There are, however, strategies based on engineering judgement that can guide the design of culverts with consideration of sedimentation. Most of the available guidelines are developed for pipe culverts that are easier to deal with due to the simpler flows that 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.

Excepting 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 known if these recommendations assure better sediment conveyance, thereby reducing the risk of structure failure. Some more considerations are available regarding the changes that the sediment induces on the hydraulic gradient and the friction factor of the flow passing through the culvert (UDOT, 2017). The guidelines notify the users that these assessments are not thoroughly scientific, therefore engineering judgment is essential in their implementation.

1.2 Study Objectives

The original overall project objective was to systematically identify the likelihood of culvert sedimentation as a function of stream and culvert geometry, along with selected characteristics of the area drained by the culvert. The conceptualized relationships are formulated to be used as design aids in conjunction with the current culvert design specifications used by IDOT and county engineers. The initial objectives (IO) of this project were to:

IO.1 Conduct analysis of aerial photograph on a significant sample of 3-box culverts located in various soil areas throughout the state.
IO.2 Estimate degree rates of sedimentation using the analysis conducted in IO.1.
IO.3 Conduct field surveys to accurately quantify degrees of sedimentation, deposit volumes, origin of materials and additional factors involved in sedimentation.
IO.4 Develop analytic relationships to capture:
  a. the relationship between stream-to-culvert width ratios and soil erodibility.
  b. the rate of sedimentation for various soil erodibility factors.
IO.5 Develop a matrix for complementing the culvert design process.
IO.6 Review culvert design specifications and formulate provisions to account for local soil characteristics in the design of culverts.

In the initial stages of assembling the information for Objectives IO.1, IO.2, and IO.4, we realized that the approaches proposed for accomplishing these tasks will benefit from changing the procedural approach. Specifically, rather than acquiring the above-mentioned data and information from individual sources (such as IDOT, Department of Natural Resources (DNR), Iowa Geological Survey (IGS), or Iowa Flood Center) for each selected culvert site, we decided to assemble all the relevant information sources in one place as a culvert-centered repository and retrieve the information from this central data and information repository instead. This led to a consolidated and more comprehensive plan of work that is grouped along the following objectives:

O.1 Review of the essential physical processes involved in culvert sedimentation and identification of the contributing factors and key drivers of the problem.

O.2 Development of a comprehensive culvert sedimentation data repository by integrating culvert sediment observations (obtained through field inspections and sediment mapping onto aerial imagery) with selected drivers identified in the previous objective.

O.3 Quantification of the sedimentation occurrence at culverts based on the outcomes of Multiple-Criteria Decision Analysis (MCDA) and integration of the research outcomes obtained in the previous two objectives into a web-based portal for forecasting culvert sedimentation in Iowa.

2. Methodology

2.1 Approach

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 information needed to make decisions, we propose some alternative and robust tools. Specifically, we adopted a data-driven approach embedded in a web-based problem-solving environment that can provide the critical information for planning, designing, and maintaining culverts that is also compatible with the stream environment. The proposed method maintains the holistic, systems approach of the problem investigation but it does so with cost-efficient and effective means. The method can only be applied in data-rich watersheds or in areas where surrogates for that data are available. Fortunately, the surrogates are increasingly available through the expansion of remote sensing technologies that survey watershed properties over large scales at a fraction of the cost compared with conventional observation means.

We hypothesize that the data-driven approaches (e.g. machine-learning, hydrologic classification) are capable of relating spatial patterns of the hillslope and in-stream characteristics with the sedimentation process under investigation without detailed consideration of the internal structure of the physical process (Dibike & Solomatine, 2001; Grabec, 1990). Use of the data-driven approaches for culvert sedimentation analysis is based on the premises summarized next. First, as major recipients of the water-borne material transported from local and upstream catchments, stream environments integrate the hydrologic characteristics of the drained area, establishing a unique correlation with the watershed-river systems (Allan, 2004). Second, abundant data about watersheds and streams relevant to erosion and sedimentation processes from various agencies are freely available for both Iowa and the contiguous United States, hence the framework tested for Iowa can be easily generalized. Third, it is possible to conveniently characterize the sedimentation-at-culvert problem by taking advantage of the aerial images that continuously cover the development of the sedimentation process in time and space. This information also exists for the other U.S. territories (although the resolutions of the maps might differ).

With these premises satisfied, the data-driven approach allows users to identify and map the relationships between predictors (i.e. independent variables defining the sedimentation process) and response variables (the ones defining the goal of the investigation). Among the predictor variables are watershed anthropogenic and hydrologic characteristics (drivers), culvert structural attributes and their relationships with the stream that they serve, and ecologic factors in a culvert's vicinity. The response variables include the degree of sedimentation (in aerial mapping) and blockage (vertical surveys) upstream and downstream from the culverts. The proposed research has the potential to allow quantification of the relationships between the sedimentation hazard and the essential drivers, thus shedding light on unknown mechanisms behind these complex transport processes involving coupled natural-human systems. The identification of the key drivers enables the development of system-wide, driver-specific mitigation strategies.

2.2 Review of Sedimentation Mechanics and Identification of Key Drivers

Identifying the key drivers underlying culvert sedimentation requires a sound and holistic understanding of its physical processes. A review of the mechanics of the end-to-end process is needed to inform the key drivers that are used in the proposed data-driven analysis. The problem conceptualization is made by grouping processes into three major actions, including (1) sediment detachment (erosion), (2) sediment transport (sediment yield and sediment delivery ratio), and (3) in-stream transport and sediment deposition (settling and stabilization due to vegetation growth). This grouping follows a causal relationship connecting sedimentation sources, pathways, receptors, and consequences that is used in dealing with other complex hazard risk systems (FLOODsite, 2004). Each action comprises numerous factors and interconnected physical processes as described below. The review entails tracking the processes and their connection and identification of the key drivers that are readily available or are easy to determine using free accessible data and information. Figure 3 illustrates the sequence of erosion mechanisms and the transport processes, along with their spatial location.

2.2.1 Erosion

Fine soil particles dislocated from drainage areas associated with the culverts are assumed to be the main source of sediment that, through downstream transport, eventually lead to the formation of deposits at culverts. The detachment of the particles is alternatively labeled as erosion or sediment production. Erosion can occur through several mechanisms, depending on their location in the watersheds. While erosion develops in undisturbed (natural) landscapes, excessive erosion levels generally stem from anthropogenic activities, such as agriculture, urbanization, and mining that reshape the landscape surface and the natural drainage waterways. Therefore, this study has to deal with specific erosion types, i.e., the splash–sheet–rill–gully erosion sequence, in-stream erosion, landslides (Foster, 1982), and construction site washouts (Emmett, 1978; Hairsine & Rose, 1992). These erosion processes vary both spatially and temporally across different hillslopes (Wilson et al., 2012). A brief review of the essential erosion types is provided below (see also Figure 3a). Table 1 lists parameters affecting sediment production and their data provenance for this study.

a) b) c)

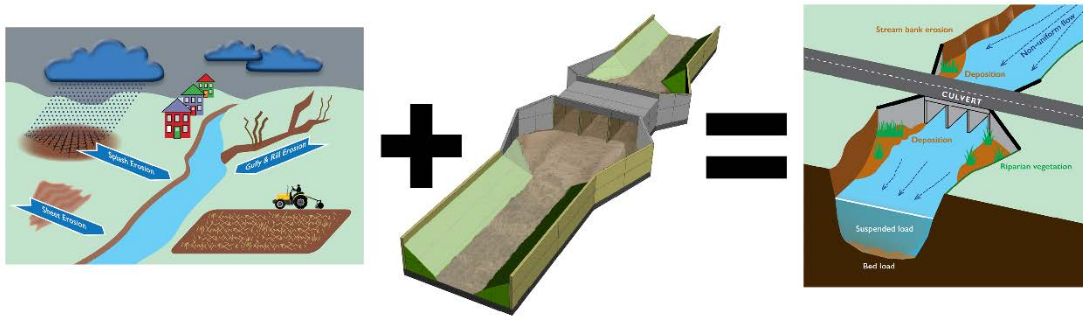


Figure 3. Overview of the processes involved in sedimentation at culverts: a) upland processes (sediment production); b) alteration of the stream geometry in the culvert vicinity; and c) in-stream processes in the vicinity of multi-box culverts.

(1) Sheet and rill erosion refers to the uniform detachment and removal of soil, or sediment particles, from the soil surface by overland flow or raindrop impact evenly distributed across a slope (Hairsine & Rose, 1992). Sheet and rill erosion is typically characterized by the Revised Universal Soil Loss Equation (RUSLE) in the form of average annual soil loss.

(2) Gully erosion occurs where runoff from adjacent slopes forms concentrated flows in drainage ways. Gully erosion is deeper than sheet and rill erosion. Its flow also differs from sheet and rill flows in that raindrop impact is not a crucial factor in terms of flow resistance or in sediment particle detachment. Under natural conditions, runoff is moderated by land cover (e.g. vegetation) which generally holds the soil together, protecting it from excessive runoff and direct rainfall. Gully erosion is considered a significant sediment supplier for culvert and road sedimentation (Carey, 2006).

(3) Streambank erosion is one of the in-stream erosions, characterized by widening and deepening of the stream channel. This process does not become a concern unless its rate is excessive. However, straightening or modifying the natural course of a channel, may significantly contribute to downstream sediment accumulation.

(4) Landslide construction sites and road erosion do not frequently occur in Iowa, as the topography is mild (mean slope below 25 degrees) and the state is not heavily urbanized. Therefore, in this study we do not consider them as critical sources of sediment.

Table 1. Independent variables related to sediment production (supply).

PARAMETER	ASSOCIATED PROCESS	DATA SOURCES
Rainfall-runoff potential	Sheet and rill erosion	SSURGO, StreamCAT
Annual soil Loss	Sheet and rill erosion	RUSLE
Land cover	Gully erosion	StreamCAT
Stream channelization	Streambank erosion	NHD Plus & aerial imageries
Channel slopes	Gully & streambank erosion	NHD Plus

2.2.2 Overall sediment transport

Erosion and its downstream transport are typically characterized by sediment yield which quantifies the erosion amount delivered to a specific location, such as a culvert. Of the dislocated material, only a fraction enters the drainage area channel system (Da & Bartholic, 1997). This fraction is conventionally estimated by the sediment delivery ratio (SDR). The SDR, also known as the sediment transmission coefficient, is defined as the percent of gross soil erosion delivered to a particular point in the drainage system. According to the USDA (1972), the SDR is related to drainage area; however, there is no precise procedure to determine the actual extent of the area from where the sediment is transported to the stream. In this study, we take advantage of existing data to find correlations between watershed characteristics, such as soil texture, distance to the main stream, channel density, basin area, slope (topography), length, land use/land cover, and sedimentation. Different soil textures create different types of sediment with the erosion processes where they are involved. For example, coarser sediments (e.g. sand and gravel particles) are linked to sheet and rill erosion that are typically more susceptible to deposition and trapping. The fine sediment (e.g. clay and silt) from upland and streambank erosion is the source for suspended load and has the potential to travel further along the stream (Bonniwell et al., 1999; Matisoff et al., 2001). Fine-grained sediments have a higher SDR than coarser sediments.

Channel density, watershed slopes (topography), and land use (land covers) are other important factors in determining sediment yield at the culvert location. From the physical perspective, a culvert with a higher channel density in its upstream drainage area tends to have a higher SDR. A drainage area with steep slopes has a higher SDR than a watershed with flat and wide valleys (Da & Bartholic, 1997). Land use change can alter the natural permeability and the cover condition of a watershed, hence anthropogenic activities must also be considered. As an example, a watershed with poor land cover (i.e. mostly agricultural land) has a high SDR because the runoff is increased and sediment retention decreases.

The in-stream sediment transport entails two transport modes, namely suspended load and bed load (Karim, 1981). Because multi-barrel culverts are usually placed on relatively large streams, the amount of bed load is small 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, as most sediment deposits are made of fine-grained sediments that are not found in the bed load material. As previous and current experimental evidences concur in their findings, this study is focused mostly on the driving factors that control the transport of suspended sediment.

Finally, the culvert design discharge has a straightforward correlation with sediment deposition at culverts (UDOT, 2017). According to Howley (2004), the flood discharge and sediment transport rate have a positive correlation. In other words, larger culvert design discharge normally leads to a larger sediment load. Furthermore, culverts that require a large design discharge are susceptible to oversizing, which is an important contributing factor covered in the next section. The list of parameters selected as predictors for analysis of the sediment transport processes are provided in Table 2.

Table 2. Main drivers of the sedimentation transport.

PARAMETER	ASSOCIATED PROCESSES/DRIVERS	DATA SOURCE(S)
Soil type	Sediment particle size & suspended load	SSURGO, StreamCAT
Channel density	Sediment delivery ratio	NHD Plus
Watershed slopes	Sediment delivery ratio, channel flow	NHD Plus
Land cover	Sediment delivery ratio	StreamCAT
Design discharge	Sediment transport rate	USGS (Eash method)

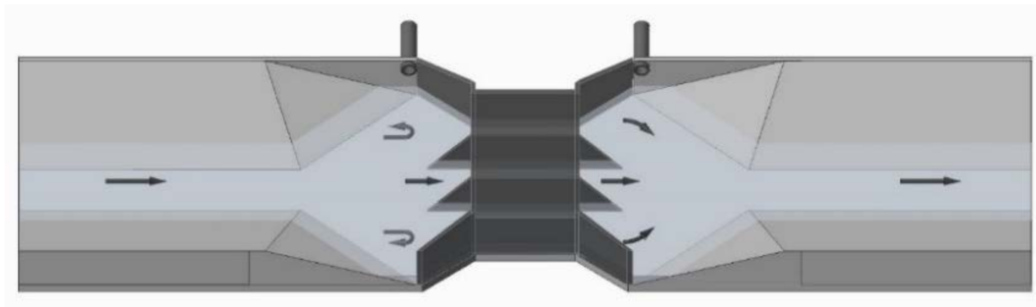
2.2.3 Sediment Deposition at Culverts

The companion problem to erosion and sediment transport is sedimentation. Most streams carry a sediment load and tend to deposit this load when their velocities decrease. In the absence of vegetation impact, culverts which are located on, and aligned with, the natural channel are not expected to develop a sedimentation problem. A stable channel is expected to balance erosion and sedimentation over time (i.e., self-cleaning regime). Sedimentation is the likely result of the processes that occur at low flow in the stream. The descriptions in Sections 2.2.1 and 2.2.2 are essentials of the mechanisms responsible for watershed erosion and sediment transport at the culvert locations. This section focuses on the local processes defining the structure-stream interaction whereby a culvert's structural characteristics play an important role in settling and trapping the sediment yield generated upstream from the culvert location. Previous studies have indicated that the following structural characteristics affect sediment deposition at culverts (Cafferata et al., 2017; Howley, 2004; Ho et al., 2013).

Stream-to-culvert width (SCW) ratio. To meet its design discharge for conveying flow during flood events, box culverts are sized for much larger than normal flow discharges. This setting creates a transition area in the channel that consists of an expansion upstream from the culvert and a contraction downstream from the culvert (Charbeneau et al., 2006; Ho, 2010). Figure 3b illustrates the culvert transition area and the geometry change this causes. Small SCW ratios promote sediment deposition by locally disrupting and slowing velocities over the stream cross-section (Ho et al., 2013). While suspended sediment and bed load are handled well by areas of stream with uniform geometry, transitions produce complex interrelated stream activities (see Figure 4). Among the most important contributing factors of sedimentation-at-culvert is the flow recirculation areas developed upstream and downstream from the culvert, as illustrated in Figures 4a and 4b1 (Muste and Xu, 2017).

In addition to flow non-uniformity, more subtle effects are introduced in the vicinity of the culvert due to flow unsteadiness, schematically summarized in Figure 4b. Flow unsteadiness occurs during the propagation of the storm flow through the culvert and it is usually neglected in analyses as it is difficult to capture with the needed detail. Flow unsteadiness induces different behavior on the rising and falling limbs of the hydrograph, a.k.a. hysteresis, as illustrated in Figure 4b2 (Ho et al, 2013). Hysteresis is currently unaccounted for in flow monitoring for the streams with culverts. Another effect related to flow unsteadiness is that the flow-sediment interaction is more complex than in steady flow interactions. Specifically, the maximum total sediment load passing through a section during a storm event is uncoupled and precedes the peal flow (irrespective of the discharge magnitude), as shown in Figure 4b3. Currently, there are considerable gaps in these non-uniform, unsteady sediment laden flows developing in three-dimensional geometry. Lack of understanding of the processes preclude making predictions with analytical tools.

a)



b)

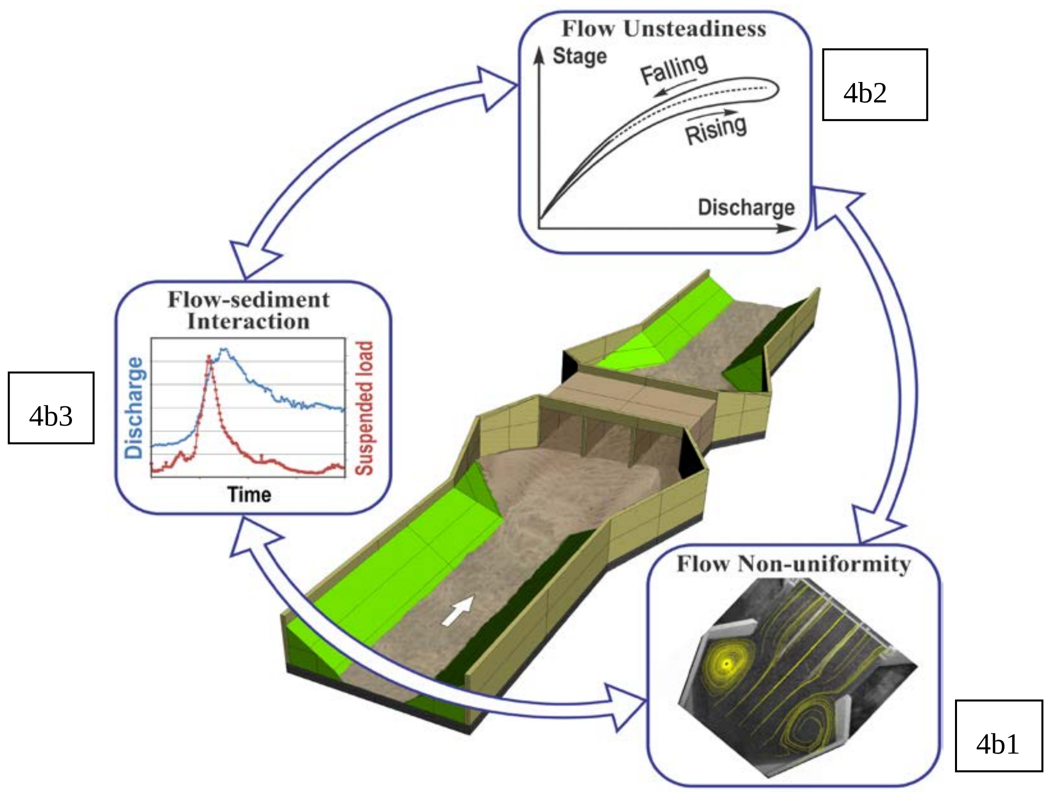


Figure 4. Flow configuration and behavior at culverts: a) non-uniform flow patterns in the vicinity of the culverts (patterns vary with the streamflow magnitudes); b) flow complexities due to flow unsteadiness.

In addition to the SCW ratio, sedimentation is dependent on the angle of incidence between the stream and culvert, and the type of control of the culvert hydraulics (i.e., upstream or downstream). Typically, the SWR ratio determines if sedimentation occurs, while the other factors determine where the sediment is deposited. For any situation, the expansion area develops non-uniform, three-dimensional flows that include areas of flow recirculation. As the flow decreases following the storms, the recirculation areas create favorable conditions for sediments to settle (Ho, 2010; Howley, 2004). Currently, there is no consideration in culvert design to account for sediment conveyance at multi-box culverts. With this perspective, it is advisable to utilize culverts that are close to the width of the active channel (Cafferata et al., 2017).

In this study, we determined the SCW ratio through site inspections and analyses of aerial photographs, as described in Muste and Xu (2017). For this purpose, we conducted multiple field investigations at culvert sites (11 trips at 257 culverts in Iowa) and analyzed 338 sites using the information provided by aerial images. These site inspections revealed that most of the deposits are made of fine-grained sediment particles (sand and clays), and no bedforms have been observed at culvert locations. We developed special tools in the Iowa Culverts Platform to estimate the stream width from aerial photographs (Muste & Xu, 2017). We then determined the stream-to-culvert width ratio for each location using the culvert width stored in Iowa DOT's Structure Inventory and Inspection Management System SIIMS database.

Stream ecology plays a critical role in accelerating sediment deposition at culverts. Once the sediment deposits develop to a height that exceeds the depth of low flow conditions (that might last for significant time intervals between storms), the vegetation grows quickly. Depending on the location of the growth, vegetation could either exacerbate culvert sediment deposits or reduce the sediment material supplies that are delivered to culvert locations. Vegetation that grows on the sediment deposits stabilizes them such that subsequent storms cannot remove the deposited material. On the other hand, we note the beneficial role of riparian vegetation or forested stream vicinities in impeding the sediment to reach the stream. Vegetation like cattail and weed may grow over time, preventing sediment from being washed away. The parameters involved in sediment deposit formation are listed in Table 3.

Table 3. Main parameters involved in the local accumulation of sediment at culverts.

PARAMETER	**ASSOCIATED PROCESS**	**DATA SOURCE(S)**
Stream-to-culvert width ratio	Culvert morphodynamics	SIIMS, aerial imagery
Vegetation presence	Sediment deposit growth	Field survey, aerial imagery
Upstream riparian corridor	Streambank erosion	StreamCAT
Angle of incidence	Culvert morphodynamics	Aerial imagery
Culvert control	Culvert morphodynamics	SIIMS

2.3 Integration of Culvert Information with Watershed Characteristics

Culvert design is based on a variety of data sources (time series, statistical analyses, maps, and other site-specific characteristics) that are typically stored with data providers in various formats. After construction, more data is produced through periodic culvert monitoring programs that report useful information on operation performance and associated problems. The post-construction data and information is especially important if they cover aspects that were insufficiently addressed in the design stage (such as the effect of sedimentation, debris, and environmental factors). These multiple variables are widely available for all U.S. territories but stored in various formats and multiple repositories, which makes their handling difficult.

In this study, phase independent and dependent variables were integrated in one digital repository hosted in a web-GIS environment. The digital repository entails culvert sediment observations (quantification of the sedimentation severity), multiple structural specifications (culvert width, length), and environmental variables (e.g. soil erodibility, runoff, channel vegetation, and watershed slope) in the watershed and the stream vicinity. Integration of the above information required: (1) spatial join to connect culvert locations with its pertaining watershed characteristics, and, (2) classification of response variables for quantification of the degree (severity) of sediment blockage at culverts. The digital repository is connected to a web-based Content Management System (CMS), in which users can easily quantify and submit culvert sediment observations, as well as access independent variables produced by various third-party sources. The repository serves as the foundation for subsequent analyses. Table 4 provides details on the data sources.

Table 4. List of data sources.

