

Web-based geospatial platform for the analysis and forecasting of sedimentation at culverts

Haowen Xu, Marian Muste and Ibrahim Demir 


ABSTRACT

Sedimentation is one of the major operational hazards for culverts located in Midwestern areas of the United States. Currently, there are no systematic efforts for mitigating detrimental effects of sediment blockage at culverts, as the problem involves complex and interlinked environmental processes that are difficult to investigate and solve with conventional approaches (e.g., experimental methods and physical modeling). In this paper, we present a new, innovative solution for addressing culvert sedimentation using a data-driven approach. This approach enables the identification of culvert sedimentation drivers and quantifies the relationships between drivers and culvert sedimentation severity, making use of an extensive set of multi-disciplinary data. The data analysis and management tools are embedded in a web-based platform, the IowaDOT Culverts. Through user-friendly interfaces and interactive visualizations, this platform facilitates the analysis and forecasting of sedimentation at multi-box culverts across Iowa. The IowaDOT Culverts web-based geospatial platform allows us to: (a) integrate, access, store, and manage diverse culvert-related information; (b) organize and document culvert inspections in real time; (c) conduct sedimentation-related analyses using computer-driven visual analytical approaches; and (d) support forecasting of the culvert sedimentation potential. The platform is developed with open-source web technologies and modular system designs, making it scalable, flexible, and extendable to other geographical regions.

Key words | culvert management system, culvert sedimentation, decision support system, decision tree, web-based

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INTRODUCTION

The increasing intensity and frequency of precipitation in recent decades (Villarini *et al.* 2013), combined with human interventions in watersheds, has drastically altered the natural regimes of water and sediment transport in watersheds over the contiguous United States (Solomon *et al.* 2007). Sediment transport-related concerns include the sustainability of aquatic biology, the stability of the river morphology, and the security and vulnerability of various riverine structures (CEI 2018; Tetreault *et al.* 2018). For the present context, the concerns are related to the acceleration of upland erosion (sediment production) and in-stream sediment-transport processes (i.e., aggradation, scouring, and deposition) that eventually lead to sediment

accumulation at culverts (structures that pass stream under roadways). This nuisance has become widespread in many transportation agencies in the United States as it has a direct bearing on maintaining normal culvert operation during extreme flows when these waterway crossings are essential for the communities they serve. Despite the prevalence of culvert sedimentation, current specifications for culvert design do not typically consider aspects of sediment transport and deposition. Developing an effective strategy for mitigating culvert sedimentation requires not only a thorough understanding of its physical processes but also capabilities to forecast the sedimentation potential under various evolving scenarios.

Addressing culvert sedimentation faces multiple challenges as tracing sediment particles from source to its final deposition location is a complicated endeavor (Wohl *et al.* 2015). The naturally occurring erosion and sedimentation activities entail processes such as soil particle detachment, the movement of sediment toward streams (erosion and sediment production), and in-stream sediment transport (through a cycle of entrainment and deposition moments). Major knowledge gaps exist in describing and simulating the dynamics of sedimentation even without culverts in the streams (e.g., Ettema & Mutel 2004). Although the knowledge of the fundamental erosion and transport mechanisms can be conceptualized to some extent, the understanding of the connection between sediment production (supply), transport, and deposition at culverts is lagging. This is because sediment transport processes, unlike the movement of water, are nonlinear, episodic, and operate at different temporal and spatial scales (Onderka *et al.* 2012). Additional unknowns arise due to the fast-evolving anthropogenic activities in streams and their drainage areas (Haan *et al.* 1994; Merritt *et al.* 2003).

It is quite obvious from the above considerations that culvert sedimentation cannot be readily addressed by conventional analytical, experimental, or physical modeling approaches. This paper suggests addressing the problem using a data-driven approach instead. Data-driven approaches have become increasingly popular in conjunction with the development of intelligent information systems and decision support systems for addressing the contemporary challenges in natural resources (Muste 2014; Demir *et al.* 2015, 2018; Xu *et al.* 2017). These systems often include real-time interactions between *in situ* data acquisition and numerical modeling or analytical processing supported by visualization engines to facilitate the handling of the vast amount of data typically involved in environmental research (Demir *et al.* 2009; Beven *et al.* 2012; Demir & Krajewski 2013).

Previous attempts to construct empirical relationships for sedimentation at culverts have been made using laboratory data (e.g., Goodridge 2009) and field datasets (e.g., Howley 2004; Rowley 2014). Studies that attempt a holistic, watershed approach for the investigation of river sediment dynamics are still rare (Fuller *et al.* 2014) due to the data-rich background required to track sediment movement

over a range of scales. The major problem faced by holistic investigations of culvert sedimentation is that the available information on the process is episodic and incomplete. This shortcoming is related to the fact that the current periodic inspections of the waterway structures conducted by transportation agencies are mostly targeting their hydraulics and structural integrity while tracking sedimentation is neither complete nor well organized (FHWA 2014). However, the data relevant to culvert sedimentation produced by many US agencies are stored in multiple locations and various formats and do not specifically target sedimentation at riverine structures. The present work offers tools and protocols that allow us to integrate and synthesize the customized and third-party relevant datasets with the purpose of better managing and supporting decisions regarding culvert operation and design.

This paper presents the design and workflows of a web-GIS platform focused on sedimentation at culverts. The system, dubbed as the IowaDOT Culverts platform, is a modular system that offers a web-based problem-solving environment for data-driven investigation. The platform provides systematic procedures to: (a) manage inventory and retrieve culvert structural information; (b) integrate diverse culvert-related datasets (e.g., culvert inventory, hydrological and land use data, and observations on the degree of sedimentation in the vicinity of culverts) in a digital repository; (c) support culvert field inspections and real-time data collection through mobile devices; (d) explore the connections among the sediment-related processes using intelligent analytical tools (e.g., visual analytics and machine-learning techniques); and (e) forecast the culvert sedimentation potential across Iowa. The data-driven insights and forecasting results produced through the Iowa platform can be extended to other US territories for aiding decisions in culvert management and informing sedimentation-sensitive culvert design as the sources of data available in Iowa cover most of the other territories.

METHODS

Given all the above-mentioned challenges in addressing culvert sedimentation as an end-to-end process, this study aims at providing an alternative problem-solving strategy.

Specifically, our research hypothesis is that the data-driven approaches (e.g., machine learning and visual analytics) are capable of relating spatial patterns of the hillslope and in-stream characteristics with the sedimentation process at culverts without detailed consideration of the internal structure of the physical process (Grabec 1990; Dibike & Solomatine 2001). In this setting, empirical relationships between culvert sedimentation-related variables (predictors) and the degree of sediment blockage at culverts (response variable) can be derived, helping us to further understand the major contributing environmental and structural factors and forecast complex watershed-scale riverine transport processes, such as the degree of sediment deposition at culverts.

Data sources

Ideally, data-driven investigations of sediment-related issues should rely on the direct measurements of sediment-related variables (i.e., bedload and suspended load) in streams (Marteau *et al.* 2018). However, these data are scarce and, when available, they cover only short time intervals (Wohl *et al.* 2015). In the absence of these data, indirect estimation of sediment regimes can be tracked over time based on the changes in river planform, substrate, or floodplain characteristics (increasingly possible now through analyses of remote-sensing imagery). Because culvert sedimentation data are relatively scarce across Iowa, the approach used in our study is based on the use of indirectly estimated drivers (deductive reasoning) rather than direct geomorphic inference (inductive reasoning). In our case, the deductive approach requires a wide variety of watershed and culvert-related data and information that are categorized as either predictor (i.e., independent variable) or response variables (i.e., dependent variable). The response variable is the degree (severity) of sediment blockage at each culvert. The predictors include culverts' structural and watershed characteristics that are analyzed as surrogates of the environmental processes behind culvert sedimentation processes. Among these processes, the most important are (Haan *et al.* 1994; Merritt *et al.* 2003) (a) soil particle detachment, (b) sediment movement toward streams, (c) in-stream transport of the sediment (through a cycle of entrainment and deposition moments) toward to culverts, and (d) sediment deposition near the culvert structure.

The use of the data-driven approaches for culvert sedimentation analysis is based on the following premises. First, it is hypothesized that stream environments are the major recipients of the water-borne material transported from local and upstream catchments; therefore, the streams integrate the geo-hydrologic activities in the drained areas. This hypothesis allows us to establish a unique correlation between watersheds and their river networks (Allan 2004). Second, there are abundant and freely available data on watersheds, streams, and culvert structures that are also relevant to erosion and sedimentation processes. Fortunately, this data-rich environment is available for the contiguous United States; hence the data-driven methodology developed for Iowa can be easily generalized at other US locations. Third, it is possible to conveniently characterize the sedimentation-at-culvert problem by taking advantage of multiple sources of aerial images (e.g., National Digital Orthophoto Program, National Agriculture Imagery Program, Google Maps, and Eagle-view). These imageries enable the quantification of culvert sedimentation degree and the continuous tracking of the sedimentation evolution within culvert vicinities over multiple years, reducing the cost of *in situ* surveys. Through this study, we concluded on the reliability of inferring sedimentation degree from aerial photographs by comparing these assessments against *in situ* conventional and drone-based imaging observations.

The data repositories for sediment-related watershed characteristics include U.S. Environmental Protection Agency's (USEPA) Stream-Catchment (StreamCat) Dataset (Hill *et al.* 2016), Revised Universal Soil Loss Equation (RUSLE), Soil Survey Geographic Database (SSURGO), and Iowa Department of Natural Resources' (Iowa DNR) High-Resolution Land Cover (HRLC) Dataset. For stream characterization, useful information can be retrieved conveniently from the National Hydrography Dataset Plus Version 2 (NHDPlus v2.0), a publicly available repository that depicts the network and essential hydrological attributes of streams and rivers within the conterminous United States based on the digitized lines of U.S. Geological Survey (USGS) topographic quadrangle maps. Culvert structural attributes can be retrieved from the structural inventory data hosted in the DOT repositories through the Structure Inventory and Inspection Management System (SIIMS)

database. Our study has used all of the above-mentioned data and information.

Despite the abundance of sedimentation-related data across the nation, implementing data-driven investigations faces several technological challenges. The first challenge is related to the seamless integration of the vast amount of the watershed and structural-related data relevant to sedimentation (uphill and in-stream). Currently, this information is distributed in various local, state, and federal agencies. Accessing and using these stored data are hampered by the so-called information gridlock syndrome (Lam et al. 1996; Xu et al. 2015), meaning that these data are not always easy to access given the diverse data format and structure. Second, the post-construction data produced over the years of field inspections are not uniformly and rigorously collected, despite the fact that this type of information would be beneficial for informing decision making during culvert design and retrofitting. The information is of the utmost importance because observing the rates and extents of sedimentation along with other possible secondary aspects (e.g., the change in the stream configuration in the culvert vicinity and the presence of debris) can be used as early warnings in the design stage.

The only set of data that is not readily available from third-party sources is the one associated with the degree of sedimentation at culverts (i.e., the response variable in the functional relationship). The sedimentation degree can be defined as the fraction occupied by the sediment deposits formed near the culvert structure (horizontal sedimentation dimension) with respect to the total area dislocated at the

time of culvert construction. Alternatively, the degree of sedimentation can be quantified by the fraction of blockage (deposited sediment) produced at the culvert entrance (vertical sedimentation dimension). In the present study, we only considered the sedimentation degree occurring in the upstream area of transition to culverts, i.e., the area connecting the natural stream with the culvert. The upstream deposition footprint is driven by local hydraulics, and it is a critical factor for the overall development of sedimentation in the culvert vicinity. After the formation of the upstream sedimentation, the sedimentation footprint grows in the downstream direction horizontally and vertically until the 'sediment island' reaches its 'stable' form. Stabilization (or 'fossilization') of the sediment deposits is a result of compaction and increased cohesion within the deposited material, but is considerably stabilized by the vegetation growth over the developing sediment islands (Ho 2010).

The information needed to quantify the degree of sedimentation (i.e., the response variable) can be collected either from *in situ* surveys or, as was done in this study, by analyzing the extent of the deposition in horizontal dimensions provided by aerial imagery. The tools for supporting the quantitative assessment of this variable are embedded in the IowaDOT Culverts platform. The previous study by Muste & Xu (2017) found that the degree of sedimentation (horizontal dimension) is strongly dependent on the ratio between the width of the stream approaching the culvert at low flow and the culvert width. A sketch of this important variable is provided in Figure 1(a). This variable can also be determined within the IowaDOT Culverts

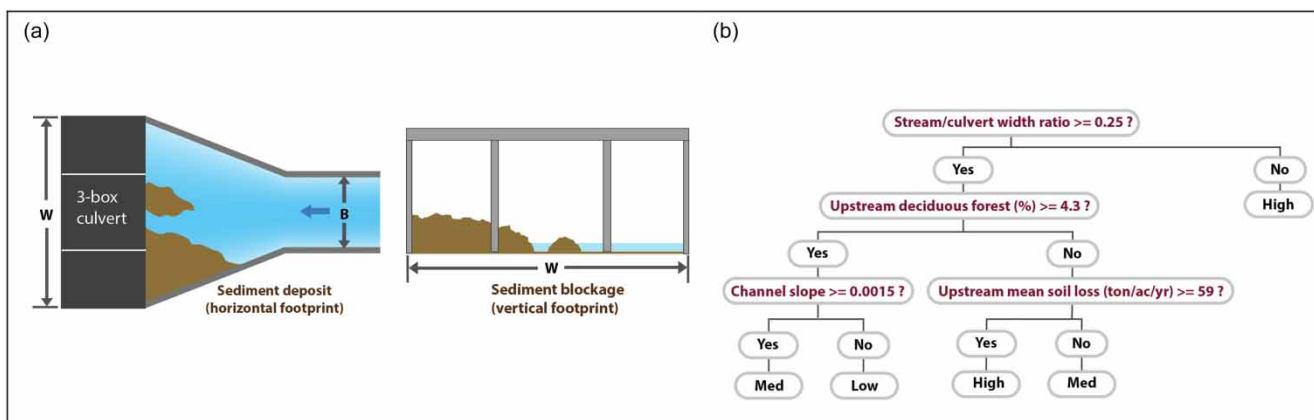


Figure 1 | (a) Definition of the SCW ratio (i.e., B/W) and (b) decision-tree representation of the cause-effect relationship between culvert sedimentation and its drivers (generated from the web platform).

platform using geo-processing tools for stream width assessment and the culvert design information retrieved from the SIIMS database. Table 1 lists the predictor and response variables used in this study.

Development steps

The implementation of the data-driven methodology is accomplished through the following steps.

The first step in the platform development is structuring the data needed for the data-driven analysis based on the multi-dimensional stream connectivity model (Demir & Szczepanek 2017) to better reflect the hydrologic processes underlying culvert sedimentation. The model reflects the principles of a river network-corridor-watershed continuum (Tockner & Stanford 2002). Namely, stream-associated hydrologic landscape units are connected in hierarchical networks, accumulating hydrologic and environmental characteristics in both longitudinal (from upstream to downstream) and lateral (from channel to floodplain and the entire catchment area) directions. The data garnered in the IowaDOT Culverts platform was organized using the NHD framework as the skeleton for stream connectivity.

In practical terms, this means that, for any culvert location, the features of the watersheds and their streams can be traced with a user-defined input (i.e., from stream vicinity to a prescribed width of the river corridor, up to the total drainage area outflowing at the culvert location).

The second developmental step of the data-driven platform is aimed at providing powerful visual analytics tools that illustrate the dependencies explicitly among the multiple variables. These tools greatly facilitate process understanding. It should be acknowledged that the visualized relationships are reliable only if the input data (i.e., predictor variables) are of decent quality and adequately sampled in space and time. For this application, the quality of the input data is not uniform as they were acquired and synthesized from various sources that might have different goals. Actually, only a few datasets are strictly related to the sedimentation process *per se*. The visual analytics tools of the platform are beneficial for detecting anomalies in the datasets and bringing in human justifications for identifying the variables that are affected by large uncertainties. Following the preliminary inspection of the multivariate relationship visualization, it was decided that additional data analysis is needed to (1) spatially partition the

Table 1 | Data sources utilized in the IowaDOT Culverts platform

Data source	Selected parameter	Associated processes	Data type
SSURGO and StreamCAT dataset	Rainfall-runoff potential	Culvert upstream basin characteristics (erosion and sediment production)	Predictor
RUSLE dataset	Annual soil loss		Predictor
StreamCAT dataset	Land cover		Predictor
HRLC dataset	Upstream riparian corridor land cover		Predictor
StreamCAT dataset	Upstream basin area		Predictor
Iowa Geological Survey landform map	Landform regions of Iowa		Predictor
NHD Plus version2	Stream channelization Channel slopes	Stream characterization (in-stream sediment transport)	Predictor Predictor
SIIMS and aerial imagery	Stream-to-culvert width ratio	Culvert structural attributes (sediment deposition at the culvert structure)	Predictor
Field surveys and aerial imagery	Vegetation		Predictor
Aerial imagery	Angle of incidence		Predictor
USGS Eash (Eash 2001) regional regression equations	Culvert design discharge		Predictor
Field surveys and aerial imagery	Sediment degree (severity) at culverts	Culvert sediment observation	Response variable

relationships by regions of similar sedimentation behaviors, (2) summarize and abstract the relationship through multi-variate clustering, and (3) reduce potential visual clutters in the visualization (Xu *et al.* 2019).

The third developmental step, the multiple-criteria decision analysis (MCDA), is the core element of our data-driven study. The MCDA pertains to cross-disciplinary research that looks for ways to provide computer support in solving space-related decision problems through enhancing human capabilities to analyze, envision, reason, and deliberate (Andrienko *et al.* 2007). It is an approach that uses quantitative and qualitative data, along with expert judgment, to support decisions even if the data are not abundant (Vulevic & Dragovic 2017). Moreover, the MCDA enables decision making when the number of alternatives or actions is evaluated in terms of more, usually conflicting, criteria. For our study, MCDA enables understanding and advising on the culvert sedimentation potential, thereby directly aiding the operational monitoring and design of multi-box culverts. The MCDA works atop of the data sources (time series, statistical analyses, maps, and other site-specific characteristics) assembled in step one of the platform development. The analytical outcomes for our study include (a) ranking watershed and culvert characteristics using feature selection techniques and (b) developing empirical relationships between culvert sediment degrees and key drivers.

This study utilizes a random forest algorithm to rank the relative importance of the independent variables and to produce quantifications and thresholds of their relationship with the sedimentation degree (Muste & Xu 2017). The algorithm is a popular supervised machine-learning technique in hydrologic studies (e.g., Breiman 2001; Francke *et al.* 2008; Tarazón *et al.* 2011). The strength of the method resides in the fact that: (1) decision trees can implicitly perform variable ranking (feature selection) to identify key drivers for culvert sedimentation; (2) the results are intuitive and easy to explain, allowing the method not only to make sedimentation forecasts but also to provide insights for an exploratory study; and (3) nonlinear relationships between parameters in the dataset do not affect the performance of decision trees. The random-forest method used in our study employs multiple decision trees to obtain a better predictive performance than could be obtained from any of the

constituent trees alone. This ensemble method derives the empirical relationship using a tree-like model of ranked key drivers and their possible thresholds regarding culvert sedimentation degrees (as shown in Figure 1(b)).

The fourth developmental step, as the most important practical outcome of this study, is the use of the culvert sedimentation forecasting tool that is developed on top of the previous three steps. Utilizing the decision trees generated from the MCDA, the forecasting tool is able to estimate the severity of culvert sedimentation at any stream location in Iowa. Initially, the culvert sedimentation forecasting was relatively coarse, hence it was subsequently improved by Xu *et al.* (2019) through regionalization, feature selection, multi-variate clustering, and sensitivity analysis on the spatial extent of different hydrologic units (watershed, river corridor, and riparian buffer).

INFORMATION SYSTEM DEVELOPMENT

All the features described in this section are hosted in the IowaDOT Culverts web-portal. Additional features designed for generic culvert management purposes, such as culvert information search and culvert monitoring, are also embedded in the platform to complement the main data-driven workflow. This section describes the design specifications and the interfaces associated with the platform. Currently, the web platform is transferred onto the Iowa DOT's cyber-framework for supporting routine culvert management and design.

Design specification

The 'IowaDOT Culverts' management system consists of four modules that group workflows by similar functionalities. The first module provides quick and efficient access to the culvert locations and inventory information on the selected culvert structure (e.g., dimensions, structure type, and inspection notes), as well as the extent of its drainage area. The search can be driven using keywords related to the culvert structural information or its location, such as the road or stream name, or the DOT garage serving the culvert. For characterizing culverts' watersheds, the platform utilizes the digital watershed (DW) concept (Muste 2014)

defined as a spatial unit for assembling multi-scale, multi-domain data (e.g., *in situ* observations) and the modeling results produced by various agencies. The selection tool offers multiple choices for the search (e.g., various catchment sizes within the drainage area) and subsequently triggers the visualization of catchment associated with the selected culverts. Based on the spatial boundary of the delineated drainage area, the portal dynamically generates a DW of the area entailing the environmental data and information stored in the database. Organization of the data in DW is made by indexing data using an identifier that relates the boundary data with the watershed. The watershed-centric data orientation of the platform enables further exploration of the interaction between culverts and their surroundings via the data-driven approach, shedding light on the complex riverine transport processes in human-natural coupled watersheds.

The second module is aimed at assisting field personnel in the routine monitoring activities and for supporting culvert sedimentation analysis. Specifically, the workflow allows users to record over time the observations at the culvert sites. The platform offers a choice of background basemaps, including high-resolution topographic maps derived from national elevation datasets, watershed and river networks from national hydrographic datasets, and 1-meter LiDAR hill shaded maps, which provide the user with a 2.5-dimensional 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 between site inspections. Useful mobile-friendly tools for navigating sites and organizing field campaigns are also embedded in this workflow for facilitating inspections of single or multiple sites. Shortly after the surveys are finalized, the monitoring results are uploaded (in real time) from the inspection site and can be viewed instantly if all the field communication tools are connected to the platform and the Internet.

The third module, the central component of the platform, integrates a set of cyber-enabled tools for sedimentation analysis that are aimed at quantifying and evaluating sedimentation as an end-to-end process. The first workflow contains several user-driven mapping tools for the estimation of the degree of sedimentation. These tools are used to derive essential information regarding the culvert

sedimentation degrees for the subsequent MCDA process. The quantification of culvert sedimentation status can be made directly on the aerial photograph using geo-referencing techniques and geo-processing services, enabling the user to delineate the extent of sediment deposit in the vicinity of the culvert with polylines. A similar geo-processing tool is available to estimate the stream width that is subsequently used to define the critical process parameter of the stream-to-culvert width (SCW) ratio illustrated in Figure 1(a). The workflow allows users to inspect the archive of sediment deposit maps, redo the mapping, or create a new sediment mapping for the culvert site.

The MCDA is supported by interactive information visualizations, consisting of parallel coordinate plots (PCPs), principal component charts, and scatter plots to improve the interpretation of the computer-inferred driver-sedimentation relationship and enable human judgments in the final stage of the decision support process. From the design specification perspective, it is important to mention the difference between the support for MCDA methods and for the MCDA process (Mustajoki & Marttunen 2017). The first method focuses on the visualization and technical implementation of the method, and the latter provides more general guidelines and good practices for carrying out the whole process in a meaningful way. Our platform adopts the first approach that basically hides the complexity of the MCDA for the platform users and does not allow them to interfere with detailed analytical settings.

The fourth module is practically the corollary of all the previous developments carried out through this study. The toolset makes available useful aids for the culvert designer or operation personnel by providing the data needed to estimate culverts' design discharge and to assess the potential degree of sedimentation at existing or new culvert sites. Based on the degree of sedimentation forecasted by the tool, the user can decide if the culvert needs to be re-evaluated in terms of hydraulic design or to prescribe measures to mitigate sedimentation. These measures can include practices that reduce erosion and sediment transport in the upland areas or recommendations for self-cleaning solutions such as those developed in a companion study on culverts (Muste & Xu 2017).

The workflows are served by friendly and graphically rich user interfaces to facilitate fast access to the needed

information. The language of the keyword-based queries is precise and uses FHWA's standard terminology as the primary category of users (e.g., infrastructure managers, designers, operational personnel, and DOT officials are familiar with this language). Rules of the responsive web design are another major specification to ensure the platform's accessibility through various devices (e.g., laptops, smartphones, tablets, etc.), especially when the platform needs to serve as an inspection support tool, which helps field personnel navigate to culvert sites and collect survey information (notes and inspection photos) through a mobile device in real time.

Platform architecture

Similar to many other modern web applications designed for supporting environmental studies (Krajewski *et al.* 2017), the IowaDOT Culverts platform adopts a three-tier architecture as illustrated in Figure 2. The architecture includes the presentation, logic, and data layers. The presentation layers are rendered in users' web browsers (client-side) to provide graphical interfaces that handle user interaction with tools under different workflows.

A web-based map of the environment is integrated into the interface for visualizing spatial information, such as culvert locations, roadways, culvert upstream watershed boundaries, and environmental information mapping (e.g., forestry map and land use map). The web map is also synchronized with various interactive and data-driven visualizations to establish a visual-analytics environment for exploring the sensitivity of different predictor variables to the sediment degree at culverts. Unlike the presentation layer, the logic layer and the data layer are deployed on the server-side. The logic layer manages the overall system logic. It contains GeoServer, a CyberGIS tool that enables the display of different map services, and an application framework (PHP YII) that supports culvert management and analytical functionality (e.g., watershed characterization, content management, and decision support). The data layer consists of web services, local databases, and a knowledge base that stores the data-driven insights (key drivers and their relationships with culvert sedimentation) resulting from the analysis.

Within the data layer, the web service interface collects the culvert-related variables listed in Table 1 to make them available for the data-driven analysis and to

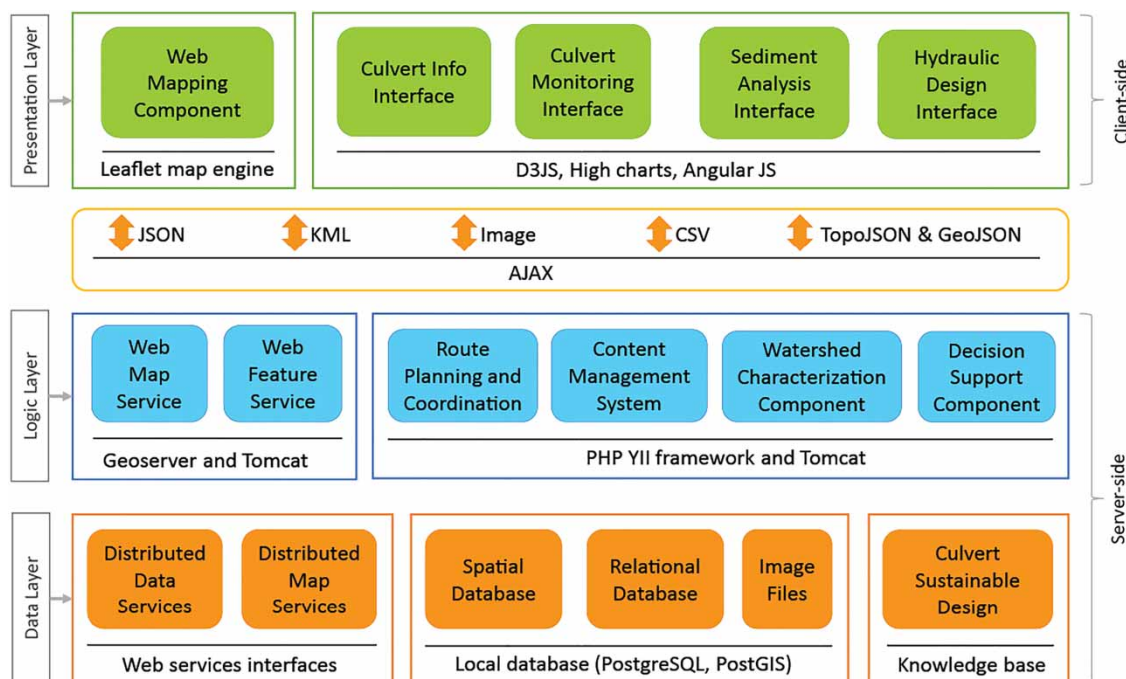


Figure 2 | Platform architecture.

subsequently store them in a local database. Afterward, the local database assembles the retrieved predictors with the response variable (i.e., culvert sediment observations) in one digital repository. Integration of the above information requires (a) spatial join to connect culvert locations with both the characteristics of their associated catchment and (b) the response variable that quantifies the degree (severity) of sediment blockage at culverts.

PLATFORM FUNCTIONALITIES

General culvert information

Information about the culverts is retrieved through a search engine. The engine is able to retrieve the boundary and characteristics of the drainage area that is upstream of a selected culvert or of any other point of interest on Iowa's stream network. 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 and 4-box culverts maintained by IowaDOT). The post-construction data contain information acquired during routine inspections and field observations that follow the occurrence of severe storm events.

The interfaces associated with this module allows us to visualize all the culverts in the local database (see [Figure 3\(a\)](#)) and identify a specific culvert based on their FHWA structure code, road name, river name, or culvert's ID (as shown in [Figure 3\(b\)](#)). The platform also provides a tool that displays subsets of culvert locations on the map by filtering culverts based on user-defined attributes (e.g., number of the box, culvert size, retrofitting type). Each identified culvert can be viewed within its own info window as illustrated in [Figure 3\(c\)](#), whereby culvert specifications are retrieved from the database along with a bird's eye view of the culvert. The drainage area and its characteristics can be quickly accessed for each selected culvert through a customized interface (see [Figure 3\(d\)](#)). Currently, the IowaDOT Culverts platform provides management information for 3-box culverts. However, the platform design is generic and can be readily extended to other

road-associated structures and in other states that use a similar digital inventory for infrastructure management.

Culvert inspection and monitoring

The 'Monitoring' module is designed to assist with both *in situ* surveys and remote inspections via aerial maps. The *in situ* surveys are assisted by a mobile-friendly tool that can turn users' mobile devices (e.g., smartphone, tablet serviced by a Wi-Fi hotspot) into digital surveying tools. The essential features of this workflow are trip planning, culvert navigation, and real-time data collection. The planning and navigation workflows are synchronized with Google's navigation service facilitating users with the creation of the routes. Moreover, this connection enables navigation through the pre-planned routes with the awareness of road connectivity and traffic aspects, making the field inspections cost- and time-efficient. The planned routes can also be saved as a spatial file for subsequent usage (see [Figure 4\(a\)](#)).

Once arrived at one of the targeted culverts, the users can collect culvert inspection data (e.g., survey notes and photos) using a mobile device (smartphone or tablet) and upload the acquired information into the platform's database via Wi-Fi and mobile data service. The culvert surveys are expected to register information related to (a) the degree of sedimentation in the culvert vicinity (photo-documentation), (b) the degree of blockage at the culvert entrance (surveys of the cross-section with tapes or range-finders), and (c) any relevant features characterizing relationships between culvert structure and the associated stream, as well as specifications on sediment deposits (notes). The *in situ* surveys are conducted with a rigorous structure and terminology that is logically sequenced for ensuring a uniform description of the culvert status at the time of the inspection. A snapshot of the data inspection up-loader is shown in [Figure 4\(b\)](#).

The monitoring workflow is powered by a content management system that provides users with the capability to search past inspection records based on different criteria and keywords, such as finding culverts with debris found in their upstream entrance. Past inspection information is open to public access, while the data collection tool is password protected. The data collected in this manner represent an efficient tool for supporting periodic inspections

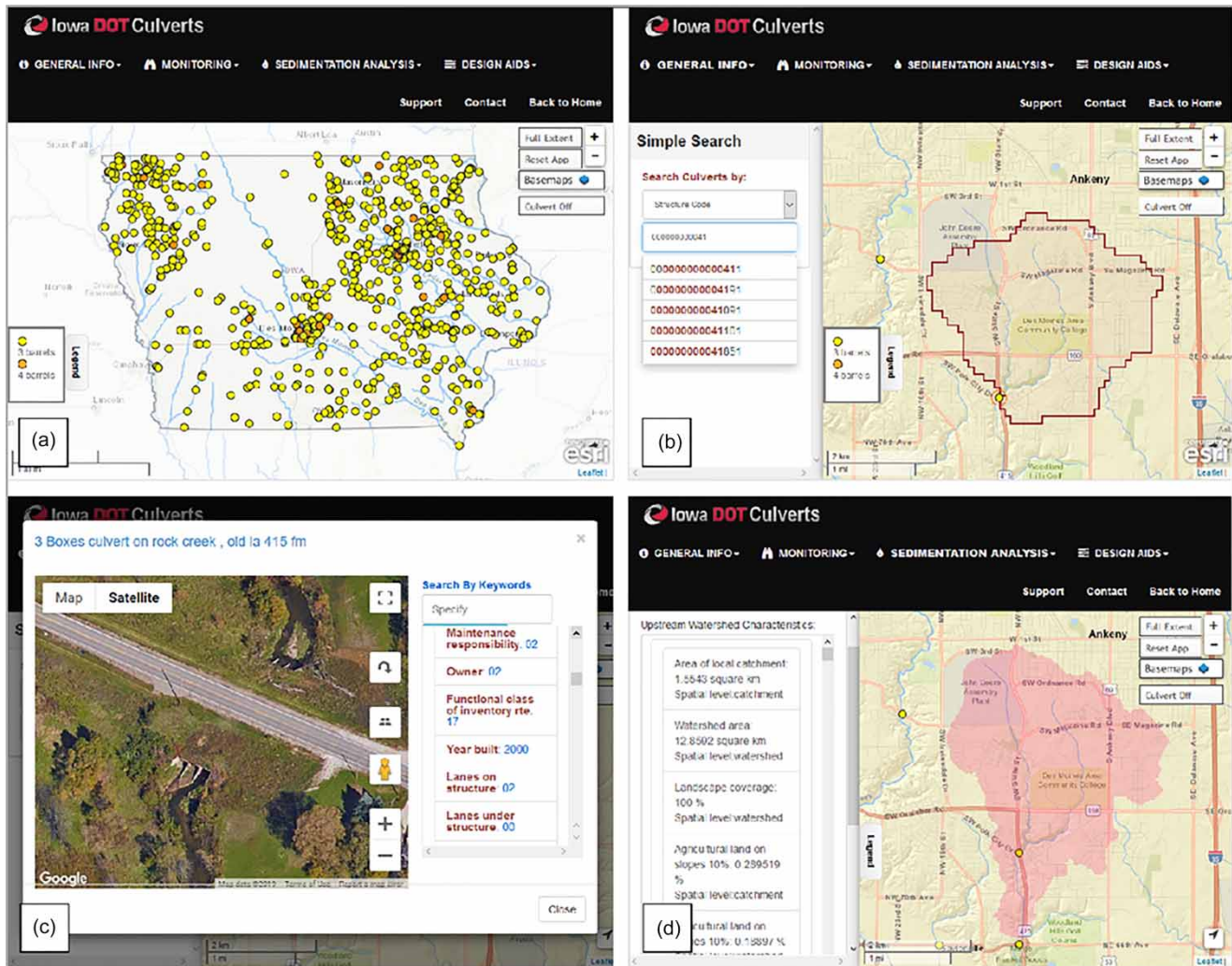


Figure 3 | 'General Info' module interfaces: (a) culvert location mapping, (b) culvert search by the FHWA code, (c) culvert info table, and (d) characterization of the culvert drainage area.

conducted by the culverts' maintenance personnel. The rigor of the data acquisition protocol and the quickness of the field data acquisition represent a significant improvement of the piece-meal (Muste & Xu 2017) and combined field and office procedures that are currently in use by county and Iowa DOT district engineers.

Also adopted in this study are *in situ* surveys conducted with real-time kinetic GPS instrumentation or drones. Results of a drone-based survey compared with the typical on-the-ground photographic acquisition at a culvert site are illustrated in Figure 4(c). These alternative survey options for mapping sediment deposits lead to more accurate quantification of 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 (the vertical sedimentation dimension). These indicators define the most important parameters of the sedimentation 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-intensive, meaning only a limited number of such surveys can be conducted. Within the same workflow, the platform enables quick access to historic aerial images taken at the culvert as illustrated in Figure 4(d). The source of the image, as well as their quality, is diverse depending on the provenance (e.g., Google, ESRI Imagery, National Agriculture Imagery Program, low-altitude photography). The photographic



Figure 4 'Monitoring' module interfaces (a) map of past surveys and routes, (b) past culvert inspection records, (c) culvert sedimentation survey acquired with drones compared with the ground-based photographic survey, and (d) series of aerial imagery for supporting sedimentation progress over time.

information is extremely valuable for assessing the rates and causes of sedimentation. The most critical information from the photographic time series is the tracking of the geomorphological changes in the culvert vicinity and of the vegetation growth. The post-survey analysis supplemented by aerial photography inspections enabled by the IowaDOT Culverts platform allows authorized personnel to garner useful information and insights related to the causality of sedimentation as well as to assess culvert structural conditions (e.g., blockage and scouring status) continuously.

Culvert sedimentation analysis

This module contains two workflows, i.e., ‘Sedimentation Deposit Mapping’ and ‘Multi-Criteria Decision Analysis’. The first workflow uses aerial imageries covering the area of interest to create a comprehensive dataset that documents all the predictor variables, as well as the degree of culvert sedimentation across Iowa. The second workflow, a simple data-driven process, is automatically rendered by the platform using the culvert dataset that is assembled and created in the previous workflows.

The ‘Sedimentation Deposit Mapping workflow’ offers the options to inspect a previous mapping, to create a new mapping at an existing or future culvert location, or to update a previously produced map of sedimentation (see Figure 5). The sedimentation mapping is accomplished with a map engine that estimates on the fly the geo-coordinates of the polyline vertices traced by the user on the

image to mark the area occupied by the sediment deposits. A second map is generated for establishing the area of reference (i.e., the area that was disturbed at the time of culvert construction). This area is typically assumed to be the transition from the natural stream width to the tips of the culvert wingwalls. The two areas are automatically processed to obtain the percentage of the sediment extent in the culvert vicinity (most often in the upstream area). If required, the geo-processing service is capable of roughly estimating the volume of the sediment of the mapped deposit using area and elevation information available in a digital elevation model.

A simpler tool is also available in this workflow to measure distances on the map. This function is useful for defining the SCW ratio, which is a critical factor in triggering and developing sedimentation. The two described tools are the only features that require user actions within the platform. The results of a new or updated mapping are automatically added to the sedimentation database for further usage. In this regard, the accuracy of the ‘Sedimentation Deposit Mapping’ workflow (solely determined by the quality of the aerial images and the skills of the user) is critical for ensuring not only the quality of the following MCDA but also the accuracy of the later sedimentation potential forecasting.

The MCDA workflow is a comprehensive multivariate visualization as illustrated in Figure 6(a). Each line of the PCP represents the relationship between the response and predictor variables for one culvert site. Currently, the

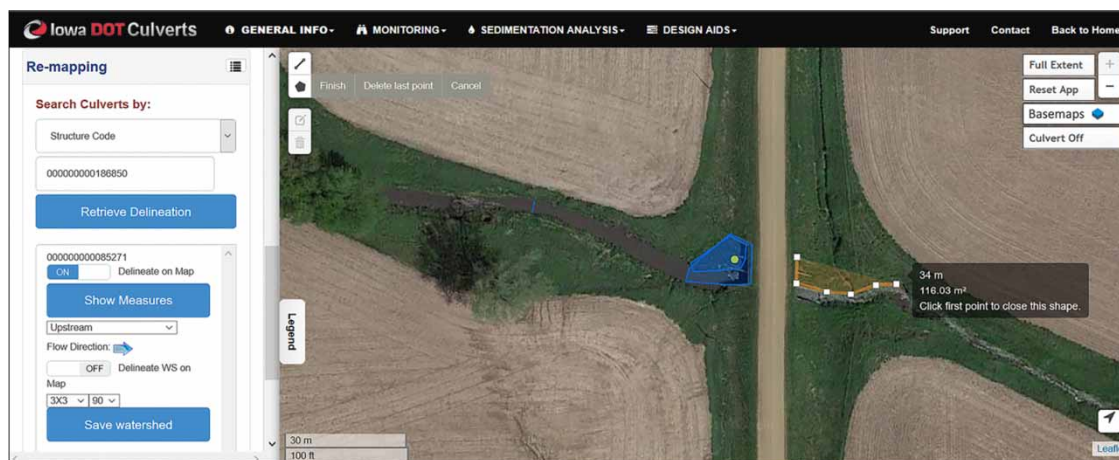


Figure 5 | The interface for the ‘Sedimentation Deposit Mapping’ workflow.

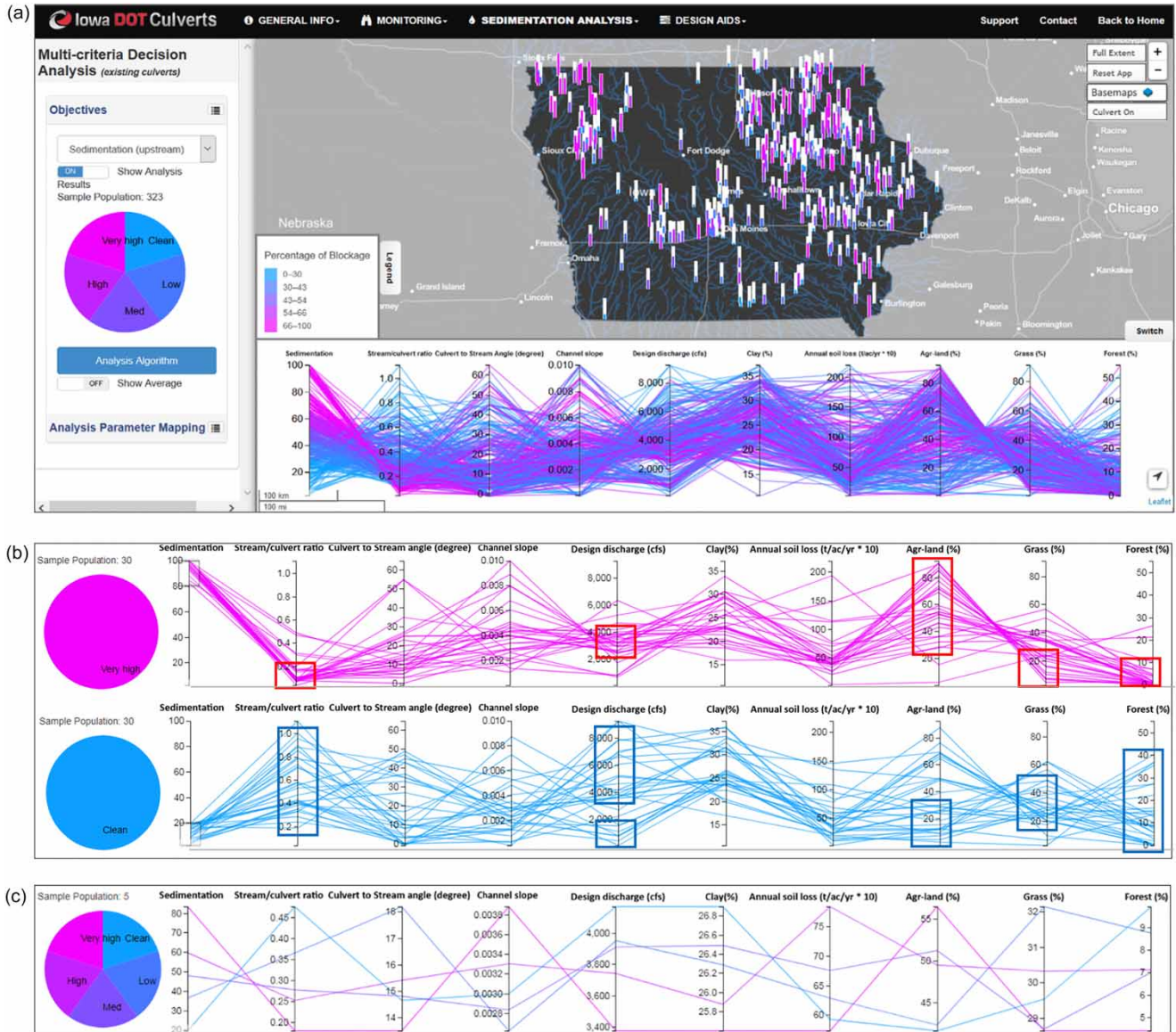


Figure 6 | The 'MCDA' workflow: (a) MCDA results visualization, (b) displays of sedimentation relationships filtered by selected variables through multivariate visualization, and (c) average trends of predictor variables in each sedimentation degree.

IowaDOT Culverts platform contains more than 323 analyzed culverts. The interface also offers other forms of data visualizations (e.g., scattering plot, principal component plot) to help users draw the needed inferences regarding data distribution and quality.

The PCP embedded in the MCDA workflow allows users to dynamically display empirical relationships between pairs, selected groups, or the entire set of independent variables used for the analysis. The most relevant initial

relationships for the present context is the one 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 6(b). By filtering the degree of sedimentation for its high values on the first axis (i.e., representing heavily silted culverts), the overall dependency looks like the one plotted in Figure 6(b) (top). By selecting the degree of sedimentation at the

opposite side (i.e., representing clean culverts), it can be observed that the two dependencies vary both in trends (see for example the second axis plotting the SCW ratio) as well as with respect of relationships consistency (bottom plot in Figure 6(b)). The cursory review of these two opposite sedimentation situations leads to two immediate conclusions: (a) the SCW ratio is a decisive variable in the sedimentation at culvert relationship and (b) a small SCW ratio (i.e., denoting a wide culvert cross-section compared with the stream width in normal flow) is a critical factor for the sedimentation at culverts. Additional patterns can be observed in other predictor variables, such as design discharge, upstream agriculture land percentage, and grassland percentage. Moreover, the PCP is synchronized with the web map, so that the selected data subsets through the PCP can be highlighted on the map to show their spatial distributions. For summarizing the relationships and reducing data cluttering in the PCP, the platform allows users to view the average trends of each variable that represents different sedimentation degrees (Figure 6(c)).

In the PCP, large dispersions of the data lines for some of the sedimentation process drivers discussed above suggest that there are potential sources of uncertainties in the current analysis and that more analytical techniques, such as multivariate clustering and regionalization, can be applied to refine the result. Overall, the PCP allows users to interact with the data through brushing and filtering, so that more useful insights and conflicting criteria regarding the effects of drivers on culvert sedimentation can be derived to support culvert management and sedimentation mitigation strategies.

Culvert design

The 'Decision Aids' module is developed to address the culvert designers' needs by providing two critical pieces of information: (a) the design discharge for sizing the culvert and (b) the forecast of the potential for sedimentation at any culvert site. The corresponding workflow is labeled on the platform as 'Design-Discharge Information' and 'Sedimentation Potential Warning', respectively. The tools can be used to estimate these variables at existing or future culvert sites. The first contribution brought by this module to the decision process is the estimation of the design

discharge that is used in the hydraulic sizing of the culvert. The discharge estimation algorithm is identical to the one currently used by IowaDOT designers (i.e., the annual exceedance-probability discharge). Our platform uses the USGS Eash method that is 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 design discharge estimates at ungagged sites for supporting various water-resources planning and management needs.

The input information required for the design discharge estimation at a planned or existing culvert includes the delineation of 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 for delineating the drainage area with consideration of the hydrologic regions defined by the USGS Eash method. The numerical results of the analysis conducted in the back end of the system are sent to the front end through geo-processing services installed on the server. On the front end, these results are plugged into appropriate regression equations selected by hydrologic region type. The outcome of the geo-processing tool is the design discharge for various recurrence intervals as illustrated in Figure 7(a). Typically, the 20- to 50-year return flows are used in the state for sizing the total cross-section for the culverts. Following additional hydraulic considerations, the actual geometry and box dimensions are established. The 'Sedimentation Potential Warning' workflow located under the 'Design Aids' estimates the degree of sedimentation for existing or new culvert sites. As mentioned before, for the present context it is assumed that if the upstream area of the culvert is blocked with sediments, the culvert operation capability becomes limited as typically the downstream sedimentation follows quite shortly. The forecast is based on the 'training' of the culvert dataset produced from the 'Sediment Deposit Mapping' workflow through a random forest algorithm. 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 through the platform (using

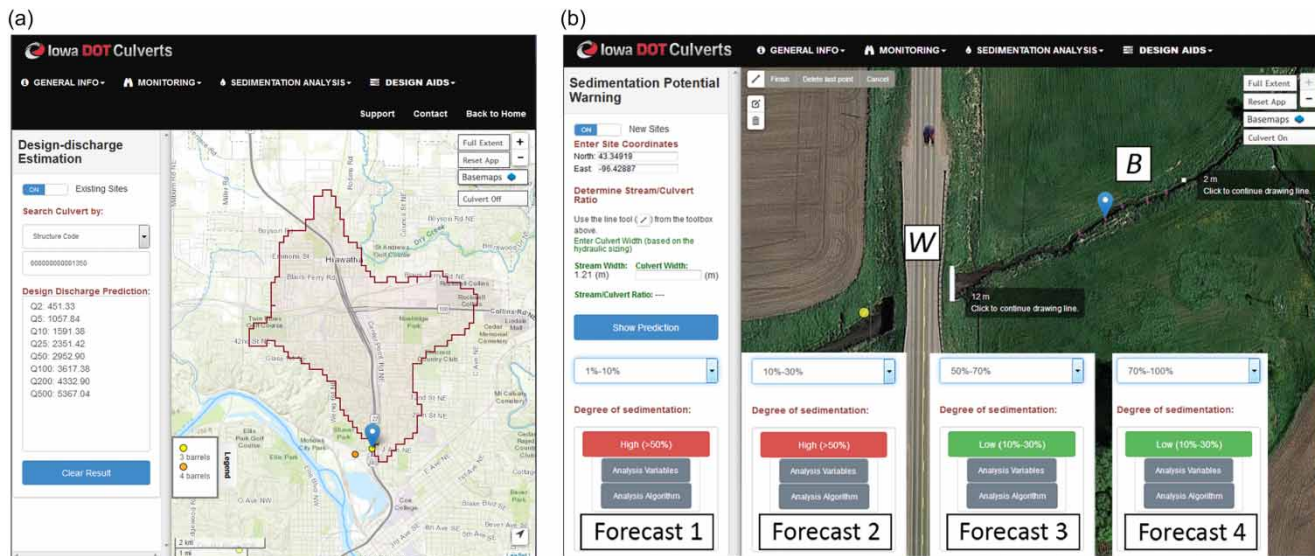


Figure 7 | Interface for the 'Design Aids': (a) the estimation of the culvert design discharge and (b) successive iterations for the forecast that were obtained by adjusting progressively the width of the culvert to be designed.

any of the methods described in the section 'Culvert sedimentation analysis') will increase the robustness of the forecast.

For an existing culvert, all the independent variables needed for forecasting are known and they are assumed to not change over short time intervals (i.e., soil type, watershed physiography, vegetation cover, etc.). The role of sedimentation forecast in this situation is to predict the degree of sedimentation at a given site for the 'as is' situation. For new culvert sites, the watershed and stream characteristics are known too, but the dimensions for the culvert as established through the hydraulic design are not yet final. This is the stage when the 'Sediment Warning Potential' starts to play its role, as following the hydraulic portion of the culvert design, there is still some flexibility for re-evaluating the culvert cross-section by changing the type of culvert or its components.

We are now at a stage of the culvert design when all non-structural parameters are known, and we can still adjust the 'SCW' (i.e., the most important driving factor for sedimentation) ratio to reduce the potential for sedimentation. In this design stage, the user has 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 in formulating the sedimentation degree forecast. The outcomes of the MCDA 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. 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 0–10%, 10–30%, 30–50%, 50–70%, and 70–100%. A view of the 'Sedimentation Potential Warning' interface is illustrated in Figure 7(b).

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 (land management) that reduce erosion and sediment transport in the upland areas or can recommend sedimentation-sensitive solutions such as those developed in a companion study on culverts (Muste & Xu 2017). The design of the two workflows is adaptive and generic enough so that other culvert operating hazards, such as debris and scouring, can be easily addressed in the same manner.

In order to assess the performance of the sedimentation forecasting workflow, we used a dataset of 125 culverts. These culverts were inspected by our research group through field inspections conducted *in situ*, whereby photographic evidence and simple measurements that quantify the degree of sediment blockage in the culvert vicinity were collected. The locations of these culverts are illustrated in Figure 8(a). The validation protocol used the workflow for prescribing the degree of sedimentation using the specifications available in the culvert database and the inferences offered by the sedimentation analysis workflow described in the section ‘Culvert sedimentation analysis’. The outcome of the sedimentation forecasting workflows was compared with the experimental evidence collected at the culvert sites, as illustrated in Figure 8(b). The analyzed dataset indicates a 90% agreement for the degree of sedimentation provided by the two alternative methods.

CONCLUSIONS

The paper illustrates the implementation of a problem-solving environment for supporting the management and optimized design of multi-box culverts with consideration of sediment accumulation in their vicinity. The proposed data-driven approach maintains the holistic, systems approach of the problem investigation, but it does so with cost-efficient and effective means compared with the other

conventional investigative alternatives. The method can best be applied in data-rich watersheds or in areas where surrogates for that data are available. Fortunately, these data 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. This study conducts an MCDA that uses quantitative and qualitative data, along with expert judgment, to develop empirical relationships between the degree of culvert sedimentation and the key process drivers within the drainage area of the culvert.

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 culvert sedimentation-sensitive design that reduces future culvert operation hazards through intelligent-aided analysis. 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.

The platform can be accessed anytime from anywhere through the Internet and thus such can be updated as

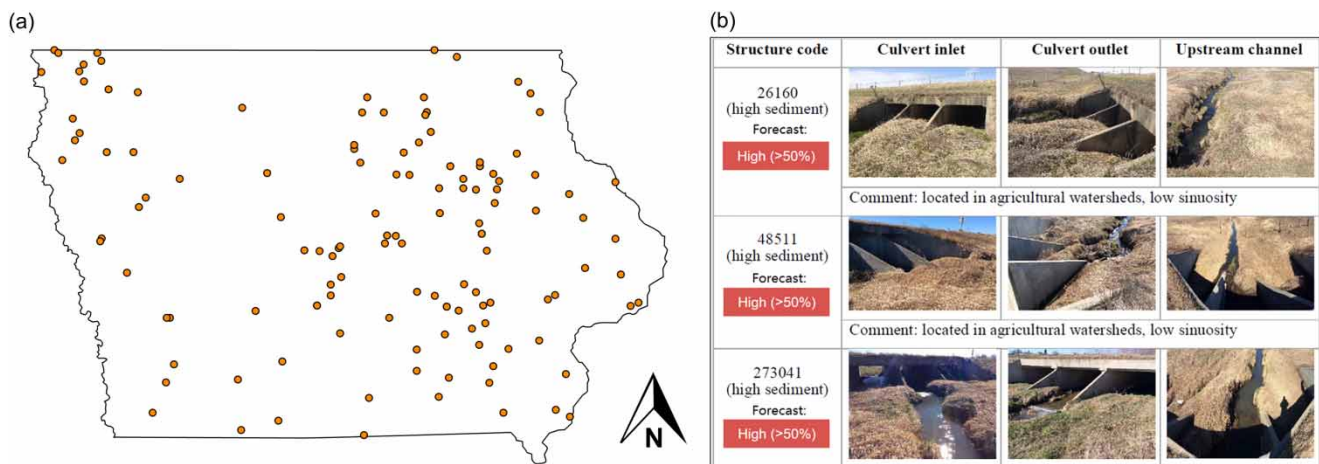


Figure 8 | Selected results of the sedimentation forecasting workflow validation: (a) locations of culverts for the validation dataset and (b) samples of predicted degrees of sedimentation and photographic observations acquired at the culvert sites.

information is produced, allowing for a central repository that can inform on the state of the culverts in Iowa. The system is developed in a flexible and extendable structure to address similar transportation asset management concerns (scouring and wood debris) at the national level. The platform is built with open-source technologies that make the system light-weight, low cost, and adaptive. The described geo-portal is a new, innovative decision support tool that facilitates making useful practical correlations between variables describing the culvert-stream-drainage area triplet that are difficult to be captured and understood using analytical or laboratory studies. The web-accessible portal is a continuously updated resource about the culvert life-cycle that plays several of the following roles: (a) informs and facilitates the design of culverts by accounting not only for the hydraulic aspects of the sizing but also for the sedimentation that is not currently considered in the design stage of these structures; (b) guides the culvert maintenance program; and (c) serves as a repository that can be mined to infer the aspects of current designs as applied for large geographic areas.

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DECLARATIONS OF INTEREST

None.

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