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Prototype hydroinformatics-based system for supporting decision making in culvert design and monitoring

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Xu, Haowen. "Prototype hydroinformatics-based system for supporting decision making in culvert design and monitoring." MS (Master of Science) thesis, University of Iowa, 2015.
https://doi.org/10.17077/etd.rrxu6kun.

PROTOTYPE HYDROINFORMATICS-BASED SYSTEM FOR SUPPORTING
DECISION MAKING IN CULVERT DESIGN AND MONITORING

by

Haowen Xu

A thesis submitted in partial fulfillment
of the requirements for the Master of Science
degree in Civil and Environmental Engineering in the
Graduate College of
The University of Iowa

August 2015

Thesis Supervisors: Adjunct Professor Marian Muste
                            Associate Professor George Constantinescu

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

Haowen Xu

has been approved by the Examining Committee for the thesis requirement
for the Master of Science degree in Civil and Environmental Engineering
at the August 2015 graduation.

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                      Marian Muste, Thesis Supervisor

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                      George Constantinescu, Thesis Supervisor

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                      Larry Weber, Committee Member

To my friends and family

ACKNOWLEDGEMENTS

It was my great honor to study and work at IIHR-Hydroscience & Engineering with many world renowned researchers and outstanding students. At IIHR, I received excellent education and training in water resource engineering, as well as established my career goals. I would like to express the deepest appreciation to my research advisor Professor Marian Muste, who has supported, guided, and enlightened me in both research and academics with his wisdom and experiences. In the past four years, he provided me with many invaluable directions in projects and led me into the adventure of Hydroinformatics and hydraulic research. I would like express my sincere gratitude to Professor George Constantinescu, Professor Larry Weber, and Professor Allen Bradley for their assistances and supports in my research and work.

I would also like to thank the IIHR support staffs and the UI geography department, without whom I cannot finish my project and research. I especially appreciate the technical help from Ibrahim Demir and Radek Goska, and the Geoinformatics guidance from Professor David Bennett of UI geography department and Assistant Professor Jerry Mounts of Montana State University.

Moreover, I really appreciate my family, especially my parents for their financial supports and living advices through my Master degree. In addition, a thank you to all the lab folks at IIHR for being good friends and colleagues. In the end, I want praise the God for creating me and giving me intelligence to learn and produce.

ABSTRACT

While notable resources of nature science are already available for solving watershed processes problems, there is a need to considerably improve the operational science which is defined as the seamless, integrated suite of high-resolution information systems for decision-making. Operational science relies primarily on the acquisition and management of observations and numerical simulation results from collaborative modeling as well as on services involving all technical aspects of watershed information systems, including system interoperability and data exchanges, enterprise GIS and Geo-Intelligence, integrated information visualization and communication (Cline, 2009). These information and communication technologies assembled in tools and workflows for aiding the decision making process are collectively forming a Decision-Support Systems (DSS) specific for a practical application. Technical definitions and examples of the DSSs are provided in Chapter 3. The scientific basis of building DSS stem from Hydroinformatics that is a generic science area allowing us to address a new class of problems around the organization of data and information and extraction of knowledge stemming from them.

The work conducted through the present thesis represents initial efforts and experiences in the development of Hydroinformatics systems for supporting the decision making in the management of watershed resources and supporting infrastructure. These systems entails contemporary cyberinfrastructure components such as scientific workflows (automated coupling of data with models), automated web publishing mechanisms, mash-ups of web technologies and semantic content repositories. The thesis

reports first on some preliminary developments of three Hydroinformatics platforms containing simple workflows.

The first is the IOWADIS (Iowa Watersheds Data & Information System), a prototype hydro information system developed under the intelligent digital watershed concept. Developed as data portal, the platform continuously streams and manages water related information, including river streamflow, water quality, and precipitation from various data providers (i.e., IIHR, USGS, EPA, Hydro-NEXRAD etc.). Iowa DIS workflows include watershed delineation at user defined location, water data query, time series visualization, data download, and data comparison between sensors. The second development is the Soap Creek watershed visualization platform for displaying simulation results of flood mitigation in Soap Creek. The results are obtained from HEC-HMS models. They include pond usage, pond efficiency, and hydrography at model-defined index points. As standard workflow for many DSS, users are required to select simulation scenarios in the first place, the platform will visualize modeling result on a web map geospatially. Different visualization methods are also provided by the platform as options. The third development is the Indian Creek watershed visualization tool. Similar to the Soap Creek watershed platform, this platform is also designed to visualize flood mitigation as well as flood damage simulation results in Indian creek watershed. The modeling results are from the GSSHA (Gridded Surface Subsurface Hydrologic Analysis) model. The workflow of this platform is identical to the Soap Creek platform, both of which entails scenarios selection and visualization methods selection.

The main contribution of this thesis is the assemblage of a DSS for the design and monitoring of Iowa multiple-box culverts. The final product is named "Iowa Culvert

DSS", a geo-portal designed for Iowa Department of Transportation (Iowa DOT) to achieve: a) automated data fetching and integration; b) inclusion of the hydraulic design software; c) guidance on preventing sedimentation; and, d) digital storage and retrieval of the culvert monitoring observations. Via information and cyber GIS technologies, the portal integrates data on: 1) watershed characteristics (river network, hydrologic and soil information for the drainage areas, streamflow statistics at gaged and ungagged sites); 2) culvert specifications; 3) specification for hydraulic sizing; 4) culvert monitoring (changes in the site-specific geo-morphological characteristics); and 5) pre- and post-construction culvert operations. In addition to data and information, the platform also provides diverse tools and web services for designers and managing personnel to query, to visualize multiple resources, as well as to estimate basic hydrologic properties. Details on platform workflows are included in Chapter 5. The platform is built with open-source technologies making it light-weight, low cost, and flexible.

PUBLIC ABSTRACT

Current guidelines for culverts design account for hydrologic, hydraulic, and geomorphological conditions at the construction site. Less attention is given to the assessment of the potential for sedimentation within and in the culvert vicinity. Sedimentation of culverts has become an increasing concern for regions where the soil erodibility is historically high (such as the US Midwest), as the recent changes in the land use and climate exacerbate the problem. Culvert design is based on a wide variety of data sources typically stored in various formats in multiple data provider repositories. Assembly of the data needed for design, as currently conducted, is time consuming and inefficient, while the wealth of information garnered through post-construction monitoring is not efficiently used to inform the design of new culverts in the same geographical area.

This thesis presents a solution to the above mentioned issue using Hydroinformatics approaches. The end product of the thesis is a geo-platform designed to achieve computer-assisted protocols for culvert design, sediment mitigation design, and monitoring of culverts in operation. The platform contains two primary workflows: culvert design and culvert monitoring. The tools and workflows inside the platform are developed using information and GIS technologies. The platform is web accessible, light weighted, and user friendly.

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CHAPTER 1 INTRODUCTION

1.1 Overview of multi-box culvert in Iowa

Culverts are common hydraulic structures that pass streams under roadways in a variety of flow conditions without producing considerable scour that threatens the stability of the structure or sedimentation in the vicinity of the culvert. Culverts are widely used in many rural U.S. Midwestern areas to convey flow through roadway embankment for small streams. While playing the same role, culverts are different from bridges as they are commonly covered with embankment and are composed of structural material around the entire perimeter (FHWA, 2012). Culverts also take advantage of submergence to increase hydraulic capacity. Culverts may comprise a single conduit or multiple conduits (thereby the terms multi-barrel or multi-box culvert). Examples of culverts with single conduit and multiple conduits are shown in Figure 1.1. In general, larger flows and road embankment heights require the use of multi-barrel culverts. Compared with single-box culvert, multi-box culverts operate with less headwater and they cost less (FHWA, 1995).

a)   b)

Figure 1.1 Culverts with a) single barrel and b) multi barrels (FHWA, 2012)

Culverts are ubiquitous for secondary roads crossing small streams in the state of

Iowa: currently, there are 723 culverts comprising 3 and 4 boxes maintained by Iowa

Department of Transportation (IDOT) (SIIMS, 2015). Box culverts are generally

designed for flood events with 50-year return period. However, flow through a typical

box culvert is considerably lower than the design flow for most of the year. Current

culvert design solely focus on hydraulic capacity, hydrologic characteristic, Aquatic

Organism Passage and geomorphological conditions. No special attention is given to

other transport processes (i.e., sediment, debris, environmental concerns). Repeated high

flows passing through the culverts lead to a gradual increase of the sediment deposits in

the culvert vicinity, eventually resulting in reduced flow and sediment capacity.

Sedimentation is a chronic problem in Iowa mostly due to the intensive agricultural

practices that trigger considerable sediment loads in the streams (Skopec, 2011).

1.2 Iowa culvert problems

1.2.1 Preliminary considerations

The main considerations in the design of culverts are attaining hydraulic

efficiency over a range of flows while preserving the structure's safety. The benefits of

constructing a large capacity culvert to accommodate the whole range of flow events with

no detrimental flooding effects are normally outweighed in the culvert design procedure

(Normann, J. M., Houghtalen, R. J., and Johnson, W. J., 1985). Due to the large range of

flows to be accommodated and practical limitations related to the height of the road

embankment, and also economic considerations, the use of multi-barrel culverts (culverts

with more than one barrel) is often chosen as the output of the design (HC Ho et al., 2013).