DATA SOURCE	PROVIDER	DATA DESCRIPTION	DATA TYPE
Structure Inventory and Inspection Management System (SIIMS)	Iowa DOT	Culvert structural specifications	Predictor
National Hydrography Dataset (NHD) Plus	USGS	Digital river networks and hydrologic connectivity	Predictor
Watershed Boundary Dataset (WBD)	USGS	Digital watershed boundary and attributes	Predictor
Stream-Catchment (StreamCat) Dataset	USEPA	Watershed characterization (ecology aspect)	Predictor
Revised Universal Soil Loss Equation (RUSLE)	USDA	Total annual soil loss	Predictor
Annual Stream Exceedance-Probability Statistics	USGS	Estimate culvert design discharge	Predictor
Aerial Imagery	Multiple sources	Orthorectified images (various spatial-temporal resolution)	Response variable
Iowa Culvert Sediment Observation Database	IIHR	Cross-sectional blockage and sediment deposit area	Response variable

2.3.1 Third-party data on culverts and watersheds

Data for multiple variables identified in the previous section driving the erosion and sedimentation processes at culverts are widely available for all U.S. territories. However, they are stored in various formats and multiple repositories which makes their handling difficult. This study's primary goal is to integrate the independent and dependent variables in one digital repository hosted in a web-GIS environment that facilitates the tasks to be conducted in a subsequent study phase. We first describe the data and sources associated with the third-party producers.

Structure Inventory and Inspection Management System (SIIMS). The SIIMS contains culvert structural and maintenance information. Specifically, data regarding culvert geometry, materials, and results of periodic site surveys are all organized and made available in a uniform format. The Iowa DOT SIIMS is the single source location for entering and reviewing condition information on all Iowa bridges, both local and state owned (https://siims.iowadot.gov/Default.aspx). The system offers web customized interfaces to store in a uniform, structured format data and information regarding culvert structural information, ownership and location, maintenance and inspections results, and observations (e.g., regarding the hydraulics and sedimentation aspects in the vicinity of and within the culvert). The system can aid in generating formal PDF reports in the SIIMS. These reports may include photos, sketches, and inspection data, along with a variety of additional information.

National Hydrography Dataset (NHD) and Watershed Boundary Datasets (WBD). These are used in our study to map the streams and hydrographic units (e.g. watersheds, catchments, and corridors). Subsequently, tools to characterize the longitudinal and lateral stream network hydrologic connectivity will be added to the platform to define the topology of the in-stream transport processes leading to culvert sedimentation (McKay et al., 2012; NHDPlus, 2006). The National Hydrography Dataset (NHD) Plus Version 2 (NHDPlusV2) is used to develop the Digital River Network (DRN) and ancillary watersheds. The original NHD is a publicly available repository that depicts the network of streams and rivers within the conterminous U.S. based on the digitized lines of U.S. Geological Survey (USGS) topographic quadrangle maps (Hill et al., 2016; McKay et al., 2012).

The NHDPlusV2 is a value-added product of the original NHD that integrates ridgelines from the Watershed Boundary Dataset (USGS & USDA, 2013) and the National Elevation Dataset (USGS, 2006) with the original USGS digital stream networks (USGS, 2001). The NHDPlusV2 aims to fulfill the same role as the original NHD but has a number of considerable refinements and data extensions. The integration validates the NHD hydrologic connections (i.e. stream topology) with the flow depictions (i.e. flow directions and accumulations) across the 30-m digital elevation models (DEM) from the National Elevation Dataset (NED), improving the overall accuracy and resolution of the dataset. Meanwhile, through the integration, flow rasters derived from the NED were then used to delineate catchments for each stream segment in vector format and serving as a hydrographic dataset, the NHD also provides a geospatial framework for storing, indexing, and organizing water-related information in a relational data structure.

Each hydrographic unit within the datasets is indexed with unique IDs (e.g. stream segments are indexed "COMID" in NHDPlusV2). The indexing provides the datasets with the flexibility to extend stream-associated attributes and spatial entities (e.g. stream connectivity, stream-associated catchments). In terms of data organization, the NHDPlusV2 also divides the original data structure into "core" components and "extended" components. The set of "core" data components are mostly the spatial description of hydrographic units (e.g. stream networks, catchments) from the original NHD, WDB, and NED. The "extended" components are numeric descriptions that are indexed with the spatial "core" components containing additional information, such as stream topology, flow estimation, and catchment attributes (e.g. VAA table). Most of "extended" components are stored in value-added tables that can be joined with hydrographic units in the "core" components through the NHD indexing.

This study uses the spatial and numeric descriptions from the NHDPlusV2 to create digital river network (DRN) and ancillary watersheds within the proposed study area, the Iowa-Cedar Rivers Basin. The study also adopts the conventions (e.g. indexing, data structure) of the NHDPlusV2 geospatial framework to develop river corridor datasets (both spatial and numeric).

Stream-Catchment (StreamCat). This dataset is the primary source for characterizing watersheds, including anthropogenic impacts and contains extensive synthetic summary statistics for ~2.65 million stream segments and their associated catchments within the U.S. (Auerbach et al., 2016; Hill et al., 2016). The dataset is publicly available (http://www2.epa.gov/national-aquatic-resource-surveys/streamcat), and provides landscape summary statistics for both local catchments and full upstream watersheds of any stream reach. Developed by the U.S. Environmental Protection Agency following the NHD data convention, the StreamCAT serves as an NHDPlusV2 extension to characterize the nation's rivers and streams. When connected with an existing geospatial framework of the nation's rivers and streams (NHDPlusV2), the spatial distribution of catchment and watershed characteristics can be visualized and analyzed for various watershed and stream management applications at the conterminous U.S scale (Hill et al., 2016).

The StreamCAT dataset contains a wide range of landscape metrics, characterizing stream segments and their associated catchments from a holistic view. Based on the domain and nature, metrics in the dataset can be classified into either nature layers that emphasize the pristine (i.e., normative) behaviors of stream environments, or anthropogenic layers that describe the degree of human activities within catchments. Natural layers consist of land cover, soils, lithology, runoff, and topography. Anthropogenic layers include roads, dams, mines, U.S. Census data on population and housing unit densities, land use (urbanization and agriculture), imperviousness of man-made surfaces, and EPA Facilities Registry Service locations (e.g., Superfund sites). Most of the landscape metrics in StreamCAT exist in the form of statistical summaries, created for hydrographic units at different spatial scales, including local catchments and buffer areas within 100-m of stream segments.

The underlying methodologies for creating these statistical summaries are zonal statistics and tabulate areas. These operations are available from ArcGIS toolboxes, ArcPy library, and many spatial databases (e.g. PostGIS). The StreamCat applies these operations to calculate cross-tabulated areas between landscape data layers (raster datasets) and the boundary of hydrographic units that define statistic zones, producing summaries for local catchments and 100-m buffer areas that are associated with stream segments. Through the stream topology (i.e. connectivity that defines the upstream-downstream relationship), the StreamCat accumulates local statistical summaries upstream of a river segment and translates them into watershed characteristics at various lateral scales.

Revised Universal Soil Loss Equation (RUSLE). These are modeling results used to characterize erosion with rill- and sheet-based erosion, which are better captured than the other types of upland erosion (Ganasri & Ramesh, 2016; Merritt et al., 2003). The RUSLE was developed primarily to guide conservation planning, inventory erosion rates, and estimate sediment delivery based on additional analysis and knowledge that were unavailable when USLE was developed. RUSLE uses the same formula as USLE with improvements in determining factors. These include some new and revised isoerodent maps; a time-varying approach for soil erodibility factor; a sub-factor approach for evaluating the cover-management factor; a new equation to reflect slope length and steepness; and new conservation-practice values. Input parameters required by RUSLE include R: the rainfall erosivity factor, K: the soil erodibility factor, L S: the slope length and gradient factor, C: the cropping management factor, and P: the erosion control practice factor.

While the capabilities to accurately predict erosion and sedimentation are limited, the RUSLE model represents a good indicator of the severity of soil loss in landscapes such as Iowa. In this study we use annual soil loss produced from RUSLE as an independent variable to estimate the sediment potential of headwater areas where culverts are located. As culvert sedimentation involves other aspects, such as gully erosion, sediment transport, and sediment deposition, which are not well addressed by RUSLE alone, the model will be used only as a reference for the severity of soil losses in the MCDA. Primary analysis of culvert sedimentation will not rely on the simulation provided by RUSLE and its siblings (e.g. USLE, RUSLE v2, MUSLE).

Annual Stream Exceedance-Probability Statistics (Eash Method). Currently, Iowa DOT uses flood-frequency analyses to estimate the design discharge for culverts. Two major techniques that are adopted in the department's Iowa Bridge Backwater Software are the USGS Lara method and the USGS Eash method. Both methods use regional regression equations to calculate the magnitude and frequency of floods (annual exceedance-probability discharges) at ungagged sites on unregulated rural streams in Iowa. The USGS guidelines distinguish among multiple hydrologic regions in Iowa (5 regions in the Lara method and 3 regions in the original Eash method). Each hydrologic region has local flood frequency equations and specific regression equation coefficients. As an example, the local flood frequency equations appears in the form: Qt = c Ab; where Qt is the discharge for a selected recurrence interval; A is the drainage area upstream of the culvert; and b and c are regression equation coefficients (Jones, 2013, p. 28). For a better estimation, the USGS Eash method also has a three-parameter version, which takes main channel slope (MCS) and DML (Des Moines Lobe) into consideration.

Aerial Imagery. In our study we relied on extensive aerial images for quantifying the degree of sedimentation at culverts and to establish the stream-to-culvert width ratio. Aerial images are retrieved from various sources (e.g. NAIP, NDOP, Google, Bingmap, and ESRI). These are popular cyber-GIS technologies and online resources that efficiently support the MCDA on culvert sedimentation developed in the next phase of the study. Culvert identification using the aerial photographs can be conducted easily using the Iowa Geographic Map Server – IGMS (http://ortho.gis.iastate.edu/). The site contains historic and current images with spatial resolution up to 2ft for surveys acquired from 2007-2010. In addition, we explored information embedded in Google Earth (www.google.com/earth/index.html) for complementing missing information in IGMS. The two resources include easy-to-use features and imagery, and specific tools that enable the location of targeted areas, map areas of interest using topographic or imagery layers, compute distances and areas, and capture and annotate images.

2.3.2 Surveys for assessment of culvert sedimentation.

In-situ terrestrial surveys. During this study, the survey of about 250 three-box culvert sites were in-situ inspected, garnering the project-specific data and information. The map of the in-situ surveyed culverts during the 2016 and 2017 field campaigns is shown in Figure 5. We conducted the surveys in early March and April, before the spring vegetation growth began. We uploaded the data in real time using an interface of the IDOT Culverts portal. The culvert surveys include:

- 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 culvert structure and the associated stream, as well as specifications on sediment deposits (notes).

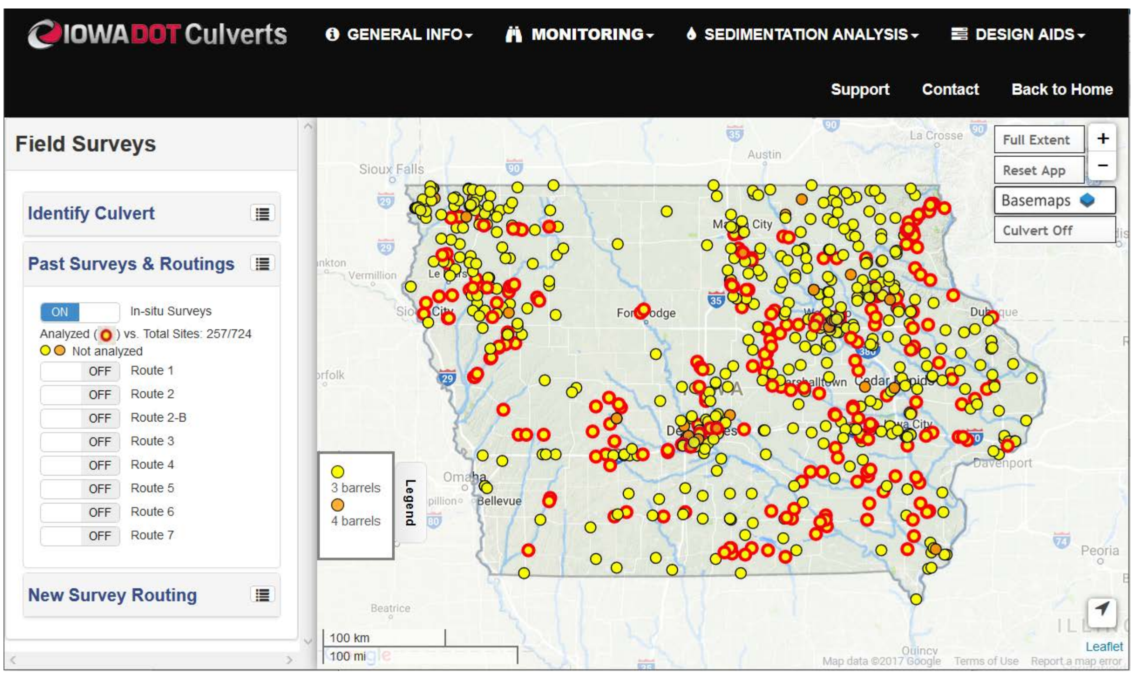


Figure 5. In-situ culvert surveys conducted in 2016 and 2017 (red symbols).

We conducted field inspections using a rigorous experimental protocol. Figure 6 documents protocols used in conjunction with the photo documentation and tracing of the sediment blockage at the culvert entrance. The instrumentation used in conjunction with these protocols were computer-embedded cameras, laser-based rangers, and portable communication hubs. We conducted this type of survey at more than 250 culverts sites, displayed on the map in Figure 5.

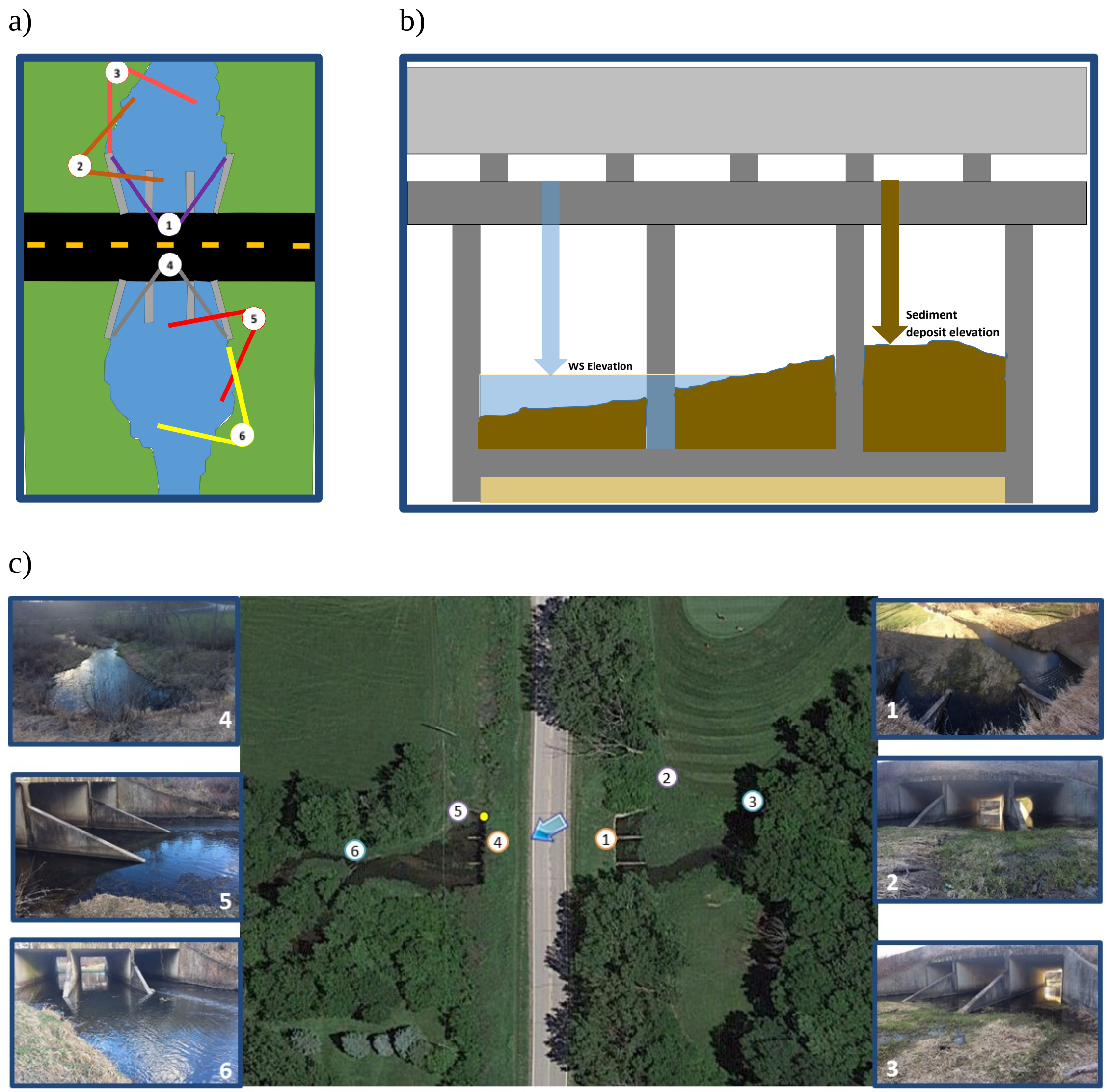


Figure 6. Field measurement protocols: a) positioning of the photo camera for the survey; b) illustration of the measurement acquired for the degree of sedimentation blockage; and c) illustration of the photodocumentation acquired at the culvert site.

The compiled information resulting from the photodocumentation, along with the field survey notes, is uploaded in real time using a customized interface of the IOWA DOT Culverts portal, as illustrated in Figure 7. Instructions of the usage for the field data uploader are presented in Appendix A of the report. The field data uploader is an efficient tool for supporting periodic inspections conducted by the culverts' maintenance personnel. The rigor of the data acquisition protocol and the quickness of the field data acquisition represents a significant improvement of the piece-meal and combined field and office procedures currently in use by county and IDOT district engineers.

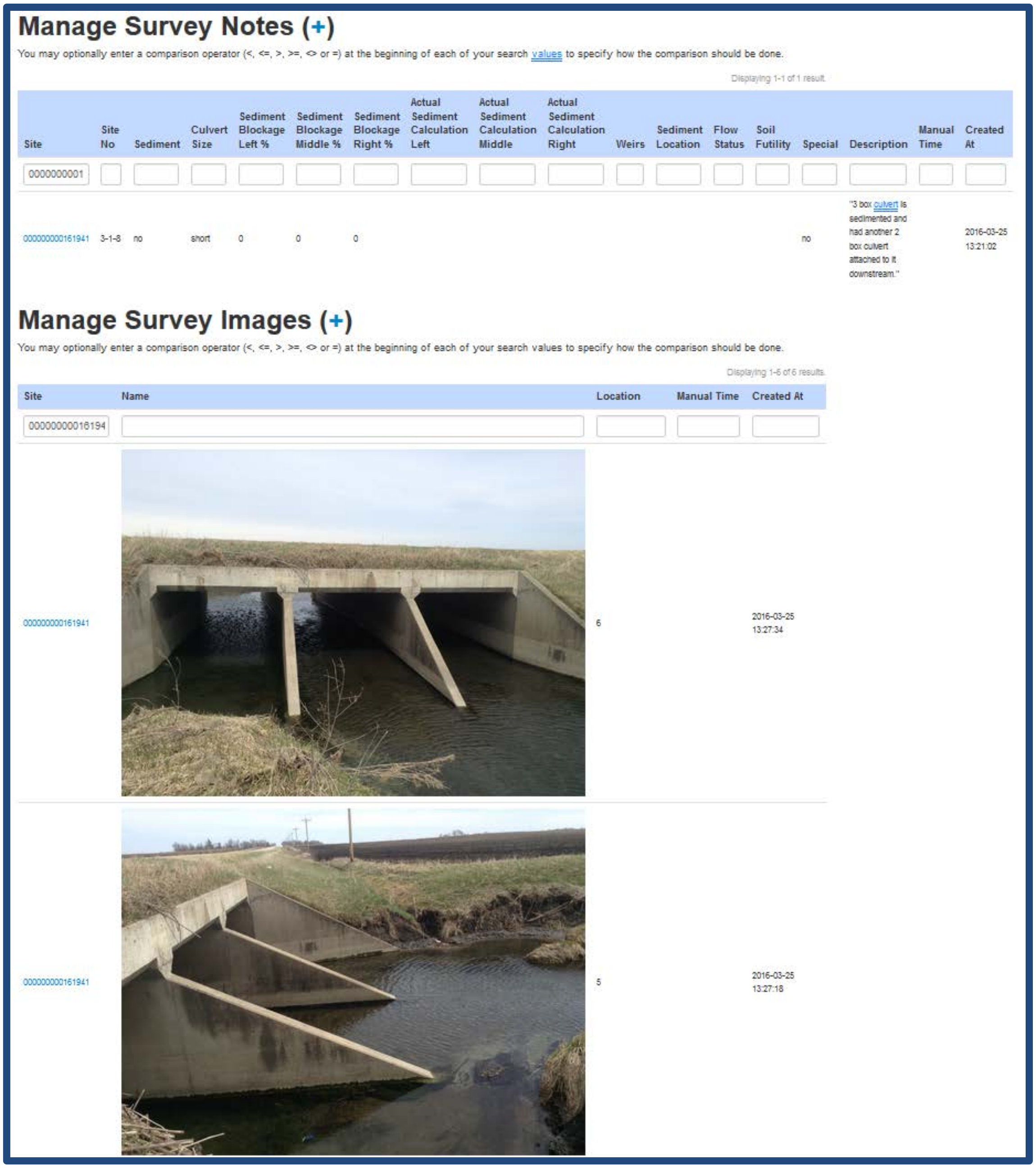


Figure 7. Illustration of the web-database storing the field surveys.

Drone-based surveys. For selected sites, the photo documentation was carried out with drone-based surveys subsequently processed with Structure from Motion (SFM) software. This contemporary type of 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. Drone-based surveys are compared to in-situ photography in Figure 8. Intermediary steps leading to the orthorectified aerial photo using the SFM software are shown in Figure 9.

a)

b)

Figure 8. Drone-based culvert surveys: a) data acquisition; b) processed data and comparison between aerial- and ground-based photo-documentation.

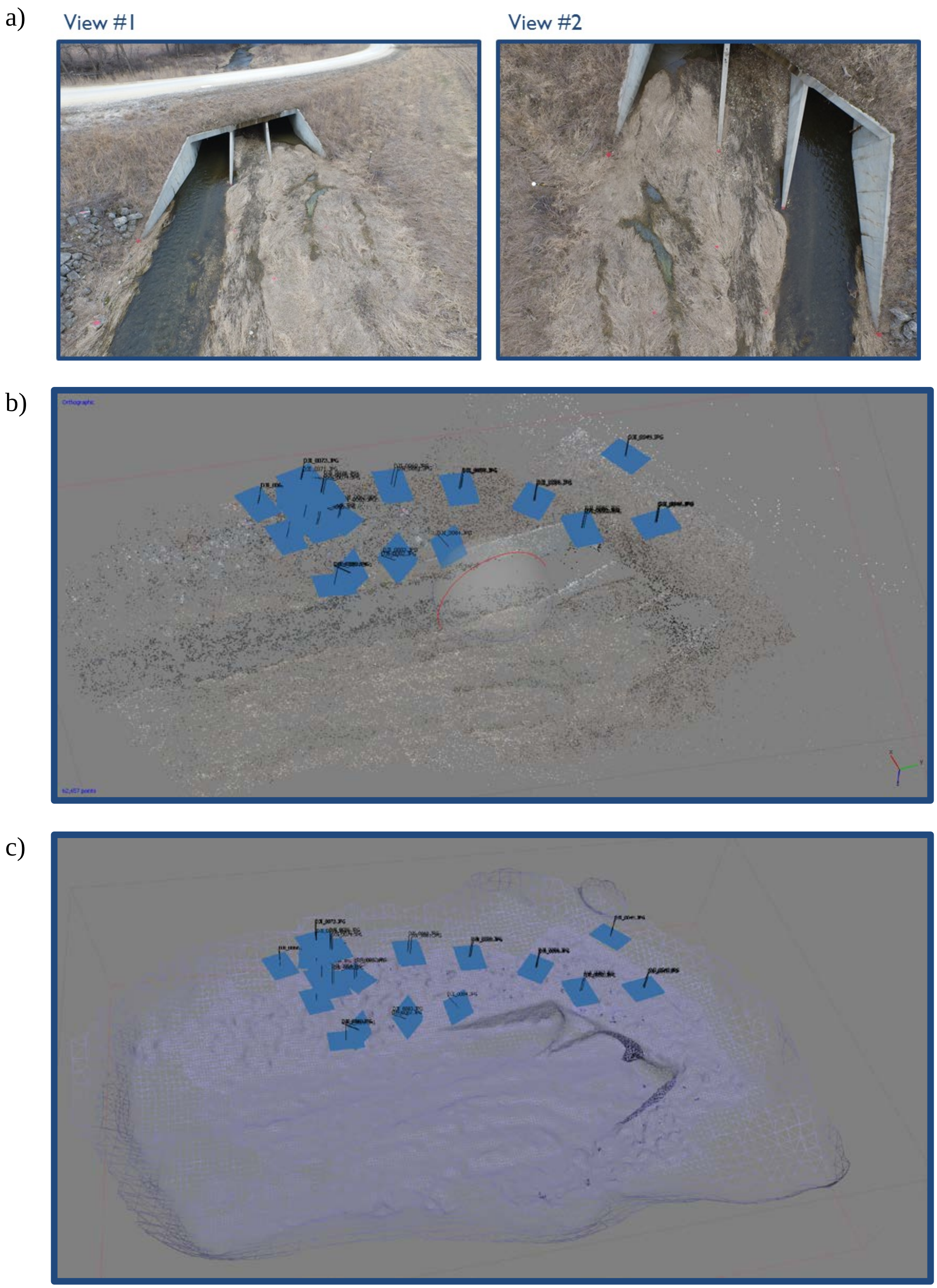


Figure 9. Structure From Motion (SFM) image reconstruction: a) raw images of the culvert inlet; b) image stitching; and c) identification of the tie points for image reconstruction.

The in-situ surveys with Real Time Kinetic (RTK) GPS instrumentation as well as the drone-based surveys of the sediment deposits 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 such-obtained estimates with those based on aerial photographs obtained, as described next.

Aerial imagery surveys. As a surrogate for the in-situ surveys, processing of the aerial photographs was considered as an alternative approach to estimate the degree of sedimentation. For this purpose, we screened the whole 3-box culvert database made available by IDOT to assess the spatial extent of the sedimentation using aerial photographs. The screening involved classification of the culvert "visibility" in a series of recent base maps. Geo-processing tools designed to work on the top of the maps enabled us to quantitatively map the area that was originally cleaned at the time of culvert construction and the current degree of sedimentation upstream and downstream the culvert. The geo-processing is made in real-time on any of the maps stored in the portals' map database. The outcomes of the on-screen measurements of the segment lengths and polygon areas are displayed on the screen as the measurement is made. The mapping data is saved in the "Iowa Culvert Sedimentation Observation" database (see Table 4).

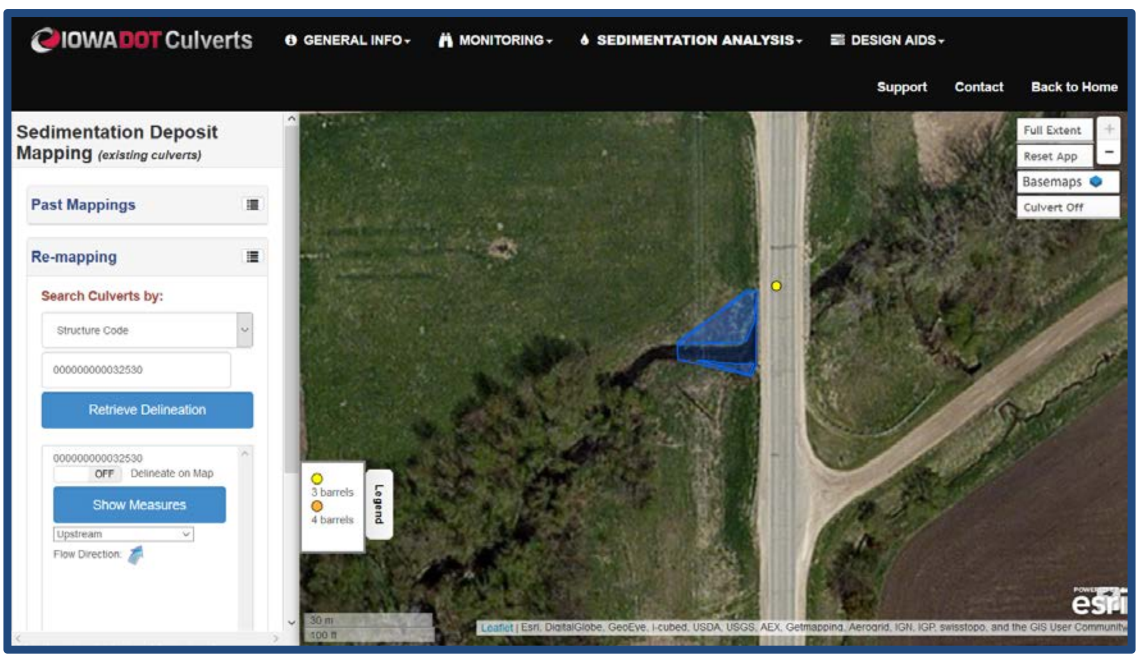


Figure 10. Geo-portal interface for the geo-processing tools associated with the estimation of the degree of sedimentation at culverts.

The visual inspection of the aerial photographs also allows for the identification of the culverts with problems, tracing the patterns of sediment development, rates of evolution over time (wherever this information is available), and the formulation of the correlations between stream geometry, culvert geometry, and the nature of the drainage area upstream from the culvert site. Simple and intuitive web-mapping tools were developed to allow users of the platform to extract spatial attributes of sedimentation and their evolution in time (the best quality for the images are for the 2004-2016 time interval).

2.4 Conduct Multiple-Criteria Decision Analysis

This study utilizes Multiple-Criteria Decision Analysis (MCDA) to advise on the culvert sedimentation potential, thereby directly aiding in the design and operation of the multi-box culverts. The MCDA is an approach that uses quantitative and qualitative data, along with expert judgment, to support decisions even is the data is not abundant (Vulevic & Dragovic, 2017). The MCDA pertains to the cross-disciplinary research that looks for ways to provide computer support to solving space-related decision problems through enhancing human capabilities to analyze, envision, reason, and deliberate (Andrienko et al., 2007). The MCDA enables decision making when the number of alternatives or actions is evaluated in terms of more, usually conflicting criteria.

According to Belton & Stewart (2002), MCDA methods can be classified as: measurement models, outranking methods, and goal/aspiration models. Irrespective of the method, special attention is needed in the initial structuring of the decision problem, which involves: a) selection of criteria, (b) selection of decision options, (c) weighting the criteria, and (d) obtaining performance measures to populate the evaluation matrix. Many researchers have found that MCDA provides an effective tool for water management by adding structure, auditability, transparency, and rigor to decisions (Hajkowicz and Higgins, 2008).

The MCDA usage in the present context has the following purposes:

(i) Ranking environmental and structural drivers behind culvert sedimentation using feature selection techniques.
(ii) Developing quantified relationships between culvert sediment degrees and key drivers within each region using deductive hydrological classification.

Development of functional relationships. From a technical perspective, the use of the decision tree analyses enable reliable quantifications of the cause-effect relationships between culvert sedimentation and its drivers. The strength of the method resides in the fact that there is no need to elucidate complex, inter-related processes and their evolution over large spatio-temporal scales as it is done in physical-based modeling approaches. Instead, the dependence among the variables in the relationships is developed by training smart algorithms on a set of data to develop the predictive capabilities needed in forecasting. The analysis outcome are dynamically visualized with parallel coordinate plots and principal component charts. This interaction allows for the itegration of human judgment in the final stage of the decision support loop. We emphasize, however, that the outcomes of the data-driven investigative approach is only as good qualitatively as the data used in the analysis.

Developing quantitative relationships between culvert sedimentation degree and the key drivers within the culvert drainage area is accomplished with hydrologic classification (Olden et al., 2012). Hydrologic classification was originally defined as the process of systematically arranging streams or rivers into groups that are similar with respect to characteristics or determinants of their flow regime (Kampichler et al., 2010; Olden et al., 2008). The classification can be categorized either as inductive (whereby classifications are made based on statistical similarity in the hydrologic data directly), or deductive (whereby environmental variables such as watershed characteristics are analyzed as key drivers of hydrology to create classifications) (Auerbach et al., 2016; Olden et al., 2012; Wagener et al., 2007). As the inductive approach requires abundant hydrologic data over a very long period of time, the data available for sedimentation at culverts in Iowa is not sufficient enough to produce empirical relationships. Thus, this study used the deductive approach. The drivers selected for classification include the watershed and stream variables identified in Section 2.2. This hydrologic classification coupled with machine learning techniques (Auerbach et al., 2016; Lins, 1985) is used to establish cause-effect relationships between culvert sedimentation and its drivers within each culvert drainage area.

The learning techniques proposed for our criteria analysis are the tree ensembles. Tree ensemble method uses multiple decision tree algorithms to obtain better predictive performance than could be obtained from any of the constituent trees alone. The tree-ensemble method derives the empirical relationship using a tree-like model of key drivers and their possible consequences regarding culvert sedimentation degrees. The method is a popular supervised machine-learning technique applied in hydrologic research (Galelli & Castelletti, 2013; Schnier & Cai, 2014; Schnier, 2016). In terms of training and testing, all culvert sediment observations are used as training datasets. The analysis outcomes are the results of decision-trees empirical relationships such as the one in Figure 11.

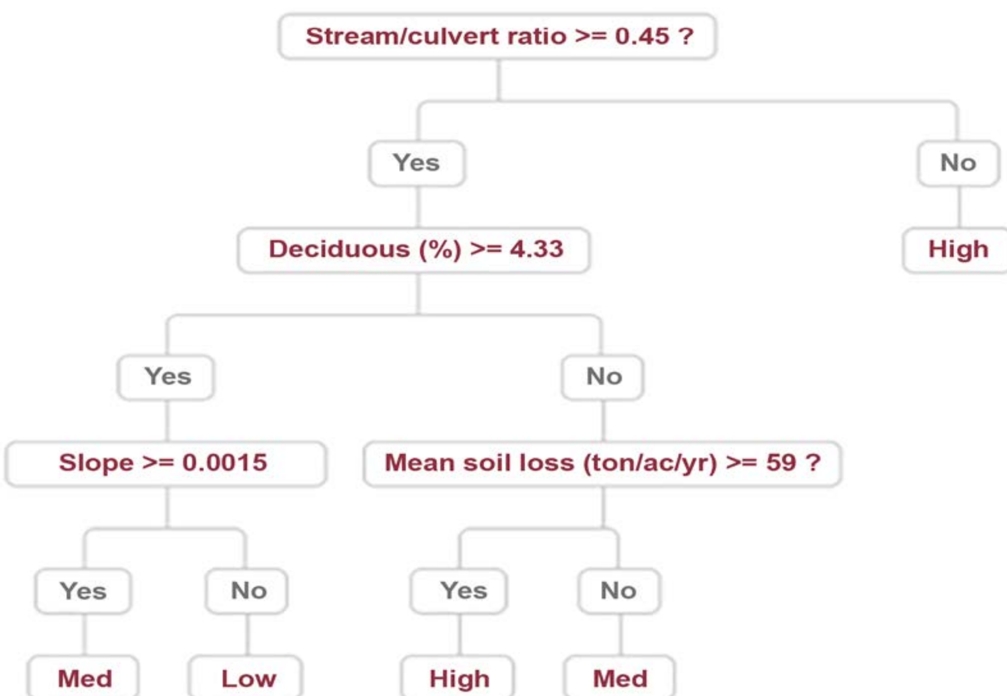


Figure 11. Decision tree representation of the cause-effect relationship between culvert sedimentation and its drivers.

Culvert sedimentation forecasting. By assembling the outcomes of the activities described in Sections 2.2 and 2.3 in a web system, we obtained a useful forecasting tool for sedimentation forecasting. To provide system-based mitigation solutions, this study uses derived relationships to predict the severity of culvert sedimentation at any location and stream in Iowa. Currently, the culvert sedimentation forecasting is relatively coarse and can be improved by creating regionalization of erosion potential through clustering and portioning, and by conducting sensitivity analysis on different spatial units (i.e., consideration of watershed characteristics within sub-areas of the culvert drainage area or imposed buffer regions along the streams). If additional effort is made to include local observations on the sedimentation degree (see Section 2.3.2), the platform can be extended to other U.S. territories.

All the features described in Section 2 are hosted in a customized web-portal developed for Iowa DOT. The workflow hosted by the cyber-GIS platform allows users to: (1) integrate, access, store, and manage culvert related information; (2) provide a web-based problem-solving platform for conducting data-driven investigations; and (3) access, analyze and visualize the data and information with user-friendly interactive interfaces. Users can predict the degree of culvert sediment at any stream location in Iowa. These tools and functions, along with the associated user interfaces, are hosted in the IOWA IDOT Culverts platform residing at iowawatersheds.org/idotculverts. Appendix A provides a summary of the menus, functions, and tools for each workflow. Currently, there are efforts for transferring the prototype web-portal to Iowa DOT's cyber-framework for routine usage in the design of culverts.

3. Iowa DOT Culverts Platform Cyberinfrastructure

Modern information and communication technologies have become the fourth pillar of scientific investigations, complementing the capabilities of the other traditional pillars (observation, theory, and analysis). Contemporary operational science and management of watershed resources are based on data- and information-rich environments. These environments are poised for progression, not only because of the recent advances in science and engineering research, but even more prominently by advancements in "hydroinformatics". This emerging discipline is defined as the science of information handling for solving water related problems (Abbott, 1991). Today's hydroinformatics capabilities to integrate data with models enable the creation of high-fidelity, first-principle based, numerical surrogates of real systems that aid quantifiable understanding of the critical processes that characterize the water cycle in watersheds.

The backbone of hydroinformatics is the cyberinfrastructure technology. According to Wikipedia, "in scientific usage, cyberinfrastructure is a technological and sociological solution to the problem of efficiently connecting laboratories, data, computers, and people with the goal of enabling derivation of novel scientific theories and knowledge". Contemporary cyberinfrastructure has become increasingly available, and sufficiently mature, so as to facilitate the development of digital platforms for supporting both scientific investigations and the management of various problems at the watershed scale. These platforms have the potential to transform our capabilities of understanding how to address ecosystem changes, protect the environment, and predict and prevent natural and human disasters through knowledge-based adaptive management.

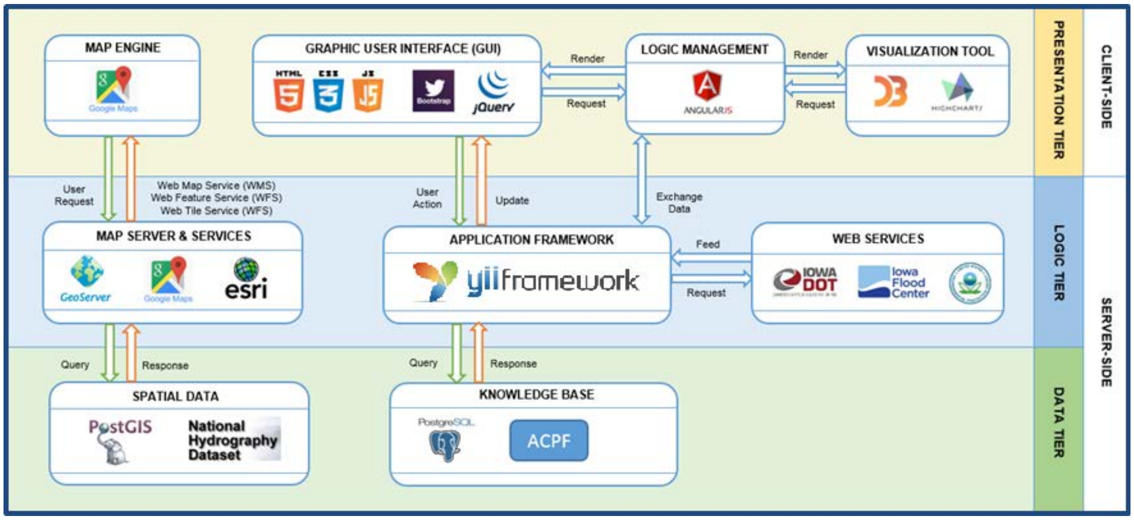
3.1 Architecture, Software, and Technologies

Most of the “IOWA DOT Culverts” platform cyberinfrastructure and components are described in Xu (2015) and Xu et al. (2015), therefore only salient features of the geo-portal are provided in this section. The IOWA DOT Culverts geo-portal comprises a front-end and a back-end component (the term “front-end” is referring to user’s computer, while “back-end” indicates the server backing the web applications; front-end is the client-side, while the back-end is the server-side section of a web platform). As is common in most modern web-application templates, the IOWA DOT Culverts platform adopts a three-tier architecture that includes the following components: (1) presentation, (2) logic, and (3) data. To ensure platform reliability, flexibility, extendibility, modularity, and maintainability industrial design patterns and architecture patterns (e.g. model–view–controller (MVC) and model-view-view-model (MVVM) software) were applied in the system development. Figure 12 illustrates the overall architecture, along with the web, informatics, and GIS technologies that are associated with each tier.

The presentation tier is primarily rendered at the front-end in a user’s web or mobile browser. It contains platform elements that a user can see and interact with. This tier provides users with Graphic User Interfaces (GUI), a map engine, and visualization tools to facilitate map operations, information retrieval, workflow control, watershed planning, and communication. The presentation tier in the IOWA DOT Culverts platform entails four components: (1) the map engine, (2) the GUI, (3) logic management, and (4) the visualization tools. The map engine is the means to visualize geo-spatial information, such as base maps, river networks, watershed boundaries, locations of the culverts, and modeling results (e.g., RUSLE). The presentation tier is developed with Leaflet JavaScript (JS) library and its extensions. The GUI provides a media for users to navigate through the platform, manage and control tools, and retrieve information. The GUI is developed using JQuery and Bootstrap JS library, which guarantees both user interactivity and compatibility for multi-screen sizes.

The logic management component contains a front-end MVC that improves fluid web page design and two-way data-binding. The main reason to have a logic management component is that our platform contains Single-Page Applications (SPAs), which make the front-end very heavy. The front-end MVC, a JavaScript library itself, helps structure and optimize the front-end developments with practical industrial conventions, which increases the maintainability and extendibility at the front-end. Visualization tools are primarily responsible for visual communication and representations (e.g. plots, chart). They are developed with D3.js and HighChart libraries, both of which are data-driven and user-responsive. The entire presentation tier is developed using common front-end technologies (e.g. JavaScript, HTML, and CSS). To perform multiple system operations (e.g. updating data & information, displaying spatial features on a map, user log-in, saving user-defined watershed plans), the presentation tier sends Asynchronous JavaScript and XML (AJAX) requests to exchange information with the server-side applications in the form of JSON, XML, and images. A summary of the software components in the IOWA DOT Culverts problem is provided in Table 5.

a)



b)

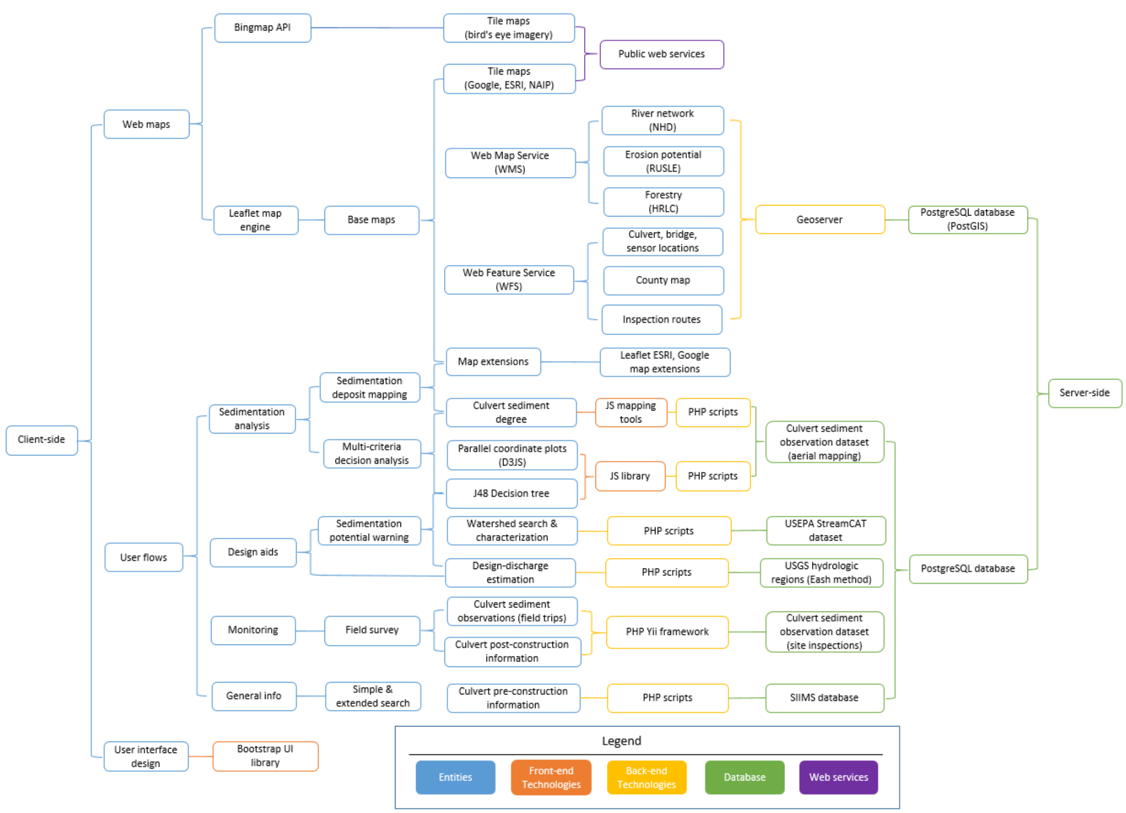


Figure 12. IOWA DOT Culverts portal: a) architecture; b) user-server flux (Xu et al., 2015).

Table 5. Summary of software components, their role, and associated programming languages.

COMPONENT	ROLE	TECHNOLOGY
Development Technology		
Back-end		
Apache HTTP Server	Web Server	-
Apache Tomcat	Web Server	-
Geoserver	GIS Map Server	Java
PostGres & PostGIS	RDBMS	SQL
PHP YII framework	Backend MVC	PHP
Front-end		
Jquery	cross-platform JS library	Javascript
Jquery-UI	Jquery UI design library	Javascript
Bootstrap	UI design library	Javascript
Bootstrap	Bootstrap switch	Javascript
Leaflet	Map engine	Javascript
Leaflet-Esri	Leaflet plugin	Javascript
Leaflet-Google	Leaflet plugin	Javascript
Leaflet-Draw	Leaflet plugin	Javascript
Highchart	Plots	Javascript
Highchart-more	Plots-extension	Javascript
D3JS	Data visualization	Javascript
D3JS_leaflet	Leaflet plugin	Javascript
Leaflet open-weather	Leaflet plugin	Javascript
Google map API	Map engine	Javascript
typeahead.js	Text autocomplete	Javascript
BingMap API	Map engine	Javascript
Leaflet geolocator	Leaflet plugin	Javascript
Geolocator control	Leaflet plugin	Javascript
Leaflet routes	Leaflet plugin	Javascript
Lagodiuk decision tree	Javascript machine-learning	Javascript
UI design double scroll	Jquery UI design	Javascript
Three-js	3D visualization	Javascript
Data Sources		
Iowa Flood Center	Stage sensor	PHP web-service
United States Geological Survey	Stage/discharge sensor	USGS web-service
USGS SSURGO	Web map service	Rasters
RUSLE	Web map service	Rasters
High Resolution Land Cover	Web map service	Rasters
SIIMS	Culvert information	CSV
EPA StreamCAT	Watershed characterization	CSV/Web services

Unlike the presentation tier, the logic tier and data tier are deployed on the server-side (i.e., "back-end" of the platform). The logic tier is responsible for organizing the data, assembling the services based on the relationship between the user scenarios and the models, and for providing the necessary information requested by the presentation tier. The logic tier consists of three sub-components: (1) the map server and map services, (2) the application framework, and (3) the web services for real-time sensors (very few sensors are connected in this platform but the connection capabilities are available). The map server and web services prepare and manage spatial information, as well as handle requests from the presentation tier for the map visualization. The IOWA DOT Culverts uses GeoServer (GeoServer, 2014), an open-source map server application for hosting spatial information stored locally on the server (e.g. river, watershed boundaries). The GeoServer complies with a number of open standards, such as Web Feature Service (WFS), Web Map Service (WMS), and Web Coverage Service (WCS), which improve the interoperability of spatial data. Third-party map services from Google and ESRI are also used to increase the diversity of the base maps (e.g. satellite imagery, topo-maps, and NHD basemap) within the platform. The application framework components manage the overall back-end logic (e.g. models, culvert design data, and data integration) and user-scenarios.

Many of the platform's tools and applications (e.g. the watershed search engine) are hosted in the application module. This module hosts, and is responsible for, managing the local web services. The system design adopts a Service Oriented Architecture (SOA) to bring multiple web services together in one place. There are two types of web services in the Iowa DOT platform: (1) local web services (that are developed within the application framework on the local server), and (2) external web services (that are hosted on third-party servers). External web services in IOWA DOT Culverts are mainly third-party data providers (e.g. USGS, EPA). The web services are important components for the presentation tier as they facilitate the communication between the presentation and the logic tier. The backbone of the application framework module is Yii (a PHP framework that also follows the MVC pattern). The data tier is located at the bottom of the architecture and consists of databases and datasets. The spatial data are stored in the PostgreSQL database with its PostGIS library, which adds support for the use and management of spatial objects.

The platform uses two (front-end) mapping engines: Leaflet and Bing Map API. Leaflet is used as the primary map engine to display base maps and most of two-dimensional features. Bing Map API is used to display 40 degree bird-eye views, considered a 2.5-dimensional representation for a map. Leaflet is a popular open-source, mobile-friendly JavaScript map engine library designed for interactive web mapping. Compared to other modern map engines (e.g., OpenLayers, ArcGIS JavaScript API, Google Map), Leaflet is the most light-weight and flexible. Leaflet supports WFS, WMS, and WMTS produced in any geographic coordinate system, geographic features or maps in geographic projection system though the usage of customized extensions. The fundamental Leaflet provides a basic method to display a base map, overlay, and data visualization in browsers, while its diverse extensions provide more advanced features in web mapping. The map services and Leaflet extensions used by the Leaflet Map Engine in the IOWA DOT Culverts platform are provided in Xu (2015).

The front-end consists of a GUI and an interactive map created using HTML, CSS, and JavaScript (MDN, 2015). The GUIs are created for function implementation, workflow navigation, and platform control purposes. In other words, through the interface, the user is able to find and select specific functions or tools for certain data or analytical demands. The GUIs also create classifications for different functionalities and workflows. The platform's GUIs are programmed with static HTML and CSS languages. JQuery (Project, 2010) and generic JavaScript language are attached to the webpage to create dynamic, interactive effects for the users. An interactive map is built to visualize geographic information and spatial data, and is composed of web map engines and web map services. The platform uses Leaflet (Agafonkin, 2010), Bing Map API (Microsoft, 2014), and various Leaflet extensions as map engines.

The back-end of the geo-portal holds the database, the GIS web server software, and the server software. The database stores local spatial data, tabular data, and model results for the platform. Other map data are obtained with web services connected to the IDOT database and other public digital repositories. The platform usesthe PostgreSQL database with PostGIS extension as the main database, which grants original Postgres with spatial capabilities. Middleware programs are used to connect the database with the front-end mapping engines and to distribute data for different applications. The platform also adopts subject-oriented data structure, which optimizes data downloading and browser caching to save system loading time. This structure is built with middleware programs. GIS web server software is used to manage and distribute spatial data.

3.2. Cyberinfrastructure for Data Integration

The Iowa DOT architecture uses the Digital Watershed (DW) concept as a spatial unit for assembling multi-scale, multi-domain data acquired in-situ or resulting from models produced by various agencies. The selection tool offers multiple choices for the search (e.g., HUC or administrative key words) and subsequently triggers visualization of watersheds associated with the selected culverts. Using the spatial boundary of the delineated drainage area, the portal dynamically generates a DW of the area entailing the data and information stored in the system's database. Organization of the data in DW is made by indexing the data with an identifier that relates the data with the watershed.

The backbone of the watershed characterization module is the NHDPlus daaset, which provides physical (e.g. shapefiles of rivers, catchments, and watershed boundaries) and topological (e.g. river connectivity, hierarchy of tributaries, hydrologic unit code system) descriptions of the real-world hydrologic system in a digital environment. The physical description includes features such as streams, catchments, and hydrologic unit code (HUC) watersheds that are either displayed on the map or spatially indexed with the data resources (e.g. raster data, point-observation) associated with them. Results of previous modeling (e.g., RUSLE) or syntheses (e.g., StreamCat) and structural information associated with culverts are also spatially indexed. The watershed data and information can be easily discovered and retrieved for each indexed watershed (e.g. by structure number, or river or road name). The NHDPlus covers hydrologic features at a national level, and it is widely used among research groups and watershed management communities in the U.S. The dataset can be easily extended in terms of spatial coverage and new attributes. The overall structure of the data integration and their sources is provided in Figure 13.

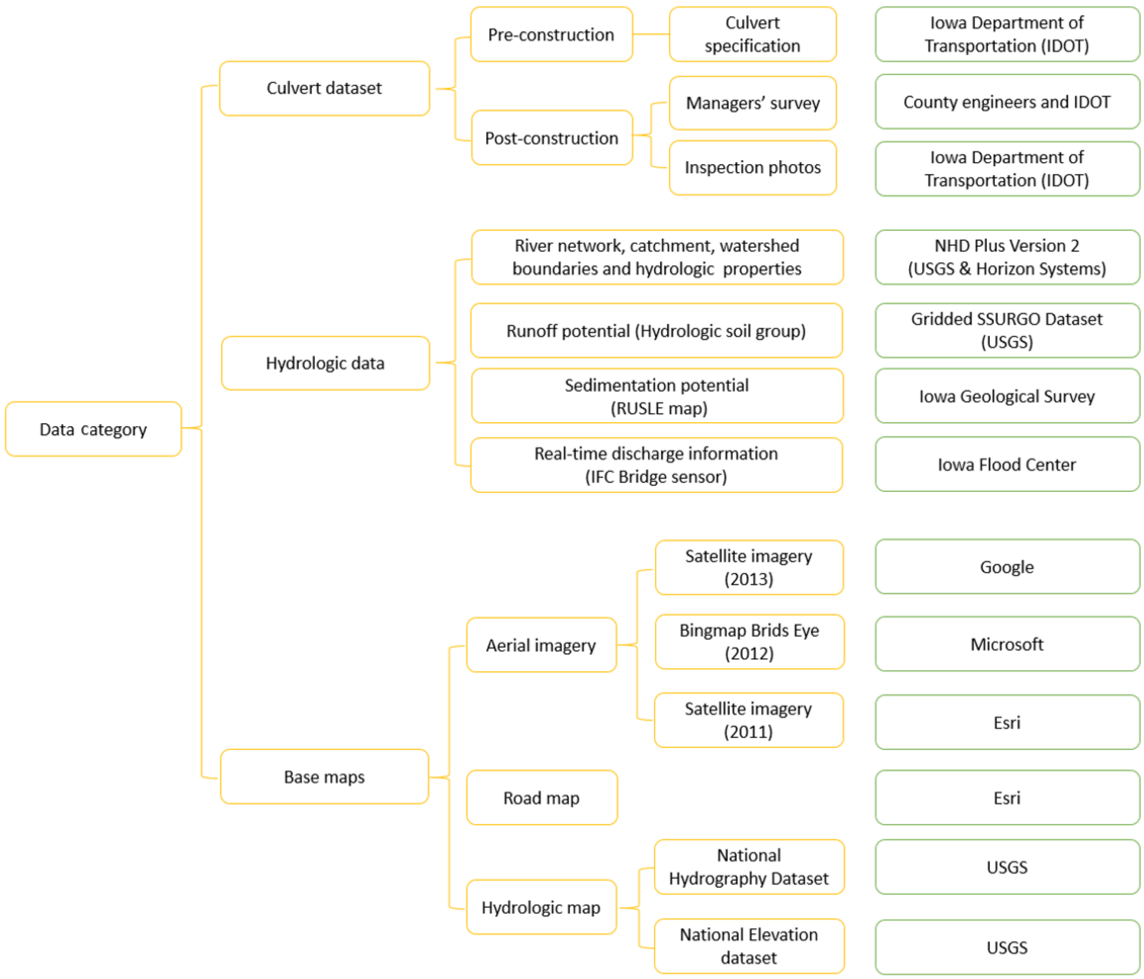


Figure 13. Structure of the data contained in the IOWA DOT Culverts platform.

Leaflet is used for 2D map visualization while Bing Map API contains 40 degrees bird's-eye views, which is used for 3D map visualizations. Both mapping engines visualize the map using map services from the map server. Extensions of Leaflet include Leaflet Projection Extension, Leaflet-Google Map API, ESRI-Leaflet API and other supporting upgrades (Agafonkin, 2010). The purpose of Leaflet Projection is to enable the Leaflet mapping engine to display web maps in miscellaneous projection systems. Leaflet-Google Map API and ESRI-Leaflet (ESRI, 2015) API are used to improve spatial data interoperability and compatibility with other GIS software and web services. Map services in the platform are materialized through Web Map Service (WMS) (OGC, 2009), Web Map Tile Service (WMTS) (OGC, 2011a), and Web Feature Services (WFS) (OGC, 2011b). The platform provides a variety of base maps including aerial imagery, street maps, topographic maps, and hydrographic maps. Aerial imageries acquired from a different time period create a time series for monitoring environmental, topographical, and infrastructural changes.

Besides the base maps, the platform allows users to visualize the culvert location, river cross-section, point of interests, and sensor locations. All these data are converted to WFS and stored in GIS web server software. The reason to use WFS, and not WMS, is that vector based web features services are much more interactive than image-based WMS. The GIS web server software can also store and execute online geo-processing services. Those online geo-processing services grants the platform the ability to run hydrologic models on the fly. The OGC GeoServer and ArcGIS servers are the two GIS web server software used in the platform. For optimization of the operations on the platform, the ArcGIS server was replaced with custom created scripts hosted on an IIHR server.

3.3. Workflows

"General Info" workflows. Information about the culverts is retrieved through two search engines. Each of the search engines retrieves the boundary and drainage area upstream of a selected culvert and can retrieve any point of interest (POI) on the Iowa state map. With this arrangement, watershed characteristics for existing and future culvert locations can be retrieved. The dataset for existing culverts contains pre-construction and post-construction culvert data. Pre-construction data include the locations and design specifications of the 723 multi-box culverts (mainly 3 & 4-box culverts maintained by Iowa DOT). Culvert locations are provided in geographic coordinates and converted into a shape file with joint specification as attributes. Culvert specifications contain elementary culvert design data, including culvert structure numbers, owner, type information, state code, and geometry information. All of the pre-construction data are stored in a PostgreSQL database. The post-construction data contain information acquired during routine trained inspections or following the occurrence of severe storm events. Maintenance information includes written comments and photographs of the culvert. This data is stored for some of the Iowa culverts in the IDOT SIIMS database. These maintenance records also contain IDOT engineer recommendations regarding the asset status. Figure 14 reproduces typical information stored in the IDOT SIIMS database.

The culvert database is connected to the GeoServer software using the FHWA structure number so that data called by the platform can be transferred to the client-side as a web feature service displayed on the map. As the caching of the entire pre-construction data at the client-side is slow, the data caching is made using a subject-oriented data structure. The location of the culverts is cached only when the platform is loading. While users request specific functions or applications, the related culvert specifications are subsequently loaded. The culvert search workflow is controlled through friendly graphical interfaces that accommodate the needs of engineers with a minimum computer programming background. The culvert search workflow combines the culvert data repository and regional hydrologic analysis with soil loss models to compensate for the lack of information on sedimentation in current design specifications. The culvert monitoring workflow allows managing personnel to query comprehensive culvert information and inspect the physical status of culverts through high quality aerial imagery taken over time. The flow diagram for culvert search and monitoring is provided in Figure 15. The results of the post-construction surveys conducted by the IDOT personnel are recorded under the "Managers' Survey" in Figure 15. More details about the workflow interfaces, associated tools, and outcomes can be found in Appendix A.

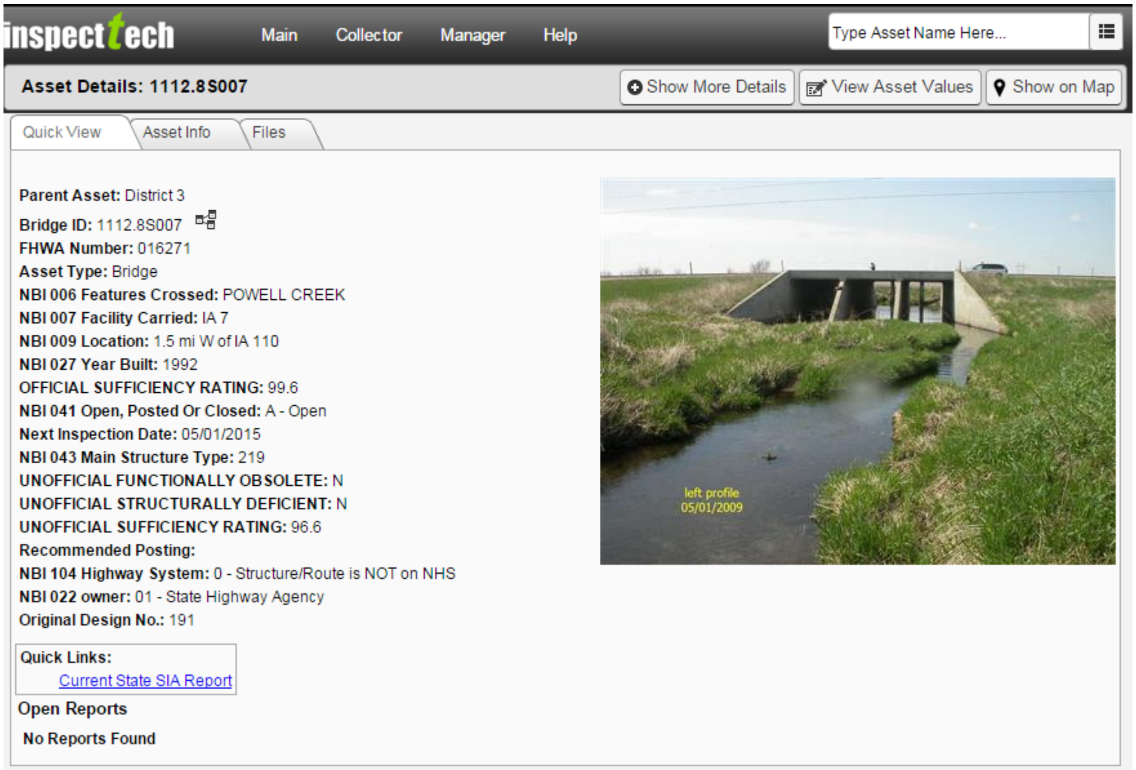


Figure 14. Maintenance record in the IDOT SIIMS database (SIIMS, 2015).

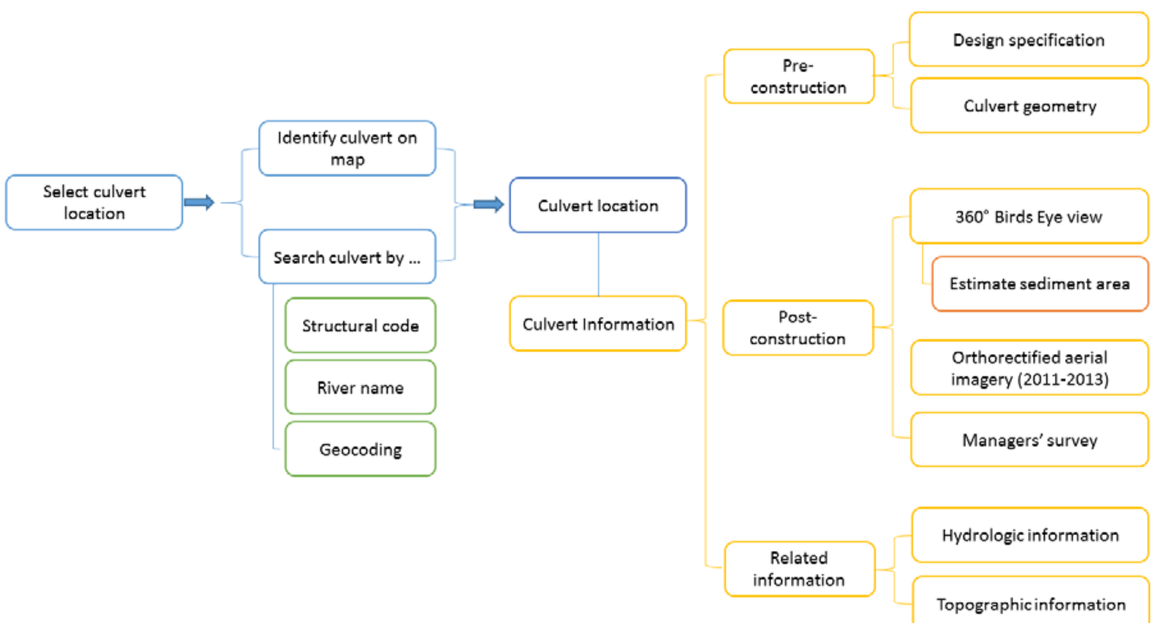


Figure 15. Flow diagram for the "General info" workflow.

"Monitoring" workflows. This cluster of tools is assembled with the intent to aid culvert monitoring activities. Specifically, the workflow assists users to inspect a culvert site and observe time series and details of the surrounding terrain provided from LiDAR maps. The flow of information for this workflow is illustrated in Figure 16a. Useful tools for navigating to sites and organizing field campaigns that cover specific purposes are also embedded in this workflow. Figure 16b shows itineraries created for this study to inspect the 250 culverts in the state. The Iowa DOT Culverts platform offers a choice of background base maps, including high-resolution topographic maps derived from national elevation datasets, watershed and river information from national hydrographic datasets, and 1-meter LiDAR hill shaded maps, which provide the user with a 2.5D view of the culvert geometry and surrounding terrain. This variety of maps allows users to view various aspects of culvert sedimentation detail and its evolution. Shortly after the surveys are finalized, the monitoring results can be viewed immediately if the field communication tools are connected to the platform. To view the information, the culvert search tool is used, first to access the culvert using the site metadata (structural code, geocoding and the river on which the culvert is located). After locating the culvert of interest, the system automatically displays two inspection windows for the selected site. The first window contains basic information about culvert design and geometry, as illustrated in Figure 16b.

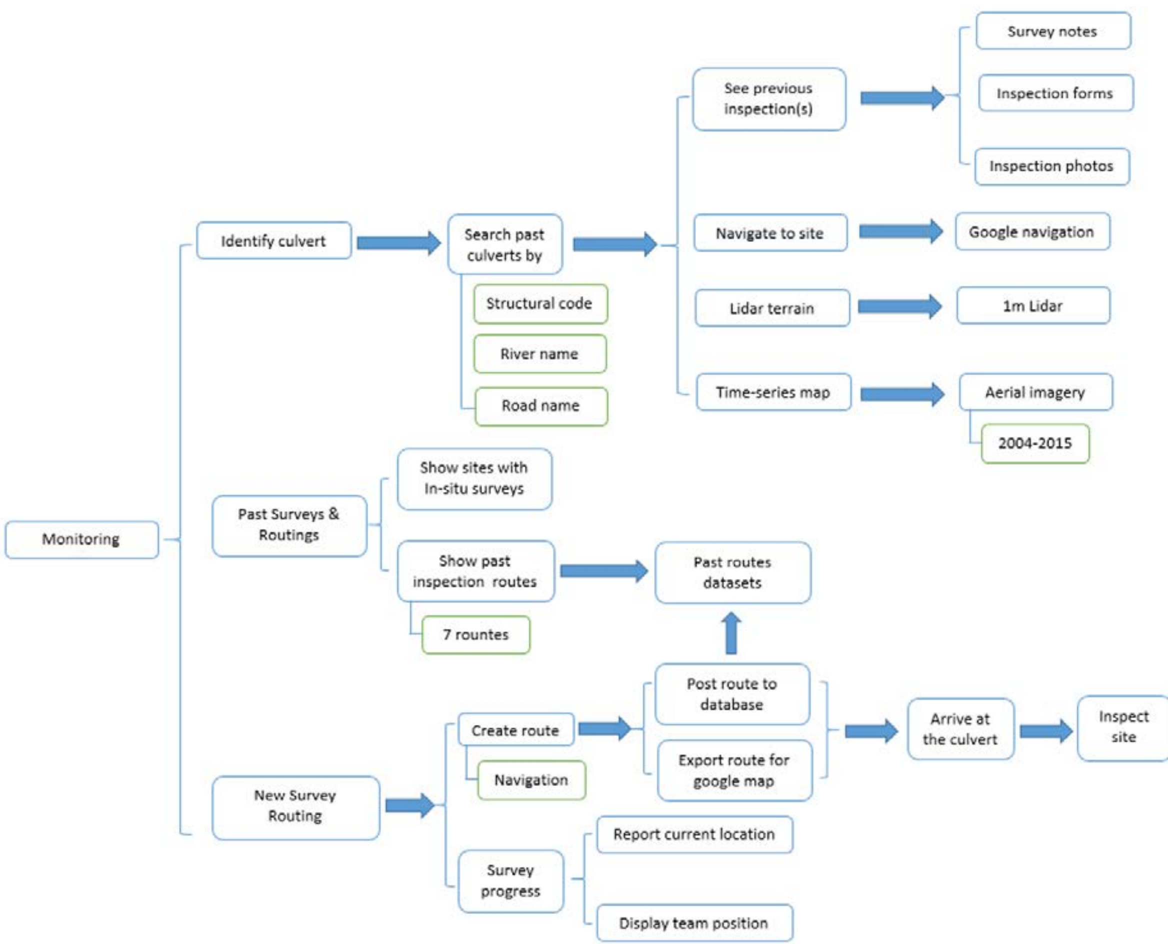
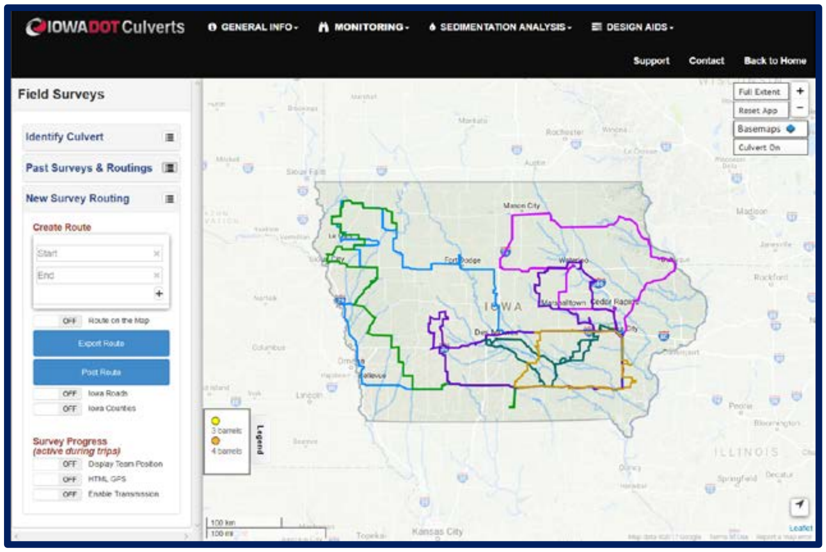
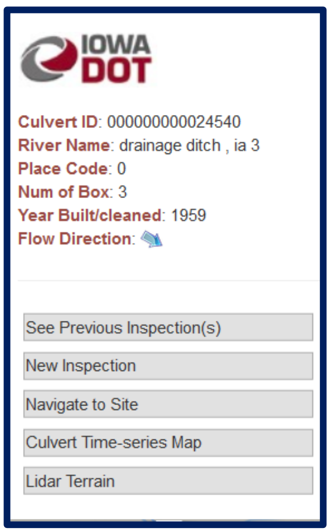


Figure 16a. Flowchart for the "Monitoring" workflow

b)



c)



d)

Figure 16 (continued). Functions associated with the "Monitoring" workflow: a) engine for aiding navigation at multiple sites in the "monitoring" workflow; b) metadata and functions associated with individual culverts; and c) time series for a culvert with recurrent sedimentation.

Another useful feature that takes advantage of the availability of orthorectified aerial imagery from 2004 to 2013 stored in the Iowa DOT Culverts platform is the culvert sedimentation time series. For example, the time evolution of the sediment deposits can be quite reliably tracked with a customized map viewer that covers the same area in the vicinity of the culvert to make the analysis efficient. A sample time series is provided in Figure 16c. The availability of the aerial images (dating back to the 1940s) allow users to make abundant inferences about the sedimentation process as a whole as the retrieved images also document morphological changes in the configuration of the stream in the culvert vicinity. More details about the workflow interfaces, associated tools, and outcomes can be found in Appendix A.

“Sedimentation Analysis” workflows. This is the central group of cybertools in the platform that are focused solely on the quantification and evaluation of the sedimentation as an end-to-end process, i.e., the “Sedimentation Deposit Mapping” and “Multi-Criteria Decision Analysis” workflows, respectively. The first workflow contains several mapping alternatives for the estimation of the degree of sedimentation that are subsequently used in the MCDA phase. The quantification of culvert sedimentation status is made directly on the aerial photograph contained in the display window, illustrated in Figure 17. Using geo-referencing techniques and geo-processing services developed specifically for this purpose, the user can delineate, using a polyline, the boundary of sediment deposit at the culvert. The map engine estimates the geo-coordinates of the polyline vertices and imports the results into a geo-processing service for area calculation. If required, the geo-processing service is capable of roughly estimating the volume of the sediment in the mapped deposit using area and elevation information available in the digital elevation model. A similar geo-processing tool is available to estimate the stream width that is subsequently used to define the critical process parameter of stream-to-culvert width ratio (see Figure 20). The workflow allows users to inspect the archive of sediment deposit maps, redo the mapping, or create a new map for the culvert site.

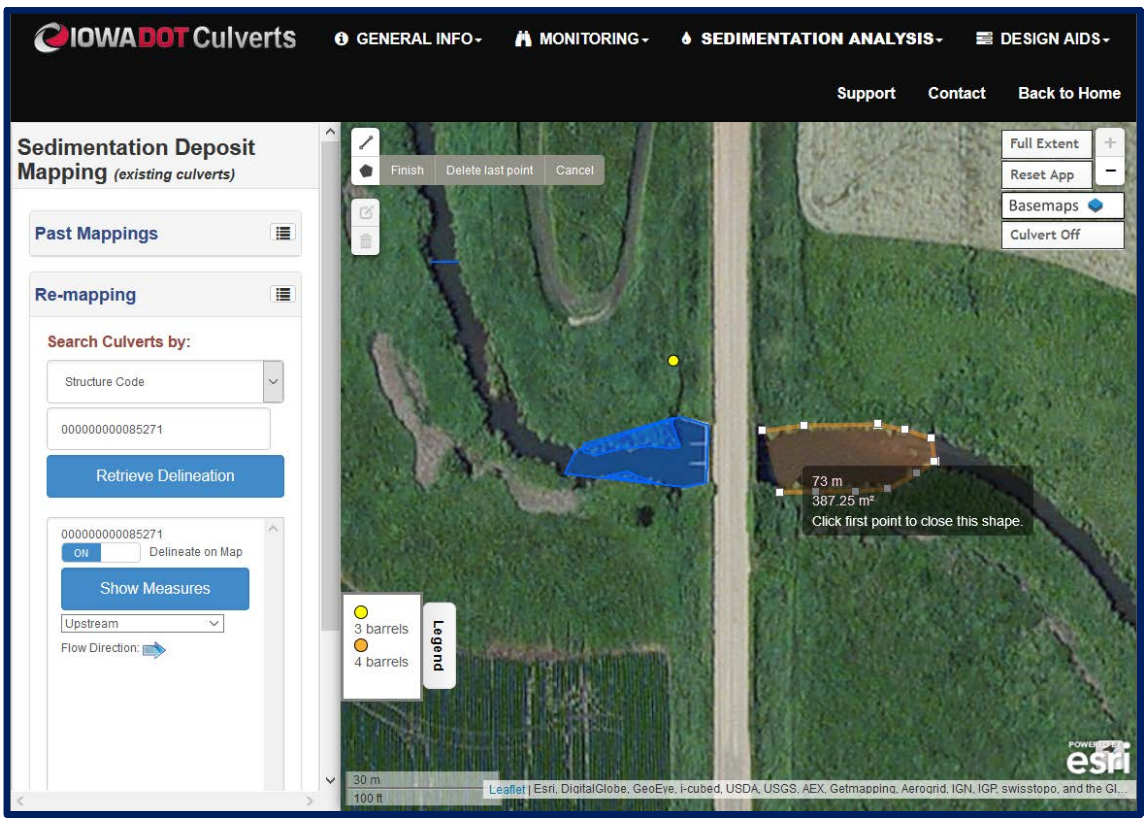


Figure 17. The geo-processing tools associated with the “Sediment Deposit Mapping” workflow.

All numerical and textual information are retrieved from the specialized IDOT database (SIIMS), while the graphical information produced during geo-processing is transmitted through Web Map Services (WMS). As the SIIMS information is continuously updated after culvert construction, it is very useful in aiding the mapping process by providing a glimpse of the dynamics of the geo-morphological processes at the culvert site. Given that SIIMS is widely used across the U.S. transportation agencies, it makes the functions developed for the IOWA DOT Culverts platform easily extendable to other settings across the nation. The flow chart for the “Sedimentation Deposit Mapping” workflow is included in the diagram provided in Figure 15, with the outcomes enclosed in the “Sediment mapping” block of the figure. More details about the workflow interfaces, associated tools, and outcomes can be found in Appendix A.

The “Multi-Criteria Decision Analysis” (MCDA) workflow quantifies the relationship between the degree of sedimentation at culverts and the predictor variables integrated in the portal’s database. The MCDA’s main objective is to develop quantitative relationships between the degree of culvert sedimentation and the key process drivers within the drainage area of the culvert using deductive hydrological classification powered by machine-learning and visual-analytics techniques. The MCDA is typically based on a tree-like hierarchy of criteria and alternatives. The structure of the tree for the MCDA used in our study is shown in Figure 18a. The overall flux of information for the “Sedimentation Analysis” workflows is illustrated in Figure 18b.

In addition, interactive scientific visualization, consisting of parallel coordinate plots and principle component charts, is used to improve the interpretation of the analysis and enable human judgments in the final stage of the decision support loop. It is important to distinguish between the support for MCDA methods and for the MCDA process (Mustajoki & Marttunen, 2017): the first focuses on supporting the visualization and technical implementation of applying the method, and the latter provides more general guidelines and good practices for carrying out the whole process in a meaningful way. Mustajoki & Marttunen (2017) analyzed 23 MCDA software tools in terms of their applicability to support environmental planning processes and concluded that none of the analyzed software tools can be used without prior experience of MCDA. Our platform hides the complexity of the MCDA from the platform users by not allowing them to interfere with the analysis settings.

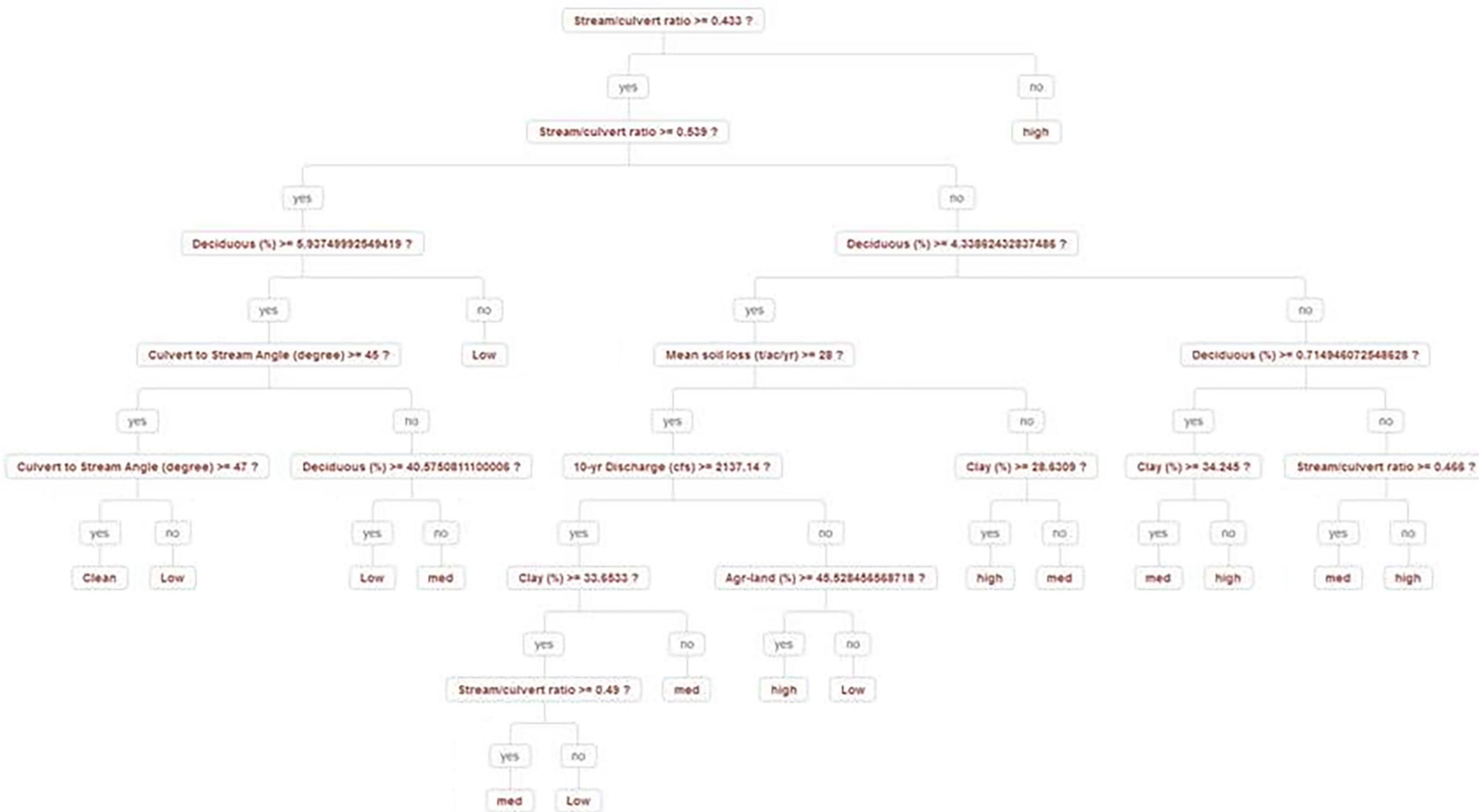


Figure 18a. The tree-like structure used for the Multi-Criteria Decision Analysis applied to the sedimentation at culverts.

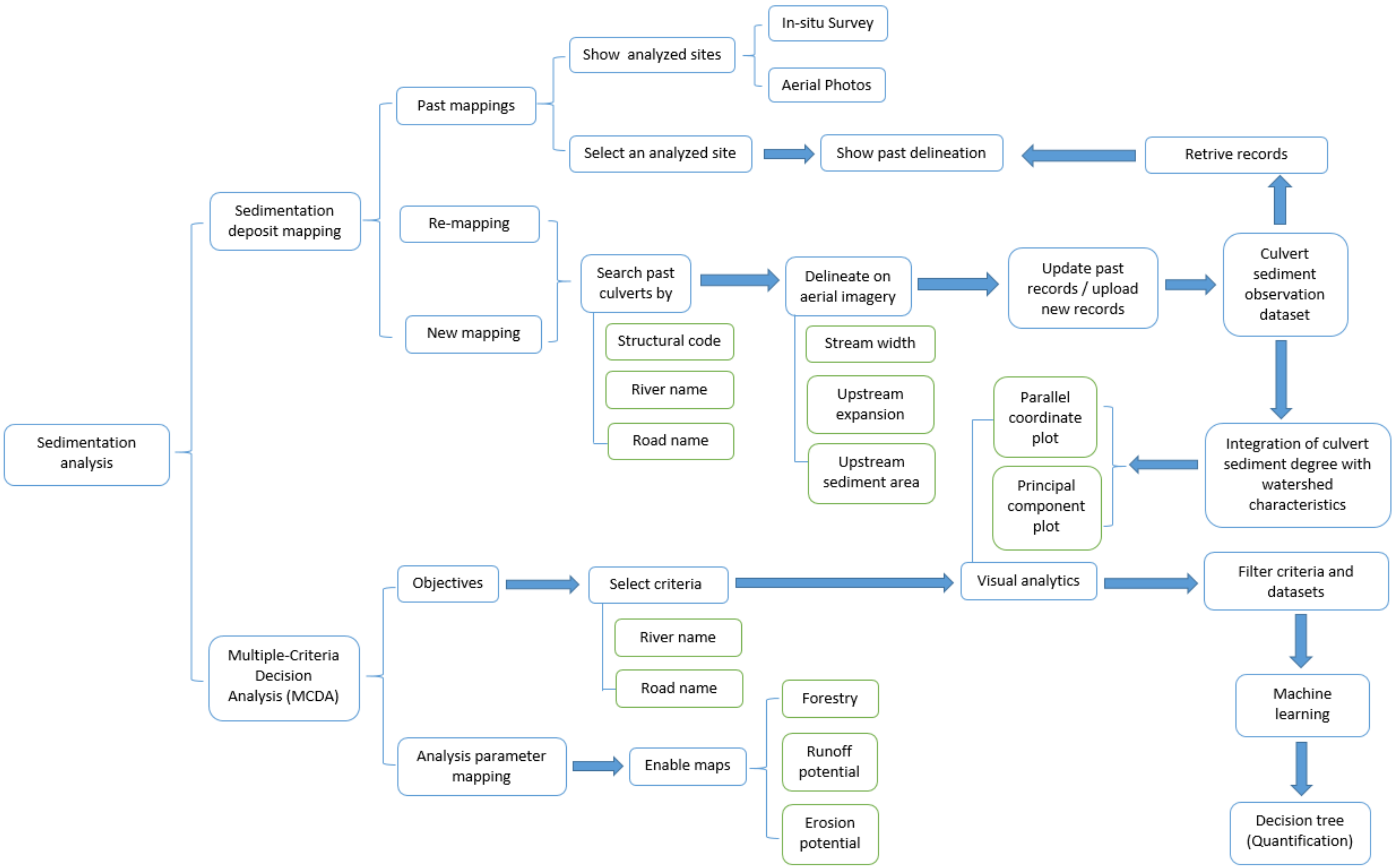


Figure 18b. The tree-like structure used for the Multi-Criteria Decision Analysis applied to the sedimentation at culverts.

As mentioned in Section 2.4, in this study we use a decision tree ensemble to establish reliable quantifications and cause-effect relationships between culvert sedimentation and drivers. This task includes hydrologic classification techniques (e.g. catchment classification and corridor classification) using both supervised and unsupervised machine learning techniques. The techniques proposed for assessing the robustness of the sedimentation prediction is based on tree-ensembles. Tree-ensemble method uses multiple decision tree algorithms to obtain better predictive performance than could be obtained from any of the constituent trees alone. The tree-ensemble method derives an empirical relationship using a tree-like model of key drivers and their possible consequences regarding culvert sedimentation degrees. All the culverts with quantified sedimentation degree are used as training datasets, while the testing dataset is the one acquired through the field inspections.

The visualization of the outcomes of the MCDA analysis on the IOWA DOT Culverts platform is illustrated in Figure 19. The figures display the multi-variate plot of the dependencies among key process drivers for all the sites surveyed on the aerial images. The variables on the vertical axes can be selected for preferential ranges to illustrate the effect of various choices of selection. The results of these on-line analyses are dynamically calculated and updated on the interface in real time. Sample of these analyses are provided in Section 4. More details about the workflow interfaces, associated tools, and outcomes can be found in Appendix A.

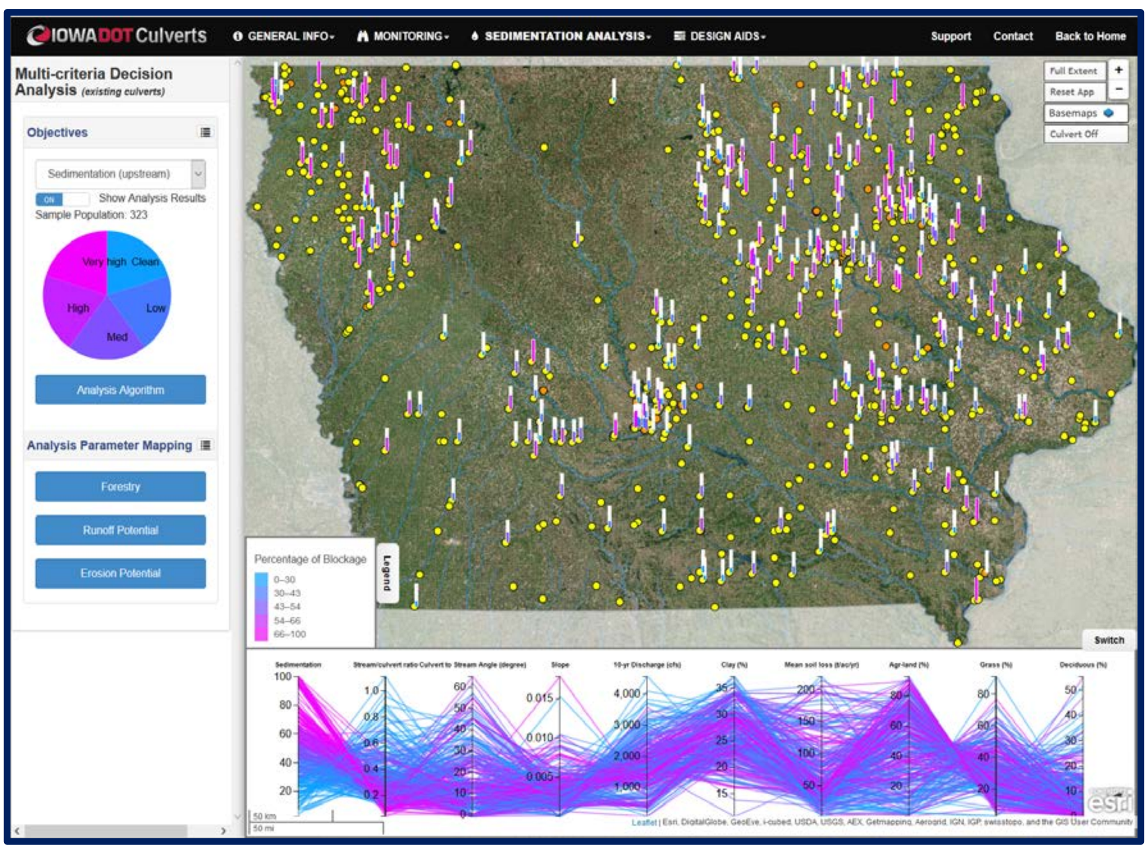


Figure 19. Outcomes of the MCDA as applied to all culverts (aerial imagery surveys).

"Decision Aids" workflows. This set of workflows is practically the corollary of all the developments carried out through this study. The toolset includes useful aids for the culvert designer or operation personnel by providing the data needed for the estimation of the culvert design discharge and assessment of the degree of sedimentation at the culvert construction site. The tools can be used to estimate these variables at existing or future culvert sites. Based on the degree of sedimentation provided by the forecasting tool, the user can decide if the culvert needs to be re-evaluated in terms of hydraulic design or to be associated with protective measures to mitigate sedimentation. These measures can include practices that reduce erosion and sediment transport in the upland areas or can recommend self-cleaning solutions such as those developed in a companion study on culverts (Muste and Xu, 2017).

The first decision aid of the IOWA DOT Culverts portal is for the estimation of design discharge that is used in the hydraulic sizing of the culvert. The discharge is calculated using the current IDOT estimation protocol whereby its value is set to the magnitude of the annual exceedance-probability discharge. There are several methods to estimate this probability. This study used the USGS Eash method based on regional regression equations applied to the culvert drainage area (Eash, 2001). The discharge estimation algorithm is the same as the one incorporated in the StreamStats software package developed by USGS to provide users with assistance when using various water-resources planning and management tools (https://water.usgs.gov/osw/streamstats).

The input information required for the design discharge calculation for a planned or existing culvert includes the watershed boundaries and hydrologic observations in the enclosed drainage area. In order to accommodate this input information, the portal uses a geo-processing service based on python scripting and ArcPy (i.e., Arc Toolbox Python API) for delineating the drainage area, with consideration of the hydrologic regions defined by the USGS Eash method. The delineation is done using intersect tools in ArcPy library. Numerical values for each drainage area are calculated using an Arc Toolbox script called "Calculate Areas" under "Spatial Statistics". The numerical results of the analysis outcomes are sent to the front-end through the geo-processing service provided by the ArcGIS server. At the front-end, these results are plugged into the respective regression equations corresponding to the hydrologic regions their divided area lies within. The outcome of the geo-processing tool is illustrated in Figure 20.

The forecasting of the degree of sedimentation at culverts is the premier product of this study as it embeds all the artificial intelligence tools incorporated in the IOWA DOT Culverts platform. This workflow is labeled "Sedimentation Potential Warning" and is located under the "Design Aids" cluster of the IOWA DOT Culverts platform. The tool provides the degree of sedimentation for existing or new culvert sites. The degree of sedimentation is defined as the ratio of the total area of the expansion upstream from the culvert divided by the area covered by sediment deposits. The forecast is currently based on the "training" of the MCDA that used all the culvert sites analyzed with aerial imagery with the "Sediment Deposit Mapping" tool. From this perspective, it is obvious that the accuracy of the forecast can be improved by adding new analyzed cases to the statistical sample used for training the forecasting. The MCDA is dynamically linked to the mapping database, therefore every addition of a culvert mapping to the database (using any of the methods described in Section 2.3.2) will increase the robustness of the forecast.

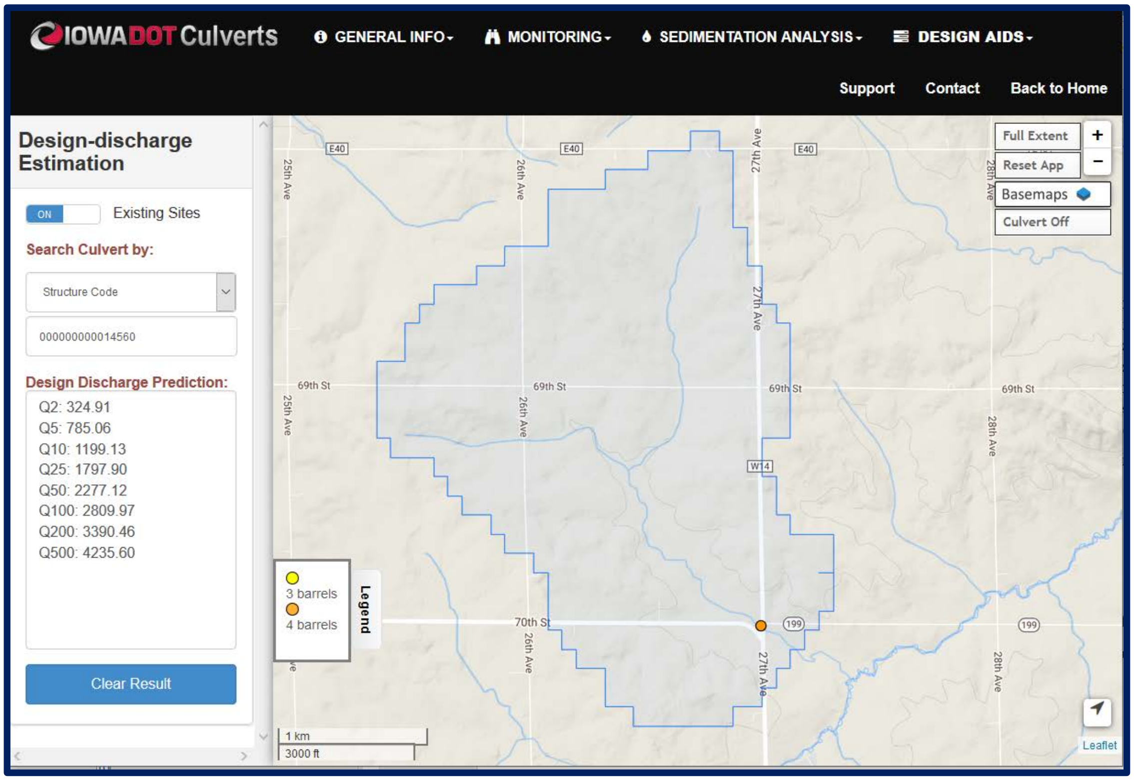


Figure 20. The interface for the estimation of the culvert design discharge (discharge estimates for various return periods are provided in the lower box of the left info panel).

The MCDA ingests multiple independent variables (predictors) that define the status of the dependent variable (response variable). For an existing culvert, all the independent variables are fixed as they are related to structural, watershed, and stream characteristics that do not change over small time scales (i.e., soil type, watershed physiography, vegetation cover, etc). The role of sedimentation forecast in this situation is to validate the forecast prediction for the degree of sedimentation at a given site. For new culvert sites, however, the forecast can play a role in sizing the culvert, as the hydraulic portion of the culvert design allow some freedom in terms of selecting the culvert cross-section or changing the hydraulic controls at the culvert. The flowchart of the information within the "Sedimentation Potential Warning" is provided in Figure 21.

Out of all the independent variables of the MCDA, the "stream-to-culvert width" (SCW) ratio is the only variable that can vary at the design stage. Specifically, if the hydraulic design suggests a certain size cross-section, the designer has several choices to combine with the prescribed box shape and sizes that result in wider or narrower total culvert width (labeled with *w* in Figure 21a). The designer has also to decide if the inlet and outlet wingwalls associated with the culvert are set oblique or straight. To account for this flexibility, the forecast workflow embedded in our portal allows the user to adjust the SCW ratio when searching for the sedimentation potential. The outcomes of the MCDA analysis are different for the same culvert site commensurate with the value selected for the SCW ratio. In order to support decisions on mitigating sedimentation both in design and operations, the workflow provides the option to adjust the SCW ratio for both existing and new culvert sites (see Figures 21b).

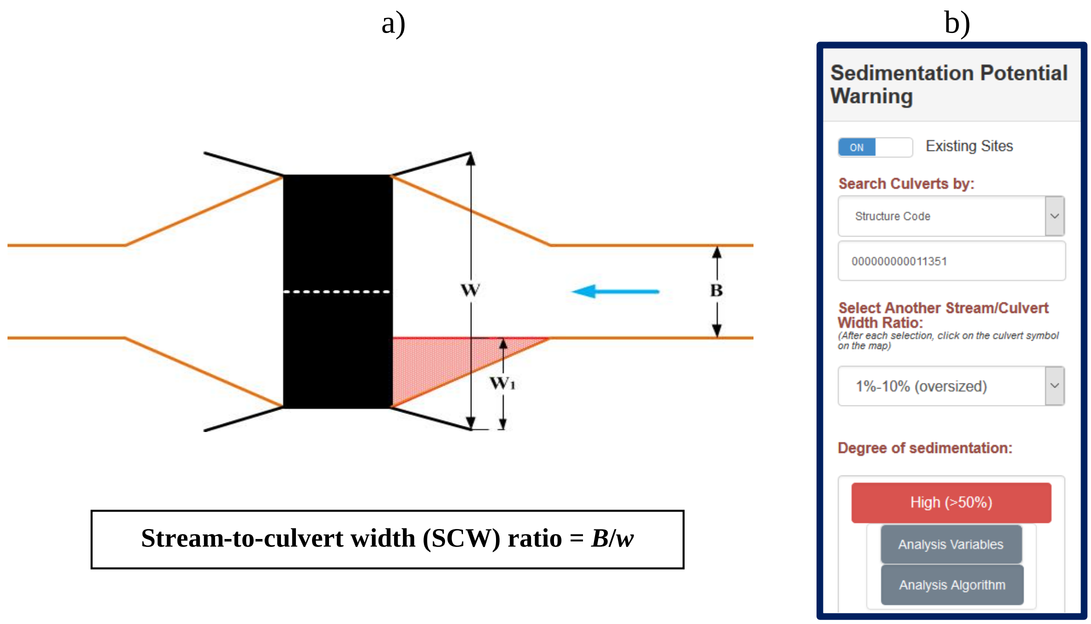
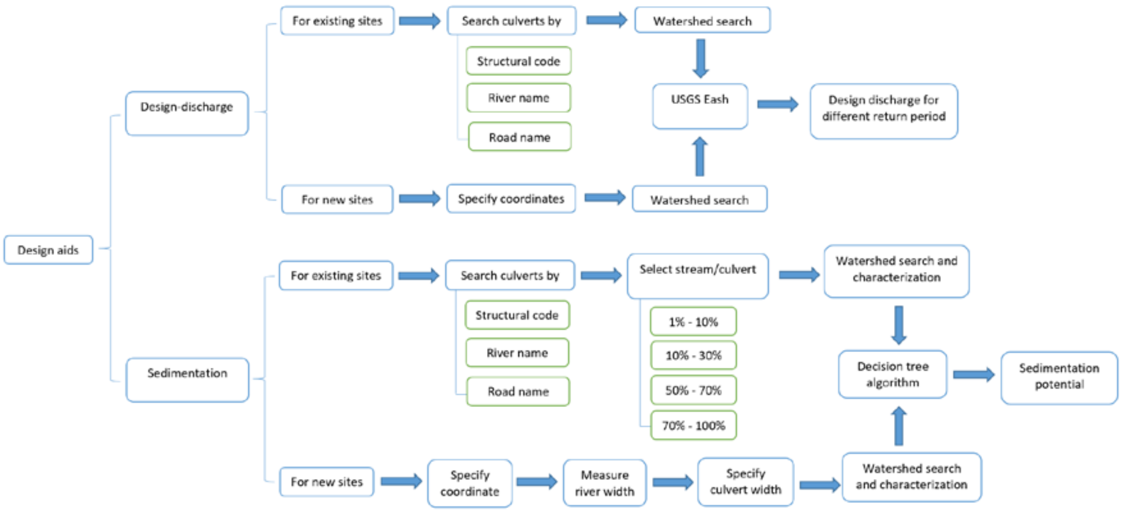


Figure 21. “Sedimentation Potential Warning” workflow: a) definition sketch for the stream-to-culvert (SCW) ratio; and b) forecasting interface for existing culvert sites.

For new culverts, an additional step required for the MCDA input is the establishment of the stream width at the site. The workflow for the sedimentation forecast at new sites is provided in Figure 22a. The stream width required for the forecasting input can be estimated using the workflow by using the same geo-processing tool described in the Sediment Mapping workflow. For this purpose, the length measurement tool is activated (see Figure 22b). The stream reach approaching the culvert can be affected by morphological changes; hence, it might be difficult to detect a “representative” stream width in the upstream area.

For getting such a representative stream width we suggest making a visual inspection of the stream upstream and downstream from the culvert to get a good sense of the reaches where the stream appears undisturbed, i.e., lacking channel non-uniformities such as bends, naturally occurring weirs, or other obstacles in the stream. Once that inspection is finished, select a “representative” channel reach. Several cross sections are sequentially measured with the geo-processing tool on the representative stream reach. The portal geo-processing tool records each individual measurement and provides an average of the measurements that can be subsequently used to calculate the SCW ratio. Once this ratio is determined, the forecast is automatically produced in a similar manner as for an existing culvert site case. The degree of sedimentation is expressed in forecast bins corresponding to 1-10%, 10-30%, 30-50%, 50-50%, and 70-100%. More details about the workflow interfaces, associated tools, and outcomes can be found in Appendix A.

a)



b)

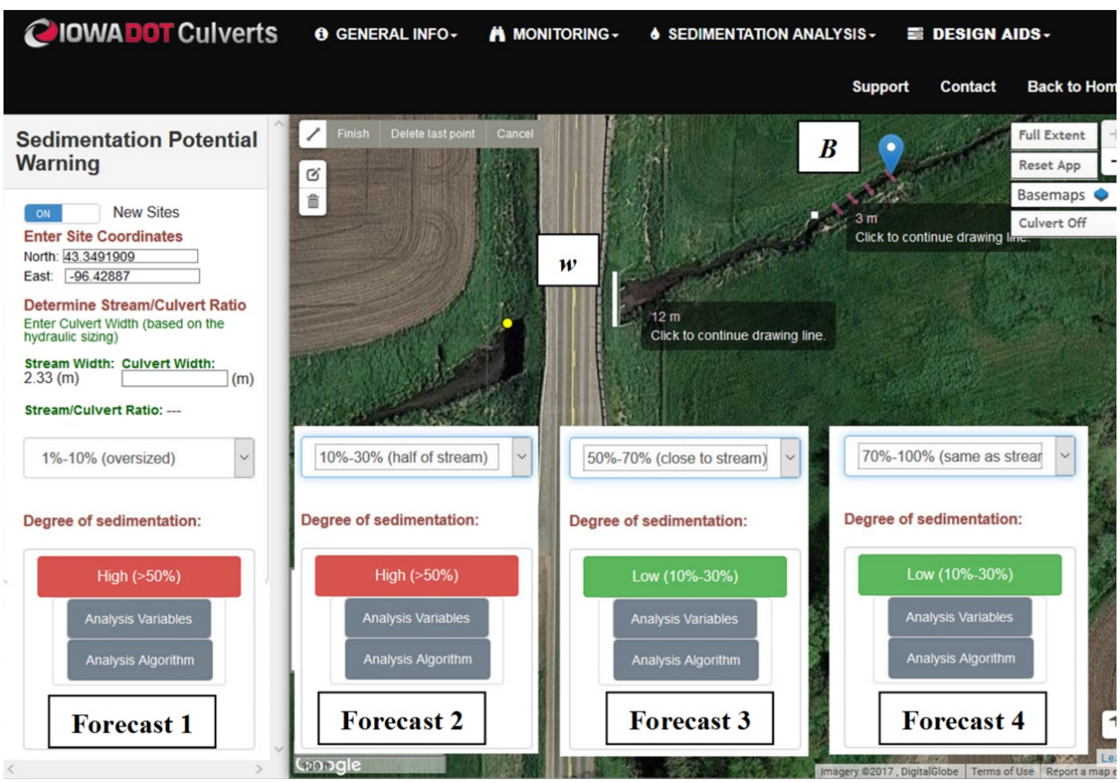


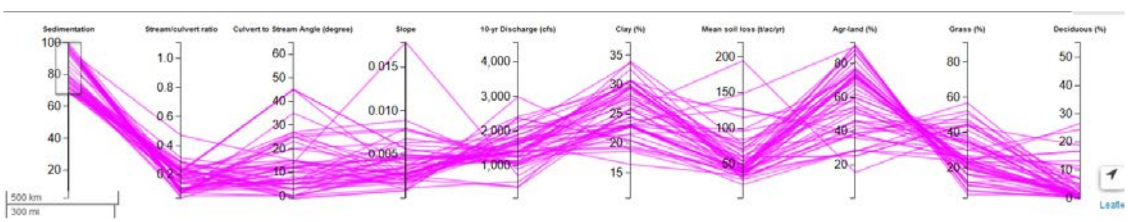
Figure 22. "Sedimentation Potential Warning" workflow for new culvert sites: a) flowchart of the workflow; and b) forecasting interface for new culvert sites.

4. Sample of MCDA Outcomes

The MCDA engine embedded in the "Sedimentation Analysis" workflow allows users to dynamically display functional relationships between pairs, selected groups, or the entire set of independent variables used for the MCDA analysis. The most relevant relationships for this study are the ones relating the degree of sedimentation at a culvert (i.e., the response variable) with all its drivers (i.e., predictors), as they enable useful insights into the processes leading to sedimentation. Two such relationships are illustrated in Figure 23. By filtering the degree of sedimentation for its extreme values (heavily silted culverts), the overall dependency looks like the one plotted in Figure 23a. The dependence suggests the following ranking for the process drivers' contribution (listed in their descending order): low SCW ratio, low design discharge (under 2,300 cfs), high mean soil loss, high agricultural drainage area coverage, low grass coverage, and forest coverages. The stream-to-culvert angle of incidence and the slope are not sensitive factors as they are within narrow ranges of variation for the state of Iowa.

By filtering the degree of sedimentation for the opposite extreme (indicating clean culverts, i.e., less than 20%), the relationship appearance changes, as illustrated in Figure 23b. The comparison of the two plots suggests that the most obvious contributing factors to sedimentation are (in their order of importance): SCW ratio and land cover in the drainage area, i.e., agricultural usage or natural cover. The large dispersion of the datapoints for some of the drivers suggests both the impact of the uncertainty of the method and direct observations, as well as the application of a coarse MCDA that lumps all the 3-box culverts in Iowa into one large sample. More reliable results and increased accuracy of the dependencies are expected if regionalization of the MCDA is made regarding the type of drainage area and a sensitivity analysis is applied across the entire watershed area that directly contributes to the sedimentation. These refinements can also be made using data-driven algorithms.

a)



b)

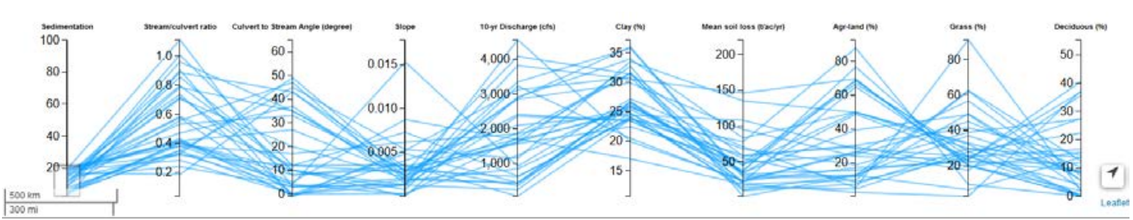


Figure 23. Filtering of the degree of sedimentation from the MCDA sample pool for: a) clean culverts, and b) heavily silted culverts.

Further insights into the processes can be obtained if the clear dependencies identified in the previous post-analysis step are quantified in one-to-one relationships, as illustrated in Figure 24. The figure displays the relationship between the degree of sedimentation and the SCW ratio, the most important driver in the sedimentation process. Specifically, as the SCW moves from small values (i.e., the stream width is considerably narrow compared to the total culvert width) to large values (the stream and culvert have similar widths), the degree of sedimentation varies from "very high" to "clean," as indicated in the figure. This relationship is expected given the physical processes: the smaller the SCW value, the more potential for the stream to develop low-velocity and a recirculating flow. These areas of flow non-uniformity were critical elements in the sedimentation process (Muste et al., 2009).

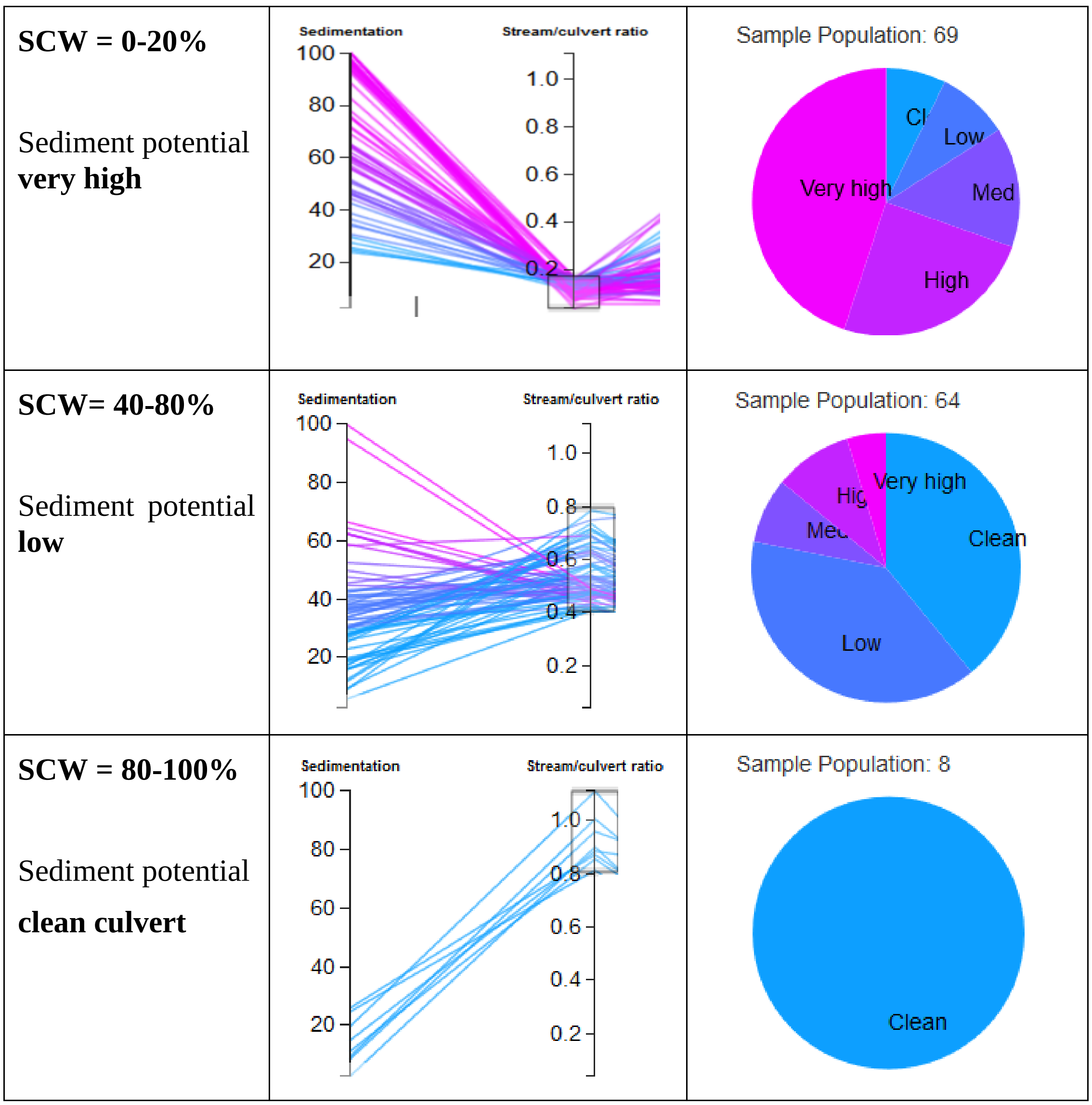
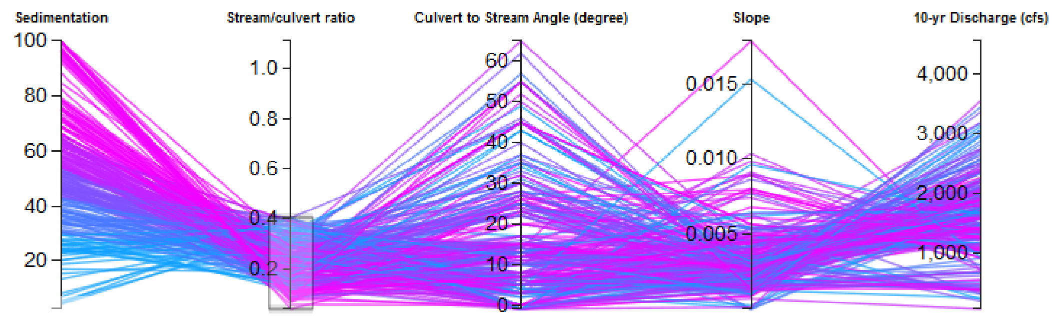


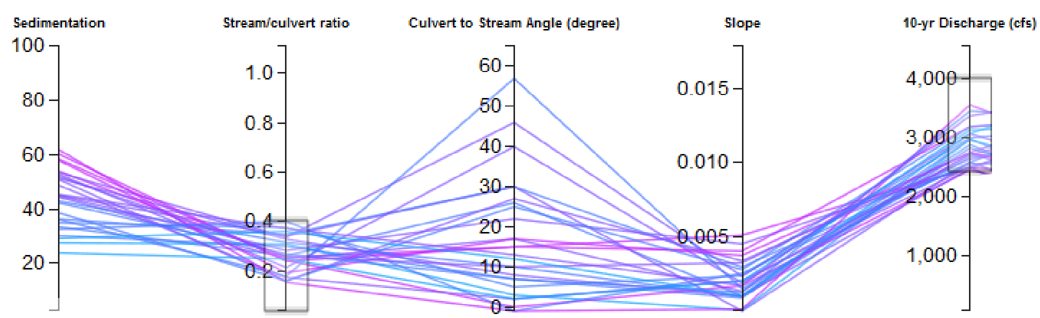
Figure 24. Relationship between the stream-to-culvert width (CSW) ratio and degree of sedimentation at culvert.

More dependencies can be obtained by "filtering" two ore more of the independent variables with the windows of pre-established values on the vertical axis subjected to analysis. Dependencies of the degree of sedimentation for SCW between 0-20% (found prone to sedimentation in Figure 24) and different values for the culvert design discharge (a.k.a. annual exceedance-probability discharge) are illustrated in Figure 25. This multi-variable dependency suggests that, for Iowa conditions in general, the dependence is inconclusive as indicated in Figure 25a. However, by further filtering the design discharge, the MCDA suggests that for high design discharges the probability of sedimentation is smaller than for lower discharges (See Figures 25b and 25c, respectively).

a) 0-4000 cfs ➔ inconclusive



b) 2000-4000 cfs ➔ low sedimentation potential



c) 0-750 cfs ➔ high sediment potential

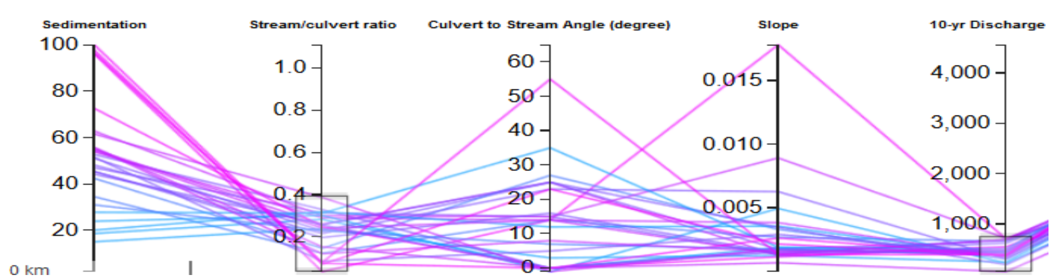
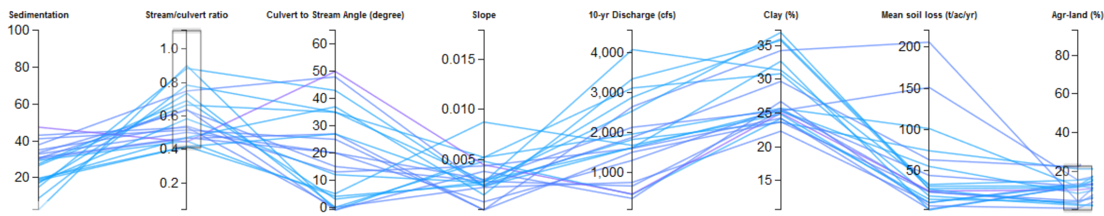


Figure 25. The MCDA-predicted degree of sedimentation for CSW ratio in the 0-20% range and variable design discharge.

The dependency illustrated in Figure 26 focuses on the estimation of the degree of sedimentation at culverts for a CSW ratio between 40 and 80% (a recommendable design value) and the type of land use in the watershed draining at the culvert. The dependency illustrated that the lower percentage agricultural use (0-25%) leads to a lower degree of sedimentation than the middle range percent value (25-60%). Some of the mixed results of the MCDA outcomes are due to the fact that the MCDA, as developed so far, is quite coarse. The outcome accuracy, and therefore the insights, can be further optimized if new data-driven algorithms are used in conjunction with the MCDA. Further improvements (currently under consideration) are expected if clustering and a sensitivity analysis to the size of the watershed that is directly contributing to sedimentation are applied.

a) Agricultural land: 0-22% (low sediment potential)



b) Agricultural land: 22-60% (mixture of low sediment and high potential)

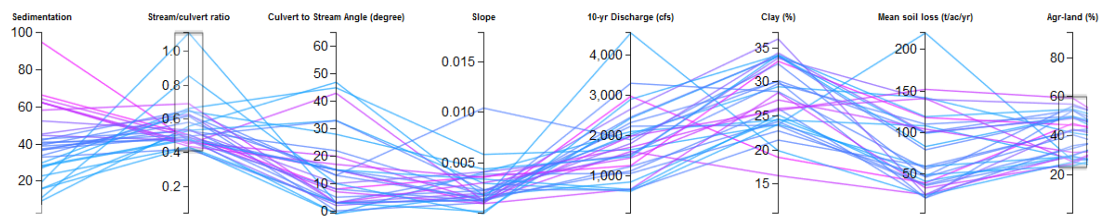


Figure 26. The MCDA-predicted degree of sedimentation for CSW ratio in the 40-80% range and percentage of agricultural use in the culvert drainage areas of: a) 0-22%, b) 22-60%.

5. Conclusion

The sedimentation at multi-barrel culverts has become a widespread problem in the U.S. Midwest as a direct consequence of changes in land use and climate. Culvert designs are preceded by analyses of the hydrologic, hydraulic, and geomorphological conditions at the construction site. Less attention is typically given to the assessment of the potential for sedimentation within the culvert and its vicinity. This is unfortunate as culvert sediment cleaning is expensive, labor intensive, and sometimes needs to be repeated. The web-based geo-portal developed through this study aims at filling this gap by assembling in one place the pre- and post-construction data and information on culverts, along with relevant watershed characteristics, to aid culvert design and monitoring processes.

The aid of these activities is multi-faceted. First, the web-portal integrates sources of data that are currently available in various formats and repositories. Most of these data are online so they continue to be updated by specialized agencies following verified and sustainable protocols. By connecting those sources to the IDOT Culverts platform, we created a new, customized resource that is continuously updated during the culvert life cycle, enabling two significant monitoring and analysis activities: a) informing and facilitating on-going culvert related activities (e.g., updates on the status of sedimentation at the level of county or IDOT district for resource planning purposes); b) serving as a living repository that can be mined to infer aspects of current designs in relationship with the location of the culvert in diverse geographic areas.

Second, the software tools embedded in the platform allow for the exploration of various relationships between a culvert's status and its evolution in time, commensurate with the changes in the watershed (e.g., correlating changes in the landscape due to socio-economic activities with the changes in conveyance capacity of the culverts over time). This exploration is made through the usage of Multi-Criteria Decision Analysis (MCDA) applied to a training dataset incorporated in the platform. The MCDA is a tree-based analytic technique popular in classification and prediction application as the decisions are made on a few important variables identified in the training stage, thus overcoming the correlation and nonlinearity issues encountered in conventional regression models. The method is popular because the decision trees are intuitive and, therefore, easy to explain outside the software developer community. Lack of sufficient data and overfitting the training dataset are, however, downsides that should be avoided. Further improvements for the prediction of sedimentation can be brought in by enhancing the relevance of the raw watershed dataset through clustering and sensitivity analysis of the independent variables prior to implementation of the MCDA.

Lastly, data sources and software are hosted in a customized web-portal developed with the end user in mind. Therefore, the platform's tools and functions are controlled through user-friendly graphical interfaces that accommodate the needs of engineers with a minimum computer programming background. The platform is built using open source technologies that make the system light-weight, low cost, and flexible. The end product usefully complements current culvert design specifications with conceptualized ground-truth information that correlates sedimentation at culverts with their geometry, stream, and watershed characteristics draining to the culvert site, irrespective of its location in the state. Currently the prototype IOWA DOT Culverts portal is transferred to the Iowa DOT.

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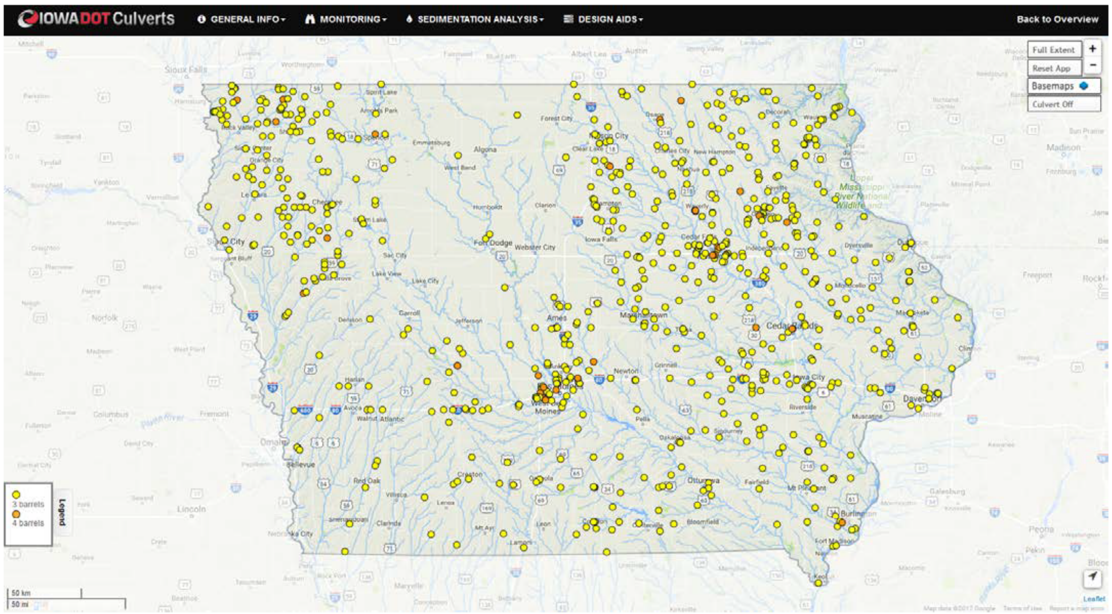
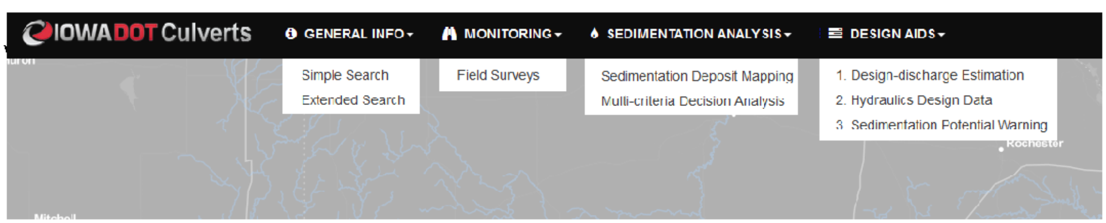
APPENDIX A: IOWA DOT CULVERT PLATFROM INTERFACES AND THEIR FUNCTIONS

1. Overviews of the portal workflows

The "Iowa DOT Culverts" geo-portal prototype describes the potential for inception and development of sedimentation at culverts. By combining information from data-driven analyses at hundreds of culvert sites in Iowa with watershed and stream information available in national and local databases, the portal enables users to establish the degree of sedimentation at any existing or planned culvert location in the state. In addition, the platform aids designers and operation personnel to store, retrieve, analyze, and visualize a wide range of information about culverts using friendly web-interfaces.



The prototyping geo-portal contains four major workflows: (1) General information, (2) Monitoring, (3) Sedimentation analysis, and (4) Design aids for promoting culvert information access, inspection, and facility culvert sediment mitigation design through data-driven sediment analysis. The present documentation provides detailed guidance on the Graphical User Interface (GUI) for each of these workflows. The GUIs are presented in the order display below (from left to right).

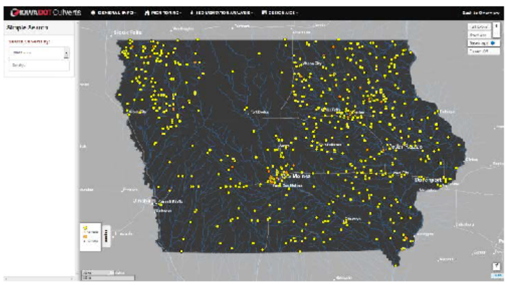


2. “General Info” Workflow GUI

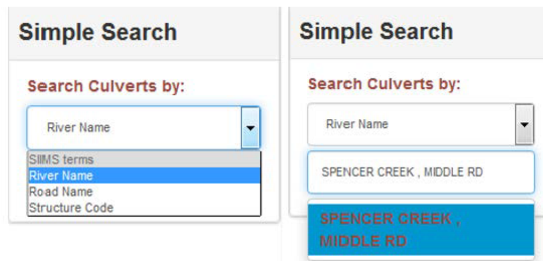
The “General Info” workflow is intended to create an easily accessible repository based on culvert specifications. The workflow contains two tools which provide accurate culvert identification based on different specifications.

2.1 Simple Search

The “Simple Search” identifies the location of culverts based on three fundamental criteria: (1) river name, (2) road name, and (3) structure codes.



Overview of the “Simple Search” Interface displaying the application panel (left) and map tools (right).

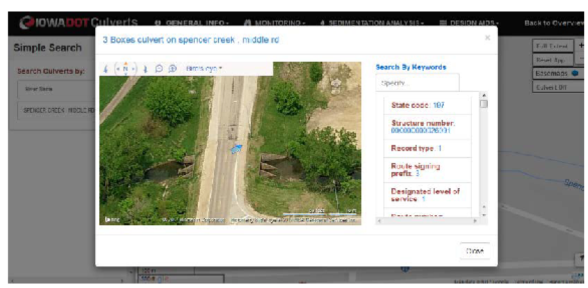


Choices of search criteria with autocomplete features embedded.

Let’s assume a scenario where the user wants to locate a culvert on Spencer Creek in Iowa. As the user only knows the river name where the culvert is located, the user would select “Search culverts by” and then the “River Name” option and type in “Spencer Creek”. Subsequently, the tool locates and zooms to the culvert location.

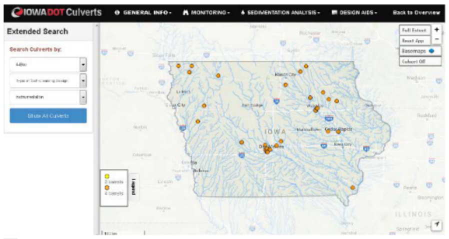
Zoomed view to culvert location.

By clicking on the culvert location on the map, a culvert information window that contains a bird's-eye view of the culvert and detailed culvert structure specifications appears in the window. Using the rotation tools in the bird's-eye view, users can visually inspect culvert structures from four different directions. Meanwhile, culvert structure information is displayed in the culvert information window. On the right-hand side, detailed culvert structure information, including culvert geometry, site codes, and maintenance information is displayed. All culvert specifications are retrieved from Iowa DOT SIIMS database and can be filtered by keywords.

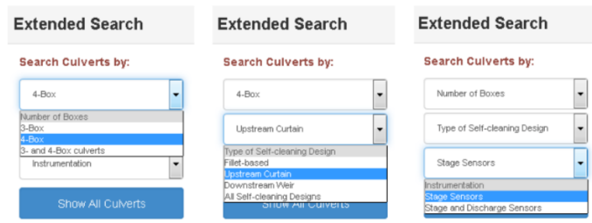


Culvert information window.

The “Extended Search” menu provides users with capabilities to filter culverts by additional attributes, such as number of boxes, types of self-cleaning design, and instrumentation. Click the “Show All Culverts” button to restore the default culvert map.



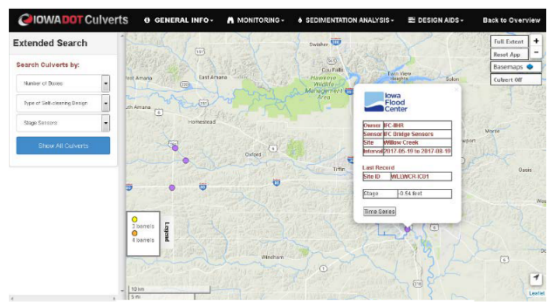
Display of 4-box culvert locations.



Choices of search criteria.

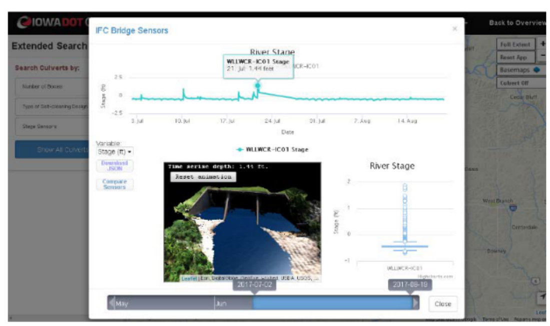
In a user case scenario, users can filter culverts with specific attributes on a map. Through the tool, the user can also display culvert sites with self-cleaning designs (e.g. filet-based, downstream weir, and upstream curtain).

In addition to culvert structure attributes, the portal connects and visualizes real-time sensor measurements at culvert sites. The user can display locations of sensors from the United States Geological Survey (USGS) and the Iowa Flood Center (IFC) by switching the “Instrumentation” dropdown menu to “Stage Sensors”. By clicking on sensor location (●), an information tab showing sensor meta-data (e.g. measuring variables, locations, site-ID) is displayed. To view sensor measurement, click the “Time Series” button to launch the “time-series window”.



Filter culvert by “Stage Sensors”.

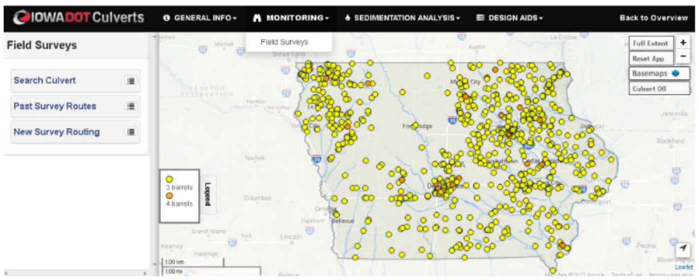
At some culvert sites, a “local view” that visualizes a realistic digital culvert structure with free surface level dynamically generated from real-time sensor measurements. The digital culvert model illustrated in the figure is surveyed using Unmanned Aerial Vehicle (UAV)-based photogrammetry. By hovering on time series plots, inundation scales in the “local view” are changed



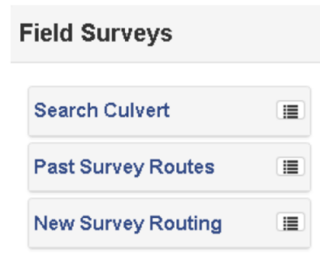
Time series of stage measurements visualized in a realistic digital culvert view

3. “Monitoring” Workflow GUI

The “Monitoring” workflow provides tools to retrieve past survey information (data & routes) and plan new survey trips (navigation, field data uploader, and routes planning). The workflow contains a “Field Surveys” tool with three functional tabs: (1) search culverts, (2) past survey routes, and (3) new survey routing.



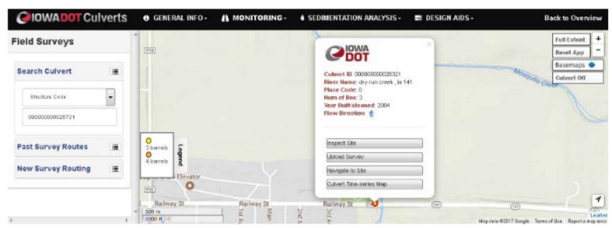
“Field surveys” interface overview.



Application panell.

3.1 *Search Culvert*

The “Search Culvert” tab provides an easy way to search for culvert locations based on culvert specifications such as road name, river name, and structure code. The tab is similar to “Simple Search” in “General Info” to locate specific culverts, with extended field trip assistance workflows that enable users to (1) inspect sites, (2) upload surveys, (3) navigate to sites, and (4) view culvert time-series maps.



Field surveys interface overview.

Let’s assume a scenario, where a user locates the culvert of interest by searching structure code “000000000025731” in the “Search Culvert” tab. After locating the culvert, the user can access past culvert inspection data conducted by IIHR - Hydroscience & Engineering by clicking the “Inspect Site” button. The culvert survey information page contains both survey notes and survey images acquired from previous culvert inspection. To upload a new survey, a user can click “Upload Survey” to access a field data uploader to ingest real-time survey data during a site inspection. The survey uploading page is protected by password.

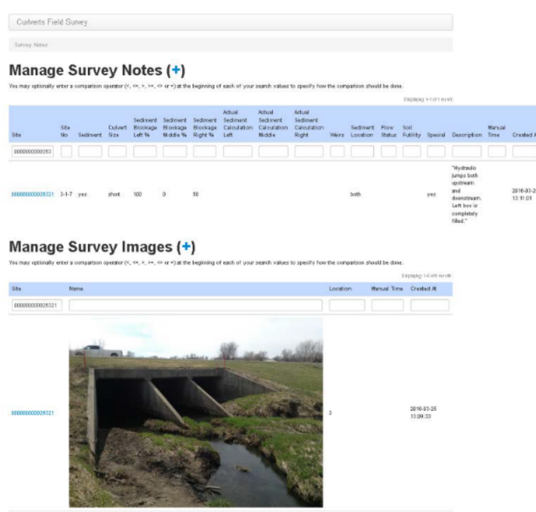
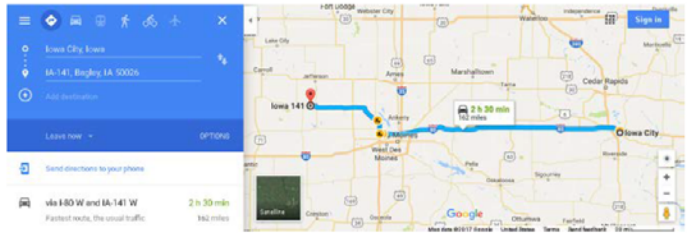


Photo acquired during previous culvert inspection

After identifying a specific culvert from the search, users can use the portal as a navigation tool to visit the site location by clicking the "Navigate to Site" button. The platform provides a Google navigation that guides users to the geographic coordinate of the site. The navigation tool is mobile-friendly and works with mobile devices that have GPS chips.

The portal also provides a culvert time-series viewer that assembles aerial imageries of culvert sites taken from different years (2004 – 2015). Sources of aerial imageries include Google, Esri, Iowa GIS server, and National Agriculture Imagery Program (NAIP), showing the development of culvert sediment at a site throughout time.

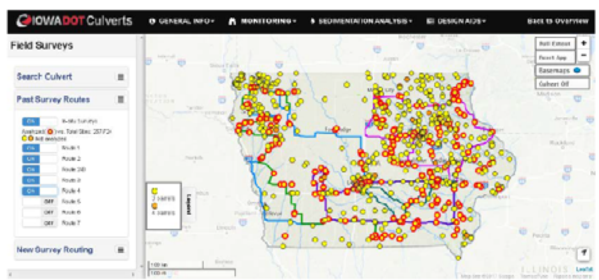


"Navigate to the site" command connects the portal with Google Map navigation tools.

Time-series of culverts using aerial photographs.

3.2 Past Survey Routes

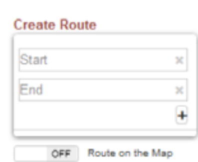
The "Past Survey Routes" tab displays the overall progress of past culvert sediment surveys conducted by IIHR - Hydroscience & Engineering. Within the tab, the switch "OFF In-situ Surveys" visualizes the locations of inspected culverts, which is color-coded in "○". Users can view past survey routes by clicking on different route switches (e.g. route 1, route 2). Past routes are displayed as colored lines on map.



Surveyed culverts and past inspection routes.

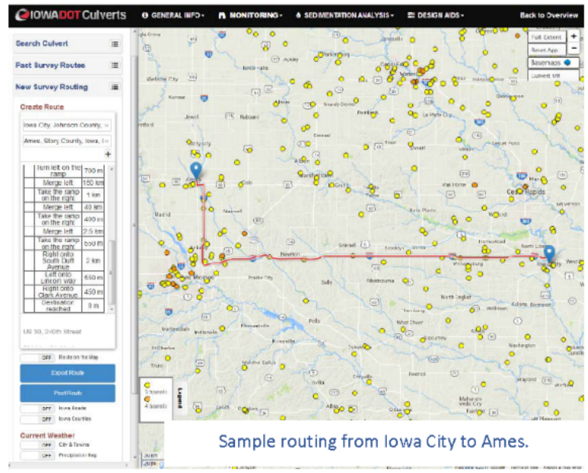
3.3 New Survey Routing

The "New Survey Routing" tab assists the planning of culvert inspection trips in surveyed areas by providing tools for address searches, route planning, and weather forecasting. The "Create Route" tool allows users to establish routing between specified addresses. In a user case scenario, a user can plan a trip from Iowa City to Ames by entering two addresses in the "Start" and "End" search boxes. Additional waypoints can be added by clicking the "+" button.



Address specification block.

If the address is not known, users can specify their destination by simply enabling the switch "OFF Route on the Map" and clicking on the map. After specifying a "Start" and "End" address, a route is generated with detailed driving directions and time estimations on the map. Routes can be edited interactively through the map by dragging to find alternative routes and clicking to add waypoints. Users can either export their routes in JSON formats or to other applications (QGIS, Google Earth) by clicking on "Export Route", or send their planned routes to "Past Survey Routes" by clicking on "Post Route". The portal also provides limited weather forecasts and reports of survey progress. Both tools can be enabled from functional switches under "New Survey Routing" tab.



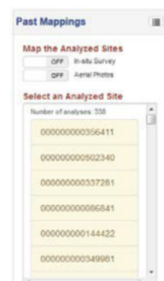
Sample routing from Iowa City to Ames.

4. "Sedimentation Analysis" Workflow GUI

This workflow provides sedimentation analysis using a data-driven approach. There are two tools under this workflow: "Sedimentation Deposit Mapping" and "Multi-Criteria Decision Analysis".

4.1 Sedimentation Deposit Mapping

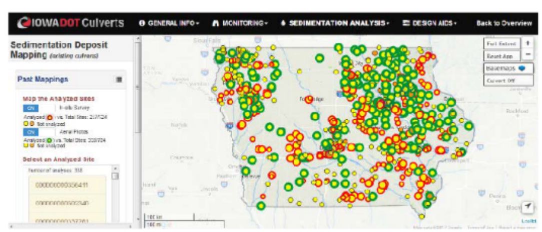
The "Sedimentation Deposit Mapping" tool enables users to determine the degree of culvert sedimentation by providing an interactive tool to delineate sediment scales from aerial imageries. The delineated sediment information will be applied in the later tool "Multi-Criteria Decision Analysis" with other data about watershed characteristics. The tool contains three tabs: "Past Mappings", "Re-Mapping", and "New Mapping".



Past Mappings tab.

Through the "Past Mappings" tab, users can view overall mapping and survey progress, as well as retrieve past sediment delineations data and visualize them on the map. To view overall progress of past surveys and mapping extent, the user can activate switches (OFF In-situ Survey and OFF Aerial Photos) under "Map the Analyzed Sites" to map field-inspected culverts and sediment- mapped culverts respectively.

After enabling the mapping, culverts with past field inspections are color-coded in red, while culverts with their sediment degree mapped are color-coded in green. In addition to the mapping, structure codes of culverts with aerial-image analysis are also listed under "Select an Analyze Site". By clicking on these structure codes, the user can access past delineations by visualizing them on the map.

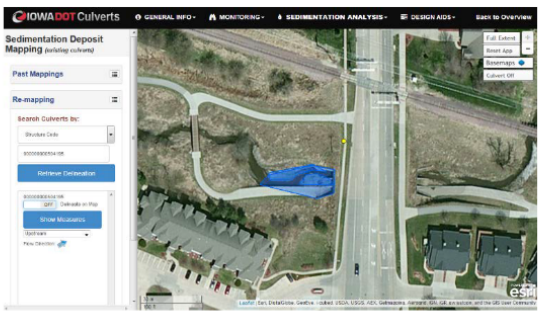


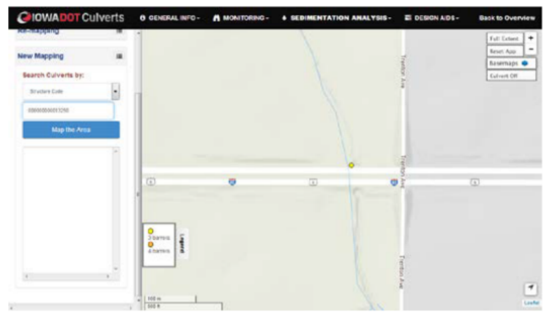
Dynamic color coding for distinction of inspection type.

After enabling the mapping, culverts with past field inspections are color-coded in ◉, while culverts with their sediment degree mapped are color coded in ◉. In addition to the mapping, structure codes of culverts with aerial-image analysis are also listed under “Select an Analyzed Site”. By clicking on these structure codes, the user can access past delineations by visualizing them on the map. On the map, sediment delineation is displayed as the blue polygons.

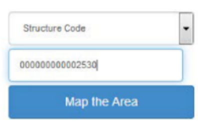

Retrieval of previous sediment mapping

The tools under the “Re-mapping” tab allow users to update and modify past sediment delineations when the latest aerial imageries become available. The “New Mapping” tab, in contrast, allows users to search and map sediment at new culverts. Both tabs have a built-in culvert search tool that only allows users to search and select culverts that have sediment mapping records.

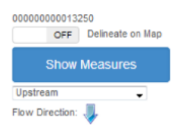

Retrieval of previous mapping under “Re-Mapping” tab.


Identification of unmapped culverts under “New Mapping” tab.

The culvert sediment delineation section in both tabs are very similar: (1) the user has to specify a culvert through the culvert search by typing in a structure code. (2) After the culvert is located, the user needs to click [Map the Area] to trigger the sediment mapping interface. The mapping interface contains a display of culvert structure codes (e.g. 013250), a switch that enables delineation toolsets on the map, a button to show attributes (e.g. length) of delineated geometry, a dropdown menu to specify the location of delineation, and a flow direction arrow that indicates the downstream of the culvert. (3) Before tracing the sediment area on the map, the user needs to activate “ [ON] Delineate on Map ” to enable the mapping toolset (the tool appears in the upper left corner)



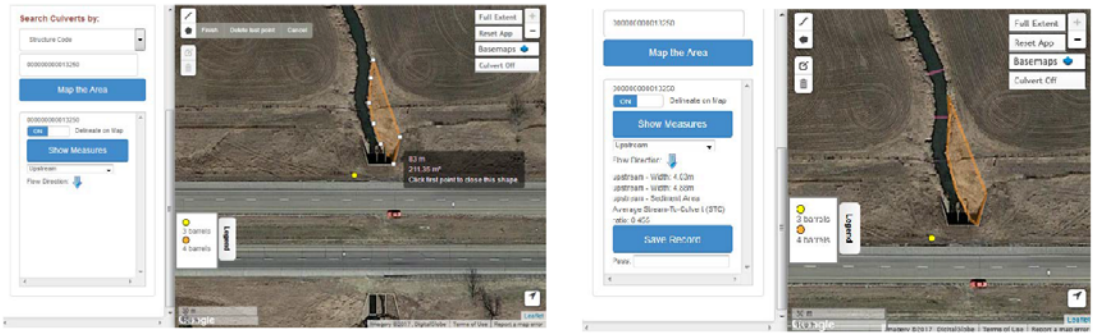
1) Select culvert for mapping.



2) Triger the mapping tools.


3) Enable mapping activities.

(4) To map sediment areas, the user simply needs to click on ⬟ to draw polygons at culvert sites using aerial imagery overlays. The ⟋ button enables users to draw lines that can be used to measure the river width on the map. When the tracing of the sediment area is finished, press “Enter” on the keyboard to finalize the polygon delineation. After the delineation, the user can view delineation details by clicking the “[Show Measures]” button.

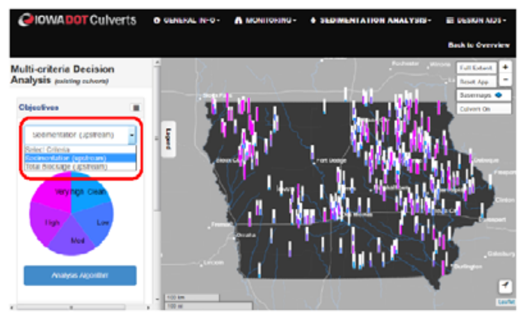


4) Delineating sediment area at culvert upstream and showing details by clicking “Show Measurement”.

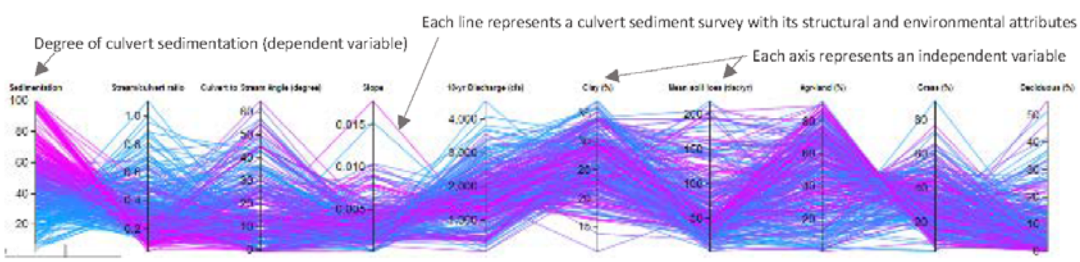
(5) To upload the delineation results to the database for later use, the user needs to click the [Save Record] button under “Multi-Criteria Decision Analysis”. The uploading is password protected to ensure data quality and integrity. To get the password, please contact our team.

4.2 Multi-Criteria Decision Analysis

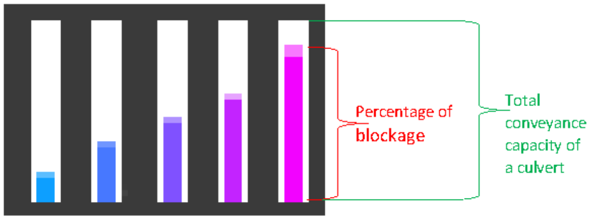
The Multi-Criteria Decision Analysis (MCDA) aims at exploring environmental drivers that contribute to culvert sedimentation in culvert upstream drainage areas. The tool reveals the causal relationships between culvert sediment degree and the structural attributes (e.g. height, design discharge) as well as the watershed and stream characteristics (e.g. channel slope, mean soil loss) using a visual-analytics approach. The results of the MCDA are visualized into a parallel coordinate plot supported by dynamic machine learning algorithms (e.g. decision tree). The tool is interactive and user-friendly, so that users can play with the tool to get a sense of how different factors affect culvert sedimentation. To conduct an analysis, the user needs to: (1) define sediment criteria in objectives via the dropdown menu, and (2) enable the data visualization (parallel coordinate plots) using the switch “ ON Show Analysis Results ”.



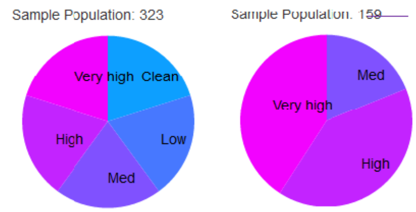
1) Two criteria are available in the dropdown menu: (a) “Sedimentation (upstream)” indicates the degree of sedimentation as obtained from the mapping of the sediment mapping (obtained from aerial imagery), and (b) “Total Blockage (upstream)” indicates the volume of sediment blockage in the vertical plane (obtained from field surveys).



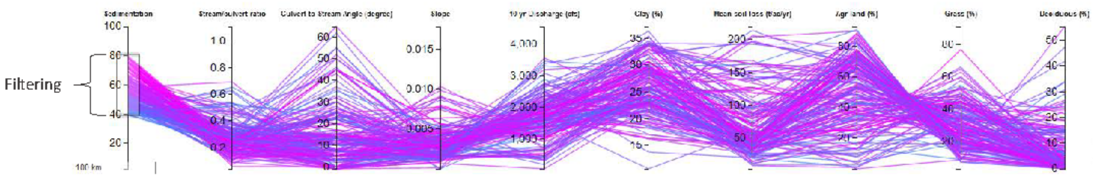
2) Parallel coordinate multi-axis plot relating culvert sediment degree with culvert structural attributes and environmental drivers.



(2) Degree of sedimentation (bar graph).

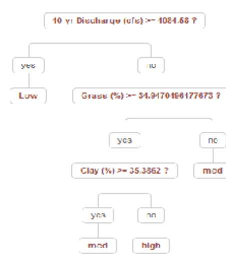


Degree of sedimentation (pie chart). Pie size indicates percentage sediment blockage.



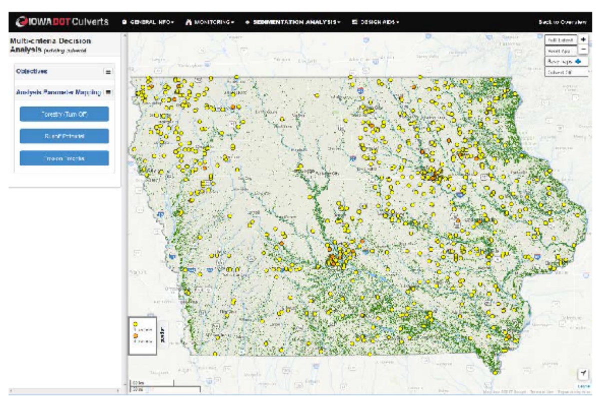
(3) Filtering the MCDA for the degree of sedimentation.

The parallel coordinate plot is connected with the web map and provides dynamic data "brushing" capabilities that allow users to filter or select data records, certain ranges, and attributes. To create a brushing range, simply click and drag on each parameter axis. In addition to the visually explicit variability revealed from the parallel coordinate plots, users can also view quantification of the MCDA by clicking the "Analysis Algorithm" button, which enables a decision tree that visualizes the sediment relationship. A detailed user case scenario is provided below. A small bunch of decision trees with only two sediment classes (med and high) and few parameters (e.g. discharge, grass, and clay) are shown in the figure as an example.



Decision tree example.

In addition to the main analysis, the portal provides "Analysis Parameter Mapping" to display spatial distribution maps of environmental parameters (e.g. forestry, runoff, erosion) that are involved in the MCDA. To activate those maps, simply expand "Analysis Parameter Mapping" by clicking the button " ☰ " next to the tab " **Analysis Parameter Mapping** ☰ ". Afterward, the interface expands and displays blue buttons for the following categories: (1) Forestry, (2) Runoff Potential, and (3) Erosion Potential. If a user wants to view a forestry map, they need to simply click the "Forestry" button to activate the map.



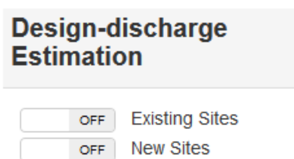
Forestry map.

5. “DESIGN AIDS” Workflow GUI

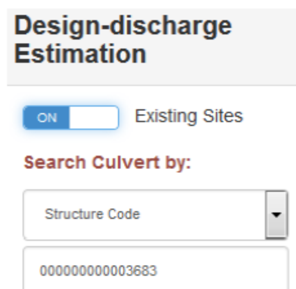
The “Design Aids” workflow uses analytical results from the MCDA conducted in previous workflows (Sedimentation Analysis) to support culvert design and retrofitting for mitigating sedimentation. The workflow contains three design-aids tools: (1) Design-Discharge Estimation, (2) Hydraulics Design Data, and (3) Sedimentation Potential Warning.

5.1 Design-discharge Estimation

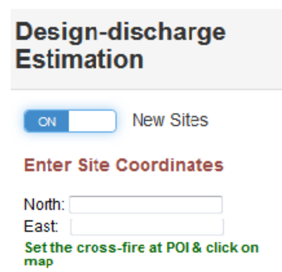
Culvert design discharge is a very important parameter that determines the opening of culvert structures. The “Design-Discharge Estimation” calculates river discharge for multiple return periods (e.g. 5 year, 10 year, 50 year) using flood probability methods (e.g. USGS Lara method). The tool is designed to estimate design discharge for both (1) Existing Sites and (2) New Sites.



Location of the site.

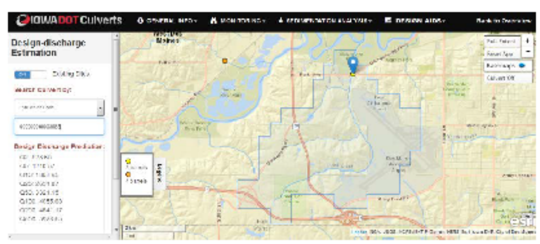


Existing site.

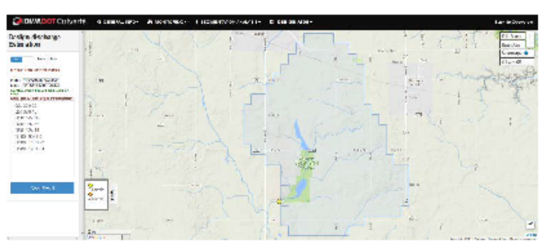


New site.

To estimate discharge for existing sites, click “ ON Existing Sites ” to enable the estimation interface. The procedure is very similar to the culvert search in that the user needs to specify a culvert location by its structural code. Afterwards, the portal traces the upstream drainage area and reports the result in the sidebar.

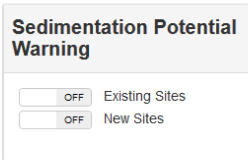

Searching for an existing site.

To estimate discharge for a new site, the user needs to click “ ON New Sites “to trigger the new site interface. When the interface is loaded, follow the guide and enter the site coordinates (point of interest). The portal automatically zooms to the coordinates and calculates the design discharge.

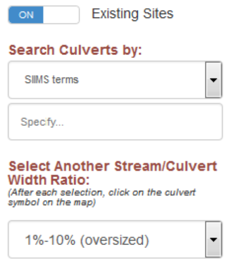

Defining coordinates for a new site.

5.2 Sedimentation Potential Warning

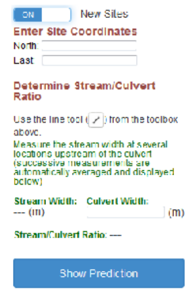
“Sedimentation Potential Warning” uses a decision tree generated from the previous sediment analysis (Multi-Criteria Decision Analysis) to predict sediment potential at both existing sites and new sites. The tool is intended to inform the designer when to apply the “Self-Cleaning Design” based on sediment potential while designing new sites. The tool provides predictions for both existing sites and new sites. General user interfaces of this tool are listed below.



Location of the site.

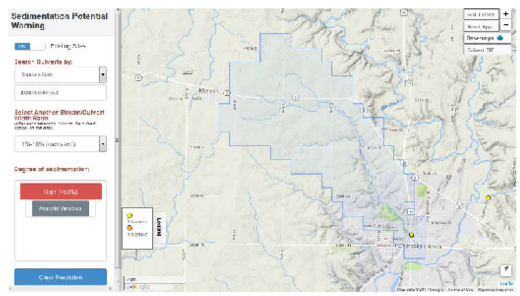


Existing sites.



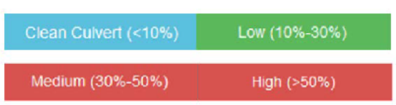
New site.

The interface of this tool is very similar to that of the discharge estimation. To estimate sediment potential for existing sites, click on the switch “ON Existing Sites” to activate the corresponding interface. First, specify the structural code for estimation--the procedure is the same as the discharge estimation. Second, define the stream/culvert width ratios through the dropdown menu “ 1%-10% (oversized) ”, as culvert geometry plays an important role in culvert sedimentation. Results of sediment estimation will be provided under the “Degree of sedimentation” section.

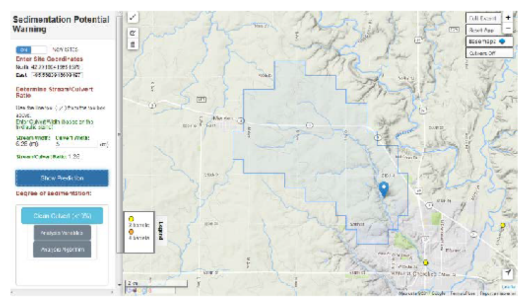


Estimating sediment potential for existing sites.

To evaluate the sediment potential at new sites, activate the switch “ ON New Sites ” to display the interface. Steps are as follows: (1) enter coordinates for a new site, (2) delineate river cross-section using the “⟋” tool to measure river width, and (3) specify culvert width using “ Culvert Width: (m) ” and click “Show Prediction”. Afterward, the result of the estimation is provided under the “Degree of sedimentation” section. The system uses four classes to describe sediment potential at a site:



Classes for sediment potential estimation.



Estimating sediment potential for a new site.