Sedimentation at culvert is one of the most costly operating culvert problems (HC Ho et al., 2013). Sediment is getting in the streams either through direct (erosion in the hillslope area) or indirect (bank erosion produced by increased runoff) transport processes. The highly erosive Iowa soil favors both processes leading to sediment accumulations at culverts sites that eventually cause partial blockage that severely impairs culvert capacity to convey design flows. The characteristics of the soil in Iowa watersheds along with the intensively nature of their agricultural use, as well as the increasing impacts due to climate changes (Skopec, 2011), are collectively making sedimentation at culverts a common problem in Iowa as well as in the entire US Midwest. Multi-box culverts with 3 and 4 conduits are especially prone to sediment clogging as they typically create a large cross sections (i.e., most often larger than 30 ft.) that is further augmented in some of the cases by oblique wingwalls attached to the entrance and exit of the culverts. Overall, this widening of the stream cross section upstream of the culvert is favorable for conveying large stream flows during extreme flow events (i.e., especially during spring season), but in the same time creates ample space for the sediment to deposit during the falling stage of the hydrographs passing through the culvert. Details about culvert sedimentation and its cause will be elaborated in Section 2.2. The present study primarily focuses on sediment mitigation for 3- and 4 - box culverts, because those culverts are more prone to sedimentation than single and double - box culverts. Details about sediment formation at 3- and 4 - box culverts are provided in

Section 2.2.4, in which the effects of culvert geometry on sediment deposition are explained.

1.2.2 Culvert sedimentation survey

To investigate the severity of multi-box culverts (3- and 4 - box culverts) clogging in Iowa, culvert sediment surveys were sent to all counties in the state of Iowa in 2009 and 2014. The survey contains a set of comprehensive questions covering extent, severity, causes, period of sediment disposition, and culvert maintenance measurements at county level. The survey questions were answered by either county engineers or Iowa DOT engineers at district and DOT garage level. Among all of the invited counties, 16 responded to the survey in 2009 and 53 responded in 2014. Figures 1.2 and 1.3 map the location of respondents in Iowa for the 2009 and 2014 surveys, respectively.

The results of the 2014 survey is more substantial than the one conducted in 2009 as it covers 24 out of 99 counties compared to 16 in 2009. Moreover, the respondents were located in areas of considerable high numbers of culverts compared with other parts of the state. Many of these culverts are concentrated in urban areas, as illustrated in Figure 1.4. The figure maps the locations of 3- and 4 - box culvert as recorded in IDOT Structure Inventory and Inspection Management System (SIIMS) system. SIIMS is the single source location for entering and reviewing condition information on all Iowa bridges and culverts, both local and state owned (http://siims.iowadot.gov). It can be observed that most of the 3- and 4- box culverts cluster in north western, middle, and eastern parts of states, where major cities locate (i.e. Des Moines, Waterloo). Figure 1.5 correlates urban areas with culvert locations in Iowa. It is obvious that multi-box culverts concentrate near Des Moines and Waterloo city areas. The general spatial information

displayed in Figure 1.3 to 1.6 (e.g., basemaps, state and county maps) are provided by the GIS library of Iowa Geological Survey (IGS, 2014).
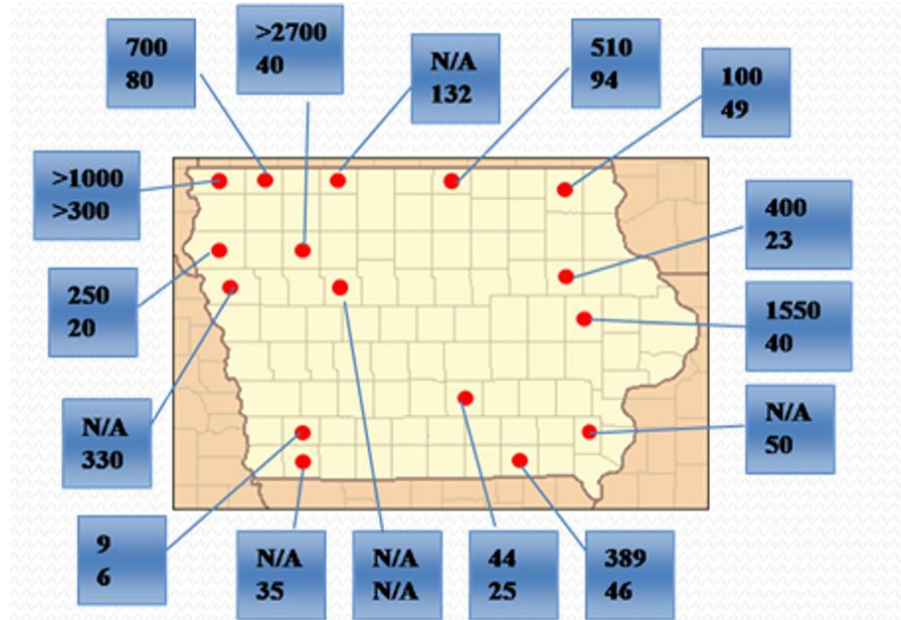
Figure 1.2 Culvert sediment 2009 survey coverage area (upper number represents the number of multi-box culverts, the lower number represents the number of multi-box culverts)
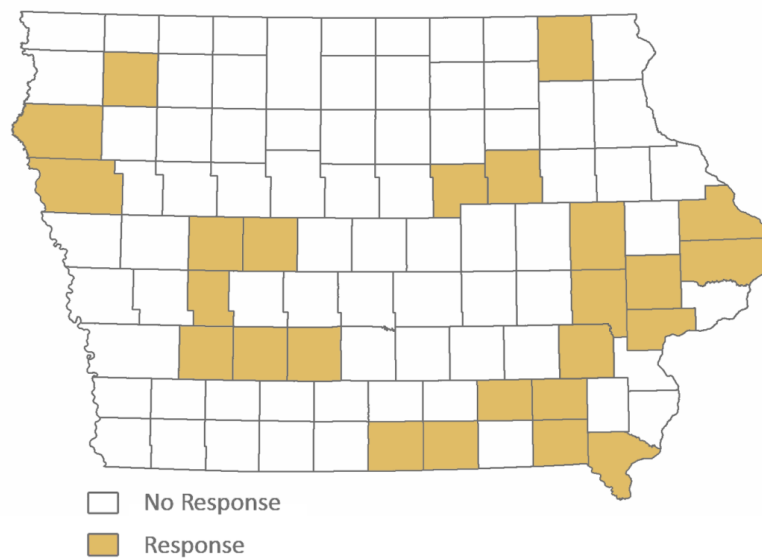
Figure 1.3 Culvert sediment 2014 survey coverage area (53 respondents: 14 District, 39 county engineers)
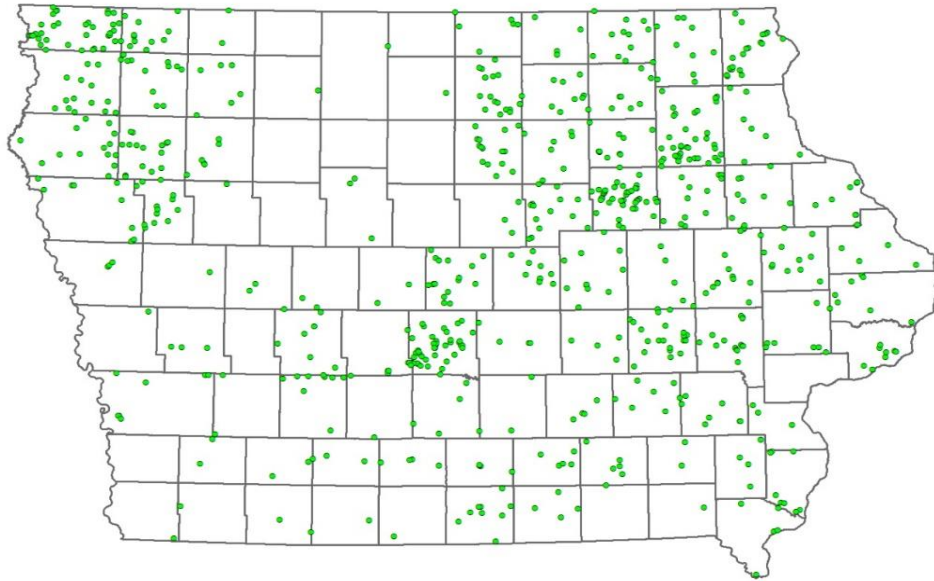
Figure 1.4 Culvert distribution in Iowa counties
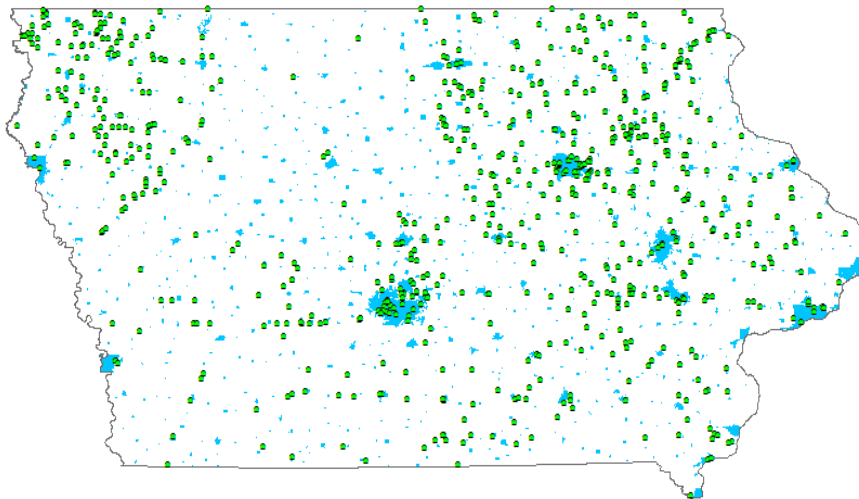
Legend

- Culvert Location
- State Boundary
- Urban Area 2010

Figure 1.5 Culvert distribution in Iowa urban areas

Almost all respondents reported the presence of culvert sediment deposits in their area of supervision. Out of 24 responders in 2014, 12 counties reported a significant proportion of culvert sedimentation (80% -100%). 9 counties reported medium level culvert sedimentation (20% - 80%). Figure 1.6 mapped the severity of culvert sedimentation at county level.
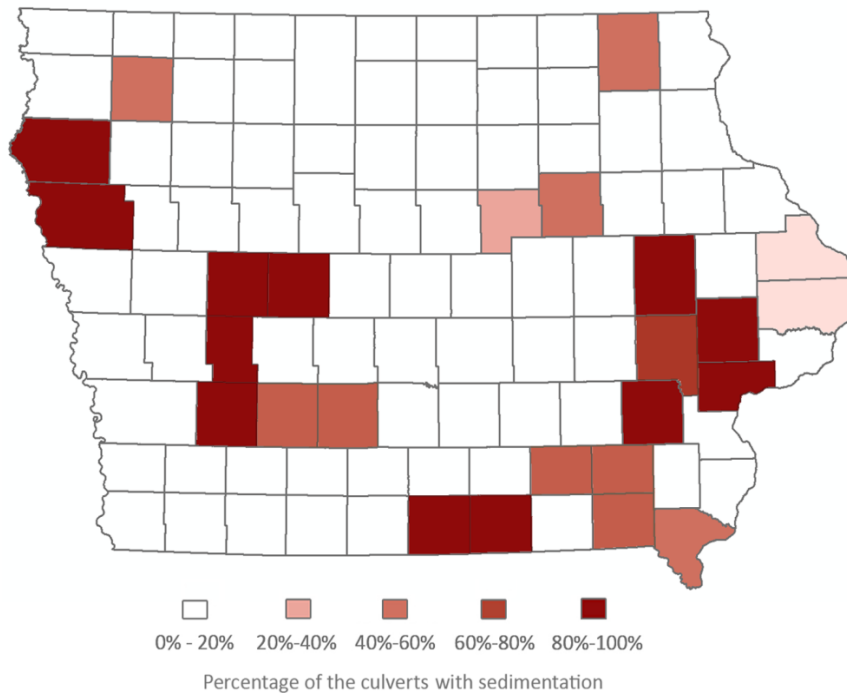
Figure 1.6 Culvert sediment survey 2014 (Percentage of culvert with sediment)

The 2014 survey also included questions related to culvert inspections and maintenances. This information is useful for finding more details on the cause of culvert sedimentation and its spatial and temporal distributions throughout the state. Also included in the survey were questions about mitigation means for culvert sedimentation and clean-up measurements when their culverts become silted. A visual presentation of these questions is provided in Figures 1.7 to 1.10.
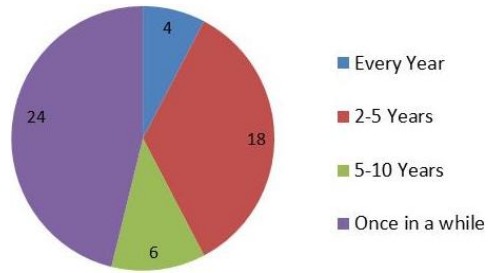
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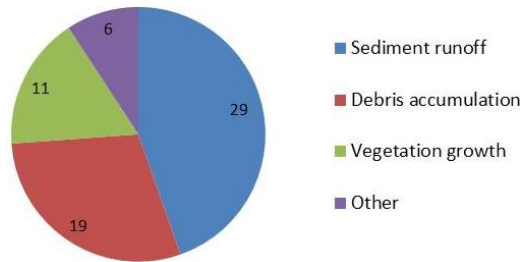
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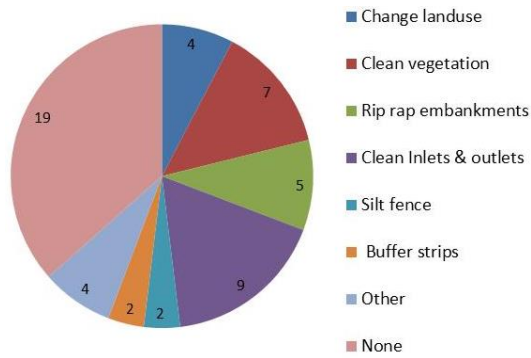
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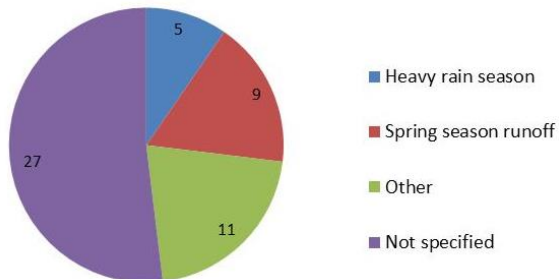
Figure 1.10 Observed connection between sedimentation and season cycling.

The surveys reveal that culvert inspection is occurring relatively sporadic despite that a good fraction of culverts in Iowa are severely silted. The most often associated cause with sedimentation is associated with sediment transport due to runoff, followed by the presence of debris in the flow. A minor role in culvert clogging is attributed to vegetation growth. The survey also showed that there are no prevalent solutions for sedimentation mitigation to guide district and county engineers to solve this chronic problem. Finally, the survey revealed that there is no association between season cycling and the rates of sediment accumulations.

1.2.3 Sample silted culverts

Previous visits conducted in Iowa counties at more than 40 multi-box culverts located in Buena Vista, Marion, Johnson, and Fayette counties illustrated the extent and severity of the sedimentation in the state (M Muste et al., 2009). During the visit, the vast majority of the culverts sites were observed to be partially silted despite their difference in location and stream sizes. This is very unfortunate as sediment cleaning at culvert requires high cost, intense labors, and repeated operations. Details and cost about sediment cleaning at culverts are presented in Section 2.2.5. Moreover, the rate of sedimentation is also very high as illustrated in Figure 1.11 which contains a set of inspection photos taken during three different visits at a three-box culvert. The inspection illustrated in Figure 1.12a occurred in three consecutive years shows that multi-box culverts at several places can be clogged in two years after their construction (e.g. IHRB proposal). Figure 1.12b illustrates severe clogging due to sediment and vegetation at

multi-box culvert located in Fayette County where sediments were rapidly developed in only two years after the culvert construction.

Figure 1.11 Culvert siltation observed through previous studies (M Muste et al., 2009): a) 3-box culvert located on the Old Mill Creek in Solon; b) 3-box culvert located on the North Branch Volga River

An extensively monitored site of a 3-box culvert is the one located on Hwy 1 in Iowa City (Muste and Ho, 2013). This culvert, draining a relatively small urban drainage

area, was silted after 10 years from a previous cleanup (as illustrated in Figure 10a) and it was then cleaned for providing a reference situation for the study (see Figure 10b). The continuous monitoring conducted over two years allowed to infer finer aspects of both the dynamics of the sedimentation process as well as the role played by vegetation in the silting process (see Section 1.4.5).

a)   b)
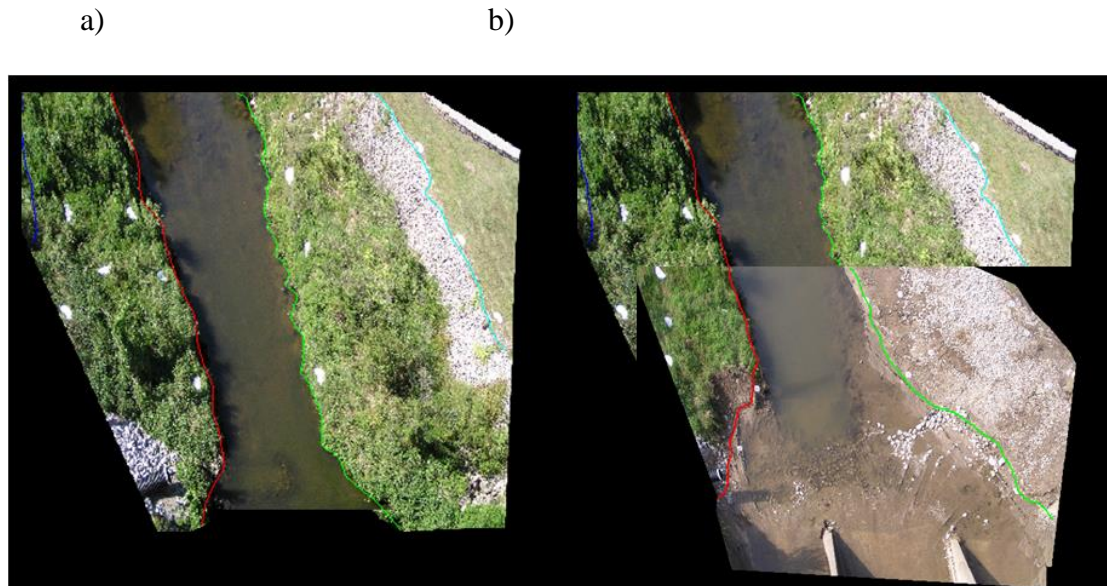
Figure 1.12 Sample 3-box culvert silted throughout the lateral boxes (Ho, 2013), a) the culvert prior to cleanup; b) the culvert following the cleanup in order to monitor sediment deposition dynamics over time

1.2.4 Study motivation

Consistent with culvert sediment survey, the direct field observations demonstrate that sedimentation at multi-box culverts is a pervasive problem at many road crossings in Iowa. Both survey results and site visits reveal the need to mitigate the sedimentation at Iowa culverts. Currently, the protocols for culvert design are preceded by analyses regarding hydrologic, hydraulic, and geomorphological conditions at the construction site. Less attention is typically given to a thorough assessment of the potential for

sedimentation within and in the culvert vicinity. This is unfortunate as sediment cleaning at culvert is expensive, labor intensive, and often it has to be repeated.

Culvert design is based on a variety of data sources (time series, statistical analyses, maps, and other site-specific characteristics) that are typically stored in various formats in multiple data provider repositories. Assessment of the sedimentation potential requires additional data sources, other than those in culvert design stage. After construction, more data are produced through periodic culvert monitoring programs that report useful information on operation performance and associated problems. Those data collected after culverts' construction are often referred as the post-construction data. The post-construction data and information are especially important if they cover aspects that were insufficiently addressed in the design stage (such as sedimentation, debris, and environmental factors). Data heterogeneity caused by various data sources, formats, and different acquisition date, incurs many challenges for engineers in culvert design stage. These challenges include data accessibility, data uniformity, and data usability (Ambreen Hussain et al., 2015).

Coping with data heterogeneity can be very difficult using the current design procedures. The present thesis proposes to address issues mentioned above using Hydroinformatics tools and workflows. The term "Hydroinformatics" is detailed Chapter 3 of this thesis. The end-product of this approach is a web-based geo-portal that: a) automates data integration process for culvert design, and b) assembles in one place the pre- and post-construction data and information irrespective of their provenance. From the data and information content perspectives, the prototype geo-portal proposed by this study integrates: i) watershed characteristics (river network, streamflow statistics,

hydrologic, soil and land use information); ii) culvert database for the region; iii) hydraulic model for sizing culverts; and, iv) monitoring data. The portal provides various means for enabling designers and managing personnel to query and visualize these multiple resources.

In terms of objectives and functionalities, the web-accessible portal is continuously updated to become a resource on culvert life cycle that plays several roles: a) informing and facilitating the design of other culverts in the area; b) serving as a repository that can be mined to infer aspects of current designs in relationship with the location of the culvert in diverse geographic areas. The platform is built using open source technologies that make the system light-weighted, low cost and flexible.

Although this thesis is focused on a Hydroinformatics development, the tools and workflows are applied to a real-life engineering problem, hence a review of the hydrologic, hydraulic and morphodynamics considerations as related to culverts are provided in Chapter 2. The background of Hydroinformatics-based systems is provided in Chapter 3. The Chapter 3 also summarizes considerations on the configuration, operation and roles of the information systems in supporting decisions in the natural resources areas. Focusing on the information technologies used in this thesis, Chapter 4 describes the design consideration and the functional specifications for the Iowa DOT Culvert geo-portal. The actual development leading to the operational geo-portal and illustration of the interfaces that are used by users for interacting with the platform are provided in Chapter 5. Finally, Chapter 6 provides some conclusions and ideas for further developments.

1.2.5 Thesis Contributions

The thesis developed a series of stand-alone workflows and cluster workflows that are aimed at mitigating current difficulties encountered in execution of the design and monitoring of culverts. The functional workflow clusters and individual workflows are listed as follows:

a. Culvert monitoring workflow cluster

   a. Culvert info

   b. Watershed information tool

b. Culvert design workflow cluster

   a. Culvert hydraulic

   b. Sedimentation

The culvert info workflow provides users a tool to spatially query culverts. Before digital monitoring and culvert inspection processes, the user can use this tool to search the desired culvert location. The watershed information workflow retrieves river, watershed information from National Hydrographic Dataset (NHD) based on users' query. Culvert design workflow cluster entails culvert hydraulic and sedimentation categories. Culvert hydraulic includes river catchments, runoff potential, search watershed, calculate discharge, and estimate culvert size. The objective of culvert hydraulic category is to support culvert design, as most of its workflows are segments of standard culvert design procedures. Sedimentation category entails current situation, erosion potential, sedimentation potential, sedimentation potential analysis, and site inspection. This category aims at assisting culvert sediment mitigation in the future culvert design.

CHAPTER 2 CONSIDERATIONS ON CULVERT DESIGN AND OPERATION

2.1. Culvert hydraulics

2.1.1 General design process

The primary concern in culvert design is to select the optimal barrel cross-section capable to pass a given design discharge. The design process involves both hydrologic and hydraulic aspects. Principles of culvert design includes hydrologic analysis, culvert type design and sizing, and culvert hydraulics design. Hydrologic analysis entails peak discharge determination, which eventually yields an estimate of the design discharge. Based on the design discharge, culvert hydraulic design determines the type and size of the culvert.

The most commonly used design guidelines in Iowa include the FHWA Hydraulic Design Series #5 (HDS-5) manual, the Iowa Culvert Hydraulic Software (Windows based model by Iowa DOT), and the HY-8 v7.0 (Windows based model by FHWA). Currently, the Iowa Department of Transportation uses the Iowa Culvert Hydraulic software to design multi-box culverts. The software contains four primary design methods: Iowa DOT standard design, the tapered inlet design, the drop Inlet design, and the general design method. Using different design methods available in the software, engineers can choose sizing outputs for various types of culverts (i.e. Reinforced Concrete Box, Concrete Pipe, Concrete Pipe Arch, Corrugated Metal Pipe, and Steel Pipe Arch (2-2/3" by ½" corrugations) based on construction cost, limitations on the upstream water-surface elevation, road embankment height, and desired hydraulic performance (Jones, 2013).

Aiming to improve Iowa DOT culvert design in sedimentation management, the present study adopts the Iowa Culvert Hydraulic Software (IowaDOT, Preliminary bridge

design software, 2014) as the design guideline and proposes series of improvements on the existing software.

2.1.2. Peak discharge determination

Despite a variety in culvert types and culvert design methods, the general design procedure starts with the peak discharge determination. The peak discharge determination step estimates the design flow (a.k.a design Q). The Iowa Culvert Hydraulic Software uses flood frequency analysis equations to estimate design Q. The analysis can be done using three alternative equations: The USGS Lara methods (1987), The USGS Eash method (2002), and the Iowa runoff chart. All equations consider the drainage area upstream of the culvert as input to produce design discharge for different return periods, including 2, 5, 10, 25, 50, and 100 years. The USGS Eash method and the Iowa runoff chart methods provide a more advanced analysis. They have additional inputs to provide more accurate outputs. The additional inputs include the main channel slope, DML (Des Moines lobe), and the land use factor. The Des Moines Lobe is also called "Prairie Potholes". This landform generally entails abundant moraines, low-relief terrain, deep natural lakes, potholes, and marshes, where surface-water drainage is sluggish and poor (Eash, 2001, p. 19).

The Iowa runoff chart is preferred when the culvert upstream drainage area is between 1 to 1000 acres (Jones, 2013, p. 28). The runoff chart is listed in Figure 2.1.

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$$Qdesign = LF \; x \; FF \; x \; Q$$

- $Q = 8.124 \, A^{0.739}$ Chart values based on:

- $A = acres$ -   50 yr recurrence interval (FF)

- $Q = ft3/sec$ -   Q adjusted for land use and slope (LF)

Figure 2.1 Iowa runoff chart (Jones, 2013, p. 30)

Both USGS Lara and Eash methods use regional regression equations to estimate the magnitude and frequency of floods 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. 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; b and c are regression equation coefficients (Jones, 2013, p. 28). Hydrologic regions of USGS Lara and Eash methods are demonstrated in Figures 2.2 and 2.3. More details about regression equations for different hydrologic regions can be found in the APPENDIX C.
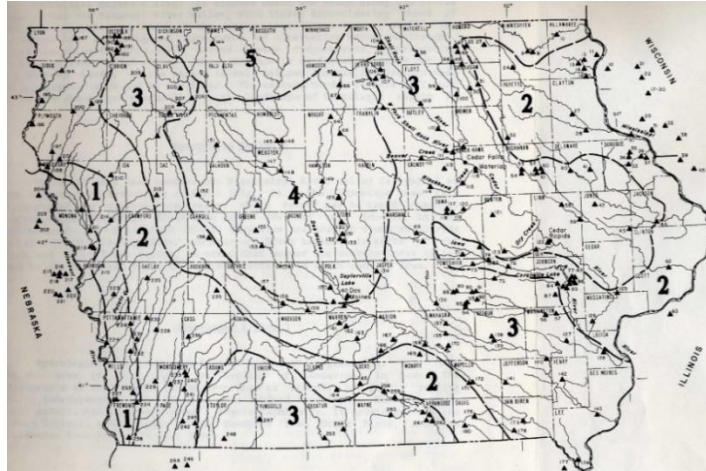
Figure 2.2 Hydrologic regions in the USGS Lara method (IowaDOT, 2010, p. 62)
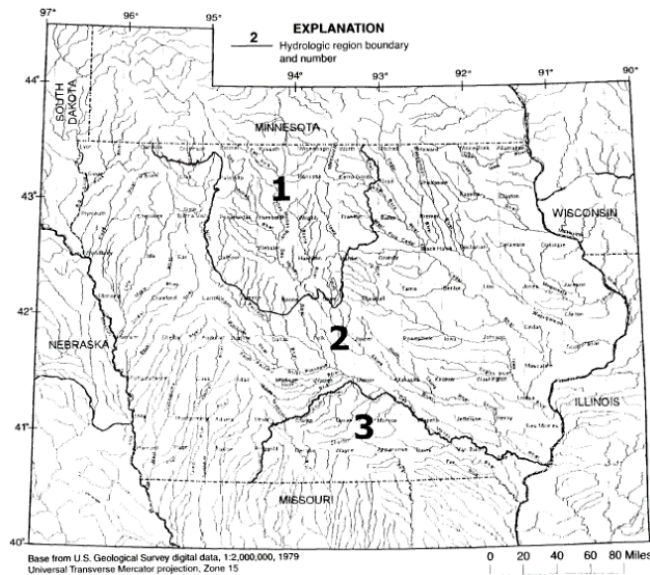
Figure 2.3 Hydrologic regions in the USGS Eash method (IowaDOT, 2010, p. 65)

Despite that the flood frequency equations are revised year by year to include more hydrological regions and parameters, they are still challenged as it is difficult to describe watershed characteristics using just one functional relationship. In addition to the above mentioned methods, the flood frequency analysis is estimated by alternative means both in the Iowa DOT software as well as in the design practice of the county engineers.

Among these additional methods are the Natural Resources Conservation Service (NRCS)'s Overland Flow Method (NRCS WINTR55) and the Rational Method.

2.1.3. Culvert types and sizing

2.1.3.1 Culvert configurations

Culvert differs among themselves through shapes, materials, inlet configuration, range of flows, and the type of hydraulic controls. Typical culvert cross-sections are mentioned in the "General Design Process" section. Culverts construction is made with numerous materials based on the structural strength, hydraulic roughness, durability, and corrosion and abrasion resistance. Among all materials, concrete, corrugated aluminum, and corrugated steel are the three most commonly used ones (FHWA, 2012, p. 1.6).

The selection of a particular shape is mostly determined by its construction cost. Other variables including the roadway embankment height, the water surface elevation, and the hydrologic performance are also considered in the shape selection process. Less attention is, however, given to relating the culvert shape in relationship to sedimentation. Such an attempt was made by the Maryland State Highway Administration (MDSHA) that proposed an arched design with side barrels to avoid sediment deposition (Kosicki, A. J., Davis, 2001). Figure 2.4 provides a view of this implementation conducted through retrofitting.
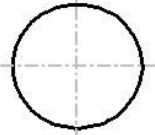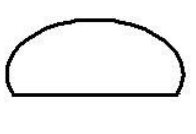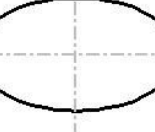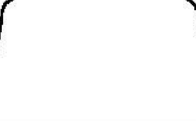
Circular	◯	Pipe-Arch	⬭
Box	▢	Arch	⌓
Elliptical	⬭	Metal Box	⊓

Figure 2.4 Culvert geometrical arrangement for limitation of sedimentation effect (AQUAVEO, 2015)

Inlet design is important because it can directly affect culvert hydraulic capacity especially in the upstream area of the culvert where a transition between culvert and the natural channel need to be provided. Either flow expansion or flow contraction can occur at the culvert inlet depending on the width of the channel and inlets. However, most often an expansion from the stream to culvert is needed. Culvert inlets can be prefabricated or constructed-in-placed. Common culvert inlet type includes projecting barrel, headwall, and wing walls, precast end section, and mitered to the slope, as illustrated in Figure 1.15 a. A comparison between the hydraulic performance of the straight and flared wingwalls configurations is provided in Figure 1.15 b.

a)
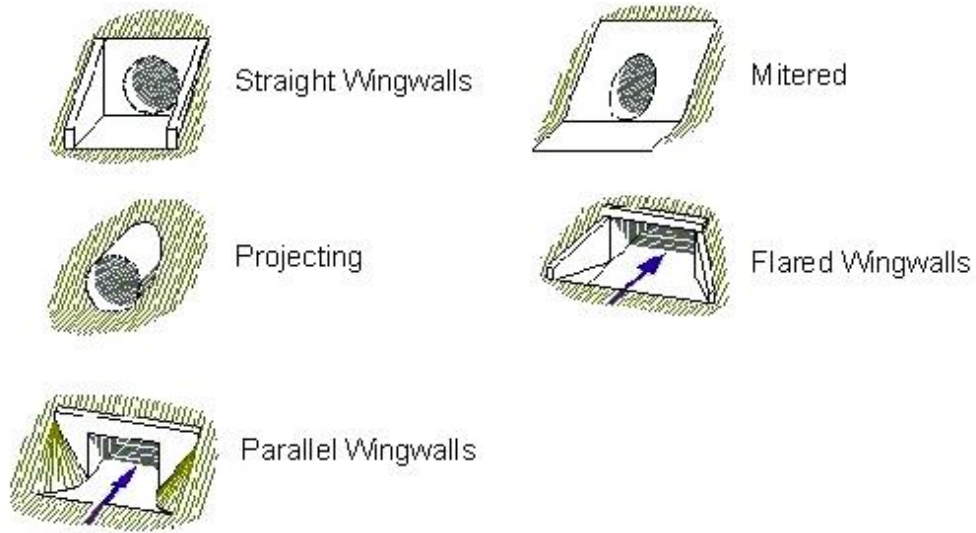
b)
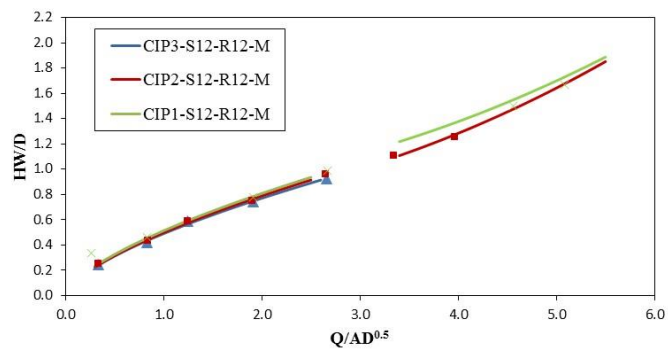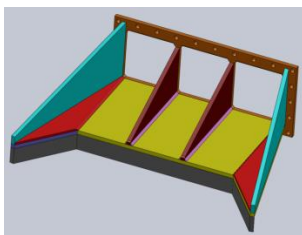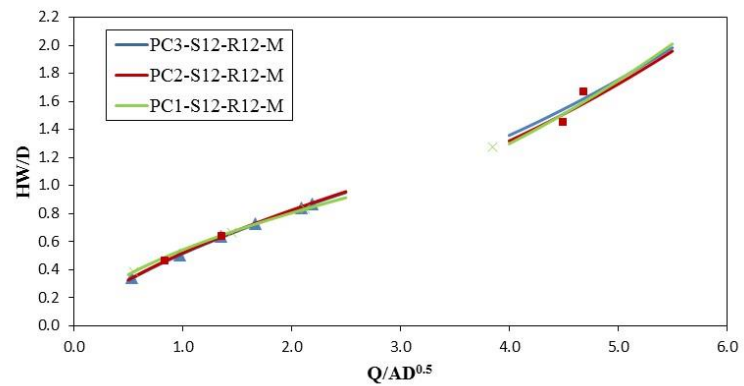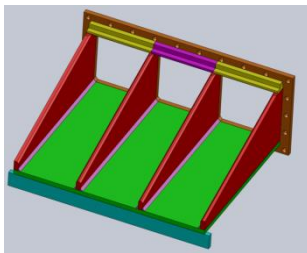
Figure 2.5 Culvert inlet types: a) various typical configurations (Marek, 2014); b) hydraulic performance of straight and flared wingwalls culverts

2.1.3.2. Types of culvert flows and sizing

Flow in culvert can be either steady or unsteady. Present culvert design protocols are solely based on steady flow condition, as research and experiments on unsteady culvert flow are rarely conducted. Comply with the existing design guidelines, this thesis primary focus on steady flow in culvert. Unsteady flow condition and its concerns related to the present study are addressed in Section 2.1.4.

Steady flow through culverts can take a variety of forms (Bodhain, 1982). This USGS report distinguishes among six types of flows depending upon the location of the control section, and the relative height of the headwater and tailwater elevations. The characteristic of the free-surface profile is affected by many factors, including culvert slope, geometry, size, flow rate, roughness, and approach and tailwater conditions.

Culvert flows can be along channel based on whether they have inlet flow control or outlet flow control. Inlet control culverts have supercritical shallow flow with high-velocity of the inlets. The control section is at inlet, which is the upstream end of the culvert barrel. Culvert with outlet control have subcritical flow, which is a deeper flow with lower velocity. The control section is situated at the downstream end (outlet) of the culvert barrel. Tailwater depth are either critical depth or higher (Mays, 2011, p. 693). The different types of culvert flows are depicted in Figure 2.5.
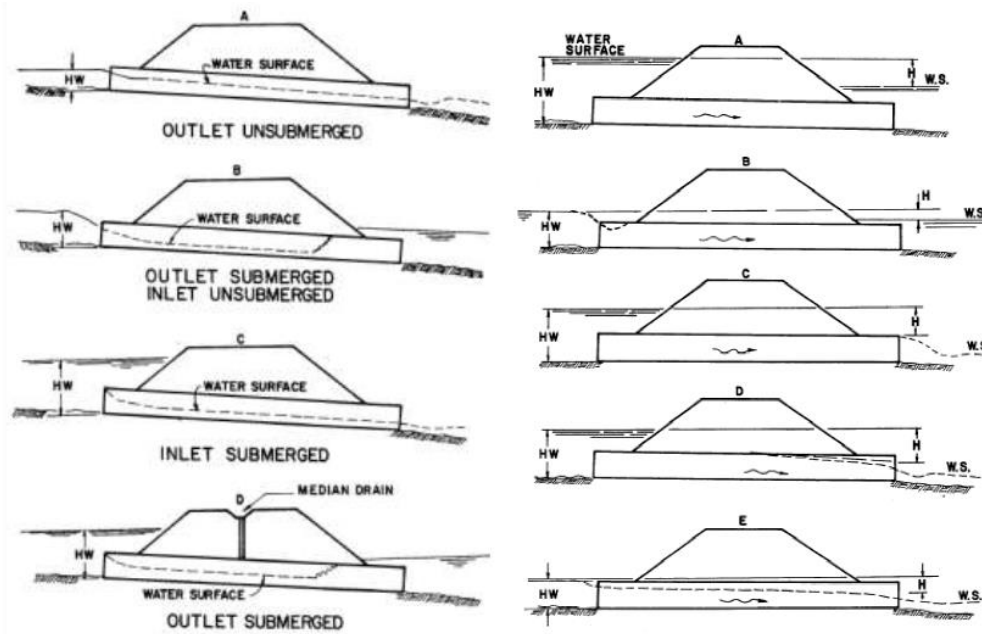
Figure 2.5 Culvert inlet control (left) and outlet control (right) with different types of flow profiles (Mays, 2011, p. 695)

The sizing of the culverts is different commensurate with the type of flow in the culvert. Culvert sizing determines multiple culvert parameters, such as the entrance geometry, culvert size, slop, culvert length, entrance/outlet conditions, and tail water conditions at outlet (Jones, 2013, p. 54). Output of culvert sizing relays on the results of culvert type selection, culvert hydraulic design, and culvert controls. Details of this design process will be discussed in the next two sections.

2.1.3.2.1 Inlet control

Culvert barrel with inlet control is capable of conveying more flow than the inlet can accept. The control-section is situated inside the entrance, where critical depth occurs. Flow immediately downstream of the Inlet control section is supercritical. Two of Inlet control design's parameter are Inlet geometry and headwater depth (HW), which is the upstream water surface elevation. Common inlet geometries are barrel shape, cross-

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sectional area, and the inlet edge. Culvert roughness and outlet conditions are not concerned in inlet control (FHWA, 2012, p. 1.8).

An inlet-control culvert functions as an orifice when the inlet is submerged and as a weir when it is unsubmerged. Equations to determine discharge under both submerged and unsubmerged conditions are listed below.

$$\left[\frac{HW}{D}\right] = C \left[\frac{Q}{AD^{0.5}}\right]^2 + Y + Z \text{ For orifice condition } \left[\frac{Q}{AD^{0.5}}\right] \geq 4.0 \text{ (2.1)}$$

$$\left[\frac{HW}{D}\right] = \left[\frac{H_c}{D}\right] + K \left[\frac{Q}{AD^{0.5}}\right]^M + Z \text{ For weir condition } \left[\frac{Q}{AD^{0.5}}\right] \leq 3.5 \text{ (2.2)}$$

In the equation for the orifice condition (submerged), HW is the headwater depth above the inlet control section invert (ft.), D is the interior height of the culvert barrel (ft.), Q is the discharge (ft^3/s), A is the full cross-sectional area of the culvert barrel (ft2), S0 is the culvert barrel slope (ft./ft.), C and Y are constants provided in the table "constant for inlet control design equations" in the APPENDIX B, and Z is the slope correction factor where $Z = 0.5S_0$ in general and $Z = + 0.7S_0$ for mitered inlets (Mays, 2011, p. 696).

For the wire condition (unsubmerged) equation, H_c is the specific head at critical depth ($H_c = dc + V_c^2 / 2g$) (ft.), dc is the critical depth (ft.), Vc is the critical velocity (ft. /s), and K and M are constants given in the table. Equation for wire condition is implemented by assuming a culvert diameter D on the right-hand side of these equations to solve for [HW/D] (Mays, 2011, p. 696).

2.1.3.2.2 Outlet control

Culvert barrel with outlet control conveys less flow than the inlet opening can accept, because the control-section is situated further downstream of barrel exit. Flows

under outlet-control conditions are either subcritical flow or full-culvert flow (pressure flow).Major outlet flow controls are the headwater depth (HW), Inlet geometry, slope, length, hydraulic roughness of the culvert barrel, and the tail water surface elevation. Tail water depth is the depth of water downstream of the culvert measured from the outlet invert, which is usually resulted by downstream obstruction or high channel roughness. Outlet-control flow conditions can be calculated through energy balance. For the full-culvert flow condition, the energy balance is consist of entrance loss H_e, friction loss (using Manning's equation) H_f, exit loss H_0, and the total head loss H.

$$H = H_0 + H_e + H_f \quad (2.3)$$

The above equation is derived for both U.S customary units and SI units. The two variants are listed below:

$$H = [1 + K_e + \left(\frac{29n^2 L}{R^{1.33}}\right)]\frac{V^2}{2g} \text{ For U.S customary units} \qquad (2.4)$$

$$H = [1 + K_e + \left(\frac{20n^2 L}{R^{1.33}}\right)]\frac{V^2}{2g} \text{ For SI customary units} \quad (2.5)$$

where K_e is the entrance loss coefficient, n is the manning's roughness coefficient, R is the hydraulic radius of the full-culvert barrel in feet (m), V is the velocity in ft./s (m/s), and L is the culvert length in feet (m).Other losses such as bend losses H_b. junction losses H_j, and grate losses H_g can also be added to equation 2.5.

Summation of energy equation and hydraulic grade lines equate the total energy at upstream and downstream of culvert. The relationship is described by equation 2.6:

$$HW_0 + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_0 + H_e + H_f \qquad (2.6)$$

The equation can be simplified to:

$$HW_0 = TW + H_0 + H_e + H_f \qquad (2.7)$$

Where HW_0 is the headwater depth above the outlet invert and TW is the tailwater

depth above the outlet invert. Figure 2.6 gives a physical demonstration of equation 2.7.
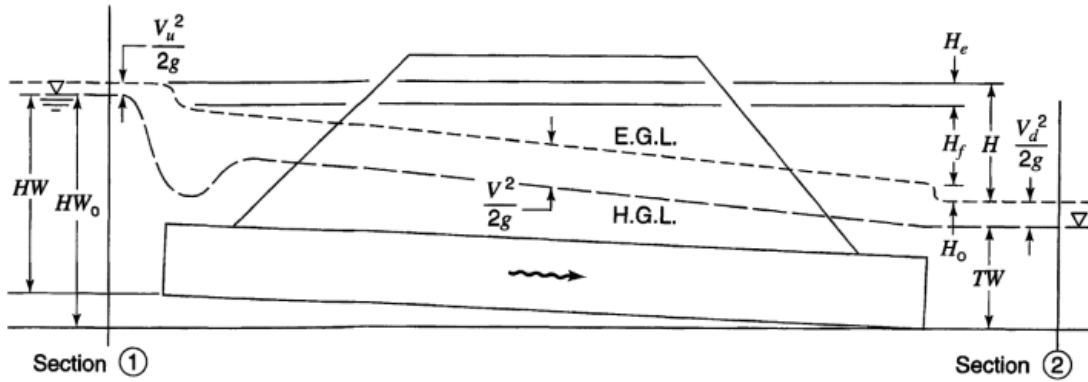
Figure 2.6 Full-flow energy and hydraulic grade lines (from Normann et al., 1985)

2.1.4. Additional considerations on culvert design

The design considerations discussed above (i.e., FHWA Hydraulic Design Series

#5) and Iowa Culvert Program (IowaDOT, Preliminary bridge design software, 2014) are

based on the assumption that the flow is steady and the water is free of sediment at all

times. Under these assumptions, Manning's equation is used to estimate flow profile in

the culvert. Steady flow condition ignores culvert flow complexities, which include

changes in flow non-uniformity triggered by the change in flow geometry (from natural

channel to culvert structure, then to channel), or flow unsteadiness due to the routing of

variable flow amounts from the catchments drained by a culvert.

The presence of flow non-uniformity and unsteadiness are however always present at

multi-box culverts operating during storms. These complexities are leading sooner or

later to problems in culvert operations. The combined effects of road site layout, highly

variable, non-uniform, and varying flow rates, along with sedimentation, vegetation, and

debris accumulation factors at times makes culvert flows rather site-specific, three-

dimensional, and unsteady. Consequently, it can be difficult to generalize flow field and

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sediment transport formulations valid for all culverts using Manning's equation (Ho, 2010).

Although consideration of the non-uniform and unsteady-flow effects could significantly improve the culvert hydraulic design in many aspects, this more complex analysis is not adopted in the culvert design guideline, because of lack of field and laboratory data that can further support the development of reliable numerical simulation tools. Research on unsteady flows through culverts is nearly nonsexist. Details on sedimentation generated in unsteady flow will be reviewed in the following chapter. The present thesis intends to improve culvert sediment mitigation design in the existing design guidelines, which assumes steady flow condition. Therefore, components regarding unsteady flow is not discussed in this thesis.

2.2 Culvert sedimentation

2.2.1. Process overview and contributing factors

Culverts, like other artificial structures, have ecological and hydraulic impacts for natural river channels. Sediment deposition at culverts is caused by many factors, including the properties of the natural channel, hydro characteristics of upstream region, culvert geometry, channel transition design, and presence of vegetation around site.

Many prior studies (Charbeneau, et al., 2002, Rigby E. H et al., 2002, Vassilios, 1995), indicate severe sediment problems induced at multi-box culvert sites. Sediment buildup in the barrels, and clogging of the barrels with debris; and erosion at the inlet and outlet. Despite these reports of problems, current culvert design guidelines give little

attention to the effects of the interactions between the stream and the culvert, and also to the sedimentation problems.

2.2.2 Channel characteristics

Culvert sediment deposition is usually related to the characteristics of the channel, on which the culvert is placed. Those characteristics comprise channel slope, channel size, channel's bed and bank material.

In terms of channel slope, culverts are generally built on mild channel slopes to avoid supercritical flow condition upstream of the inlet. Nonetheless, the mildness of the slope can raise the risk of sediment deposition around culverts. Sediment deposits when the flow speed and energy are relatively low on mild slopes. Such process even happens during extreme storm events. Sediment deposition due to mild slope is especially common at multi-box culverts because of inadequacies in approach flow distribution.

2.2.3 Upstream drainage area

Upstream watershed characteristics, include upstream soil erodibility (upstream channel bed material) and watershed hydrological characteristics. Erodibility is defined as the soil material property to resist to two energy sources: the impact of raindrops on the soil surface, and the shearing action of runoff between clods in grooves or rills (Repository, 2015) . Culverts in regions with high soil erodibility are more likely to get silted as more sediment runoff are generated in upstream.

Extreme flow events (i.e. storm, flood) at a culvert are related to its upstream watershed characteristics. Although, culverts convey flows smaller than its design discharge for

most of the time, they are required to pass large flows generated during storm events. It is a very important role for culverts to pass storm hydrograph flows, which usually happen under unsteady flow condition. To analyze sediment transport in larger unsteady flows, two unique relationships, stage-to-discharge and sediment rate-to-discharge are considered. Stage-to-discharge relationships are normally expressed by rating curves. Rating curves, do not reflect a one-to-one relationship, but include a loop curve instead. The forgoing study of looped rating curves for flow and sediment bear closely on a culvert's capacity to pass flow and sediment.

2.2.4 Culvert geometry and vegetation

Existing culvert geometry and channel transition designs also contribute to sediment deposition. Most design guidelines for culverts only target on culvert flow capacity, without considering issues caused by oversizing the culvert. Such situation generally occur in multi-box culvert design. A multi-box culvert typically has its flow area exceeds the flow area of natural channel along which it is located. Channel transitions connect the culvert with the stream channel upstream and downstream of it. The transitions include an expansion upstream of the culvert, followed by a contraction downstream of it. Although designed for extreme storm events, culverts normally convey flows with lower velocity and lesser depth than the design flows. When entering the entrance transition of multi-box culvert, flow is not uniformly distributed across all culvert barrels. In many cases, flow concentrates in one barrel, leaving the other barrels dry. Over years of low flow, stream sediment deposits in one side of the entrance transition and in one or more barrels. As a result, one of culvert's barrels may be partially filled with sediment (Ho, 2010, p. 30). This sedimentation reduces the capacity of

culverts to handle the larger flow events, and induce high headwater problems upstream of culverts. During the design stage, less consideration is given to avoid sediment deposition in the transition areas. Many engineers believe that the sedimentation will always be washed away by storm events. However, this design notation is not substantiated by experience, some storm events can aggravate sediment deposition. In a worse scenario, vegetation grown from cultivable sediment deposits may stabilize sediment deposits near the culvert. Vegetation like cattail and weed may grow in size over time, preventing sediments from being washed away. Figure 2.7 demonstrates the fast progression of the culvert sedimentation at one of the Iowa culverts.

Culvert status following 2 years from the cleaning (August 29, 2012):

- **sedimentation** upstream the culvert was initiated
- sediment deposits favors **growth of vegetation** during the summer low flows
- encroached vegetation will act as **sediment barrier** in the next seasons
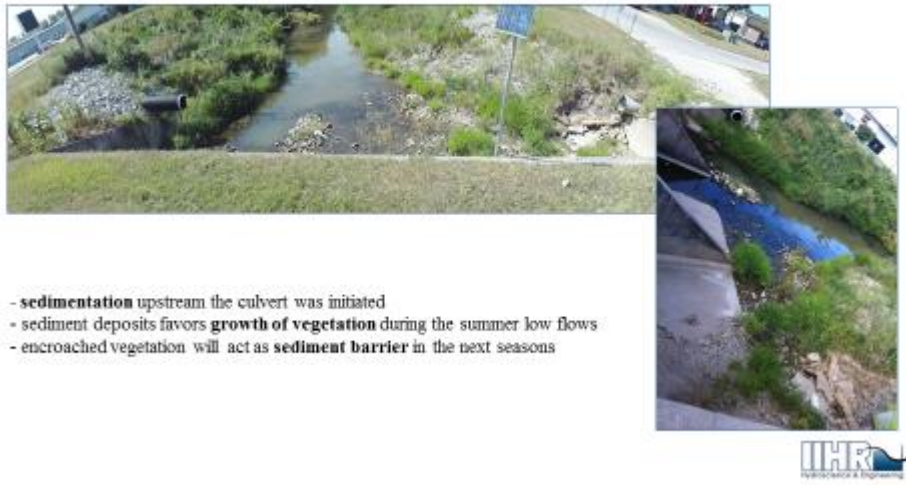
Figure 2.7 Chronological change of culvert sedimentation (HC Ho et al., 2013)

2.2.5 Culvert cleaning

When a culvert is blocked by sediment, it is no longer capable to convey its design discharge. During the extreme flood event, the culvert might get overtopped or cause flooding in headwater areas as its capacity is impaired by sediment deposition. In such situations, culvert sediment cleaning is required. Most cleaning operations are mechanical and expensive. For example, mechanical cleaning for a multi-box culvert on IA Highway 1, Triple RCB caused nearly $8000. Most of cleaning requires the involvement of heavy equipment, such as excavators. Due to the many factors discussed above, culverts in Iowa generally built sediment deposit over time. Even after single cleaning operations, the same culvert might get silted again in 2-3 years. Therefore, unless the current culvert design guides are supplemented with sediment mitigation designs and plans, such repetitive high-cost culvert cleaning operations will continue. Typical culvert cleaning operation is illustrated in Figure2.8.

Figure 2.8 Culvert sediment cleaning involve excavator (Muste, 2014)

CHAPTER 3 INFORMATION SYSTEMS FOR DECISION SUPPORT

3.1 Overview

Today, the modern information and communication technologies on which the

operational science for watershed resources have become the fourth pillar of scientific

investigations complementing the capabilities of the traditional pillars for scientific

investigations in water resources (observation, theory, and analysis). An early

development assembling information and communication technologies for water

resources is the science of Hydroinformatics (Abbot, 1991, Kumar et al., 2005). For the

present context, the term Hydroinformatics defines the water-related science and

engineering that occupies the gap between the fundamental science and research in water

resources and the operational science needed for making decisions in the management of

water resources and related infrastructure (Abbot, 1991, Kumar et al., 2005). The main

difference between Hydroinformatics and information systems for other areas is the need

to organize the data in both geographic and space and time.

The data- and information-rich environment required by a meaningful water

resources implementation is poised for progression not only because of the recent

advances in science and engineering research but even more prominently by

advancements in Hydroinformatics. Today's Hydroinformatics capabilities to integrate

data with models enable 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 cyberinfrastructure technology has

become increasingly available, and sufficiently mature to facilitate development of digital

platforms for supporting both scientific investigations and management at the watershed

scale. These platforms have the potential to transform our capabilities of understanding: how to address ecosystem changes, how to protect the environment, and how to predict and prevent natural and human disasters through knowledge-based adaptive management.

These Hydroinformatics frameworks, components, and technologies have been, and continue to be, developed in academic and research settings. Since today's natural scale processes are intrinsically connected with management practices and much of the observational infrastructure is operated by practitioners, the scientific and research communities recognize the need to develop common platforms for scientific explorations and decision making. The products of Hydroinformatics are information systems that can be used for scientific investigation as well as supporting decisions in the management in water resources.

By definition, decision is a choice that is made between two more alternatives. To make a decision, individuals have to form possible choices after clarifying certain minimum objectives, and alternatively, more demanding objectives. Lack of information and systematic analysis, institutional and organizational decisions of high complexity are difficult to make (Ramanathan Sugumaran, John Degroote, 2010, p. 1). A varieties of decision aids and tools are designed to help decision makers identify management goals and to determine a range of potential choices by providing systematic approaches and related resources. In a wide range of disciplines, geographic information is proven to be crucial in many decision making process. It is estimated that 80% of data used by managers and decision makers are geographically related (Worrall, 1991). Tremendous spatial information was collected, managed, and analyzed in late 20 century. The growth of utilizing spatial information software and hardware is huge from 1990s to the present,

and it is continuing at levels of government official, academic research, and business (Ramanathan Sugumaran, John Degroote, 2010, p. 23).

The advancements in computer and information technologies led to massive application of Decision Support System (DSS) in scientific research and operation management. As a new-born web based application, DSS typically integrates database, model library, method base, data management systems, and online repository to assist decision making process in many fields. Many systems are end-to-end designs, providing real-time information, model simulation results, and statistics feedback to decision makers through interactive graphic user interfaces. Supported by modern Geographic Information System (GIS) technologies, DSS are developed to solve problems with spatial data, such that DSS are also known as Spatial Decision Support System (SDSS) (Ramanathan Sugumaran, John Degroote, 2010, p. 1). In recent years, SDSS are applied in different areas for planning, forecasting, and natural resource management purposes, creating many new multi-disciplinary application. Spatial decision can be categorized in few groups. For example, the committee on the Geographic Foundation for Agenda 21 (Jensen, 2002) distinguishes between three spatial decision categories: (1) resource status decision, (2) resource allocation decision, and (3) strategic planning. Examples of SDSS are given in terms of the above spatial decision categories in the next section (Ramanathan Sugumaran, John Degroote, 2010, p. 2).

As both the world population and environmental concerns have rapidly increased in 21st century, decision making in the management of water resources has become a very important area. The situation of water stress resulted from raising demands and changed climate has pushed the development of Hydroinformatics, which is a water-

related science that utilizes information, communication technology and cyberinfrastructure to assist hydro-research and water management. It fills the gap between conventional scientific research and modern information technologies as an interdisciplinary subject. Started in the early 1990's (Abbott, 1991), Hydroinformatics soon received worldwide attentions. Growing popularity and demands for water data have brought Hydroinformatics into dedicated conference series, journals (http://iwaponline.com/jh), governmental projects, and academic curricula (e.g., http://unesco-ihe.org; http://euroaquae.org) over the past decade.

Hydroinformatics uses digital data, information, and related services for research and knowledge generation (Baker LA, 2006). In additional to Hydroinformatics, there are three other booming information-related disciplines: 1) cyberinformatics, 2) core informatics, and 3) science informatics. Baker and Barton defined those subjects as follows: cyberinformatics focuses on the interface with computing infrastructures and has the strongest technical and engineering component; Core informatics deals with informatics as a discipline in its own right; Science informatics delivers relevant and valuable service to a wide range of users such as researchers, decision makers and the public (Muste, M et al., 2013).

More recent development in Hydroinformatics are on-going under the effort of the Open Water Data Initiative (OWDI) developed by The Open Geospatial Consortium (http://acwi.gov/spatial/owdi/) have emerged. The Open Water Data Initiative suggest integration of water data from different sources and formats into a connected, national water data framework, which will improve existing systems, infrastructure and tools to

embrace future innovation, modeling, data exchanging, and solution development. Figure 3.1 below illustrate the structure of OWDI.

Figure 3.1 The diagram summarizes the web components of the open water data initiative (ACWI, 2015)

3.2. Sample DSS

3.2.1 Iowa Watershed Data & Information System (Iowa DIS)

Decisions on watershed resource requires availability of both static data (maps of resources) as well as dynamic data (real-time information). One of such systems in Iowa is the Iowa Watershed Data & Information System (iowadis.org). In its initial stage of development, this platform aimed at accessing and storing data provided by diverse sensors and communication means with simple numerical models into an end-to-end system that can describe electronically the watershed through data and information ((Muste, M et al., 2013). The CI-based system, operates via the Internet in real time through a user-friendly browser that does not require technical or computer skills (http://his08.iihr.uiowa.edu/uicc). The system continuously ingests time series from heterogeneous data sources collected by point and areal measurements irrespective of their provenance (i.e., IIHR, USGS, EPA, Hydro-NEXRAD etc.). Using the system, users

can query, view, download, compare and graphically visualized water data through GUI,

Some of the operational features of the system are shown in Figure 3.2.
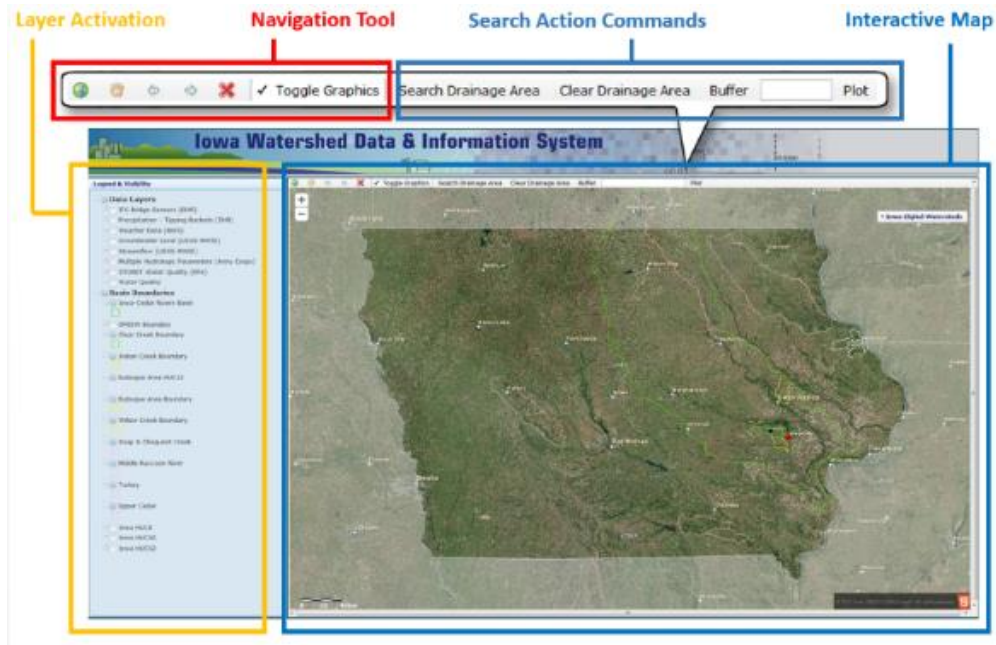
Figure 3.2 GUI of Iowa DIS and community-based flood conditions, data resources (Xu, HW et al., 2014)

3.2.2 Soap Creek watershed modeling visualization workflow

Resource allocation decisions require engineering judgments based on sound analysis. Such decisions are best supported by simulations studies using a variety of hydrologic- and hydraulic- models. Examples of resource allocation decisions in water resource management could appear in the form of the following question: where to place flood storage structures (e.g., ponds, reservoirs) in order to efficiently reduce flood risk at a certain downstream location within a watershed? This question can be addressed via modeling tools associated with various input scenarios. As part of a broader mitigation project directed toward flood damage reduction in selected Iowa watersheds, Iowa's

IIHR-Hydroscience & Engineering, conducted a hydrologic assessment of the Soap Creek Watershed. The HEC-HMS model for the Soap Creek Watershed was used to understand the effects of existing ponds, identify areas in the watershed with high runoff potential and run simulations to help understand the potential impact of alternative flood mitigation strategies in the watershed (IFC, 2014).

The web platform developed by the present research team serves as a visualization tool to deliver HEC-HMS modeling results to the public in graphical and geo-spatial manners, which allows users to develop a better understanding beyond static maps and graphs. In the platform, different flood mitigation scenarios are provided as potential options for users. The input scenarios include options in selecting the number of ponds in the watershed and type of precipitation events. For each scenario, pond location, usage, and efficiency are displayed geographically on the interactive map as color-coded symbols. Two types of color coding are provided as options: bars and dots. The color coding combines the range of numeric pond attributes together with pond locations, in this way the correlation between pond attributes and other watershed characteristics can be easily observed by users. Such visualization also helps users make comparisons between different scenarios graphically.

In addition to the model results, the Soap Creek Watershed web platform also contains static watershed and geographic information, including watershed boundary, river flow lines, watershed topography, and high quality satellite imagery. Those information could help users interpret simulation scenarios into real-life geographic and hydrologic conditions. Satellite imagery also provide user resources to visually observe

and monitor existing pond and watershed conditions. The interface of the platform is

shown in Figure 3.3.
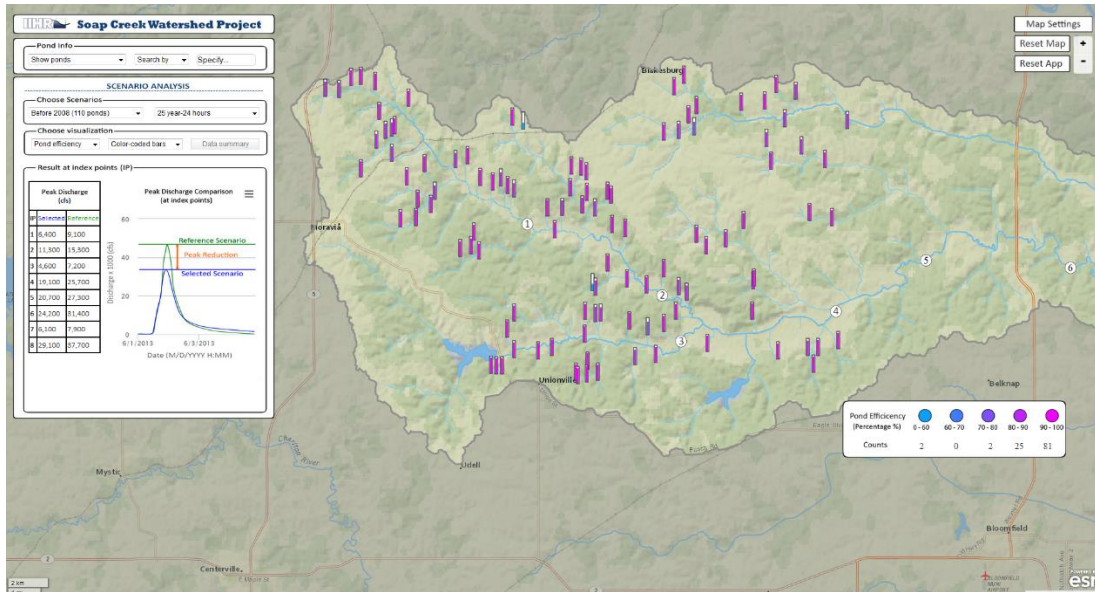
Figure 3.3 Color coding of ponds based on model results in HUD

3.2.3. Indian Creek watershed modeling visualization workflow

The third type of spatial decision is mostly related to policy decisions, which

includes the spatial implication of policy changes at government and business level. For

example, the Indian Creek Flood Mitigation platform is designed for visualizing flood

mitigation strategies. This application was developed by IIHR - Hydroscience and

Research as the geoportal of the pilot project between the US Army Corps of Engineers

and the USDA Farm Service Agency (FSA). The objective of the pilot project was to

investigate flood reduction benefits at downstream urban areas brought by upstream

Conservation Reserve Program (CRP) lands uses. This pilot project used the Gridded

Surface Subsurface Hydrologic Analysis Model (GSSHA) to investigate the importance

of physical location on specific CRP practices (Iowa-Ceder, 2012). This modeling results indicated that existing CRP lands are providing urban communities in Indian Creek economic benefits due to their flood damage reduction properties. This result also indicated that targeted implementation of additional CRP practices may provide greater economic benefits to downstream urban communities. The type and location of the CRP practice is an important factor in the cost effectiveness.

The web-based platform provides a user-friendly, interactive method to visualize the modeling results for communicating the spatial significance of conservation practices on hydrology and associated economic losses. The platform has a GUI consisting of control panels in the left and an interactive map on the right, as figure 3.4 shows. In the control panel, the user is asked to define the CRP scenario first. The CRP scenario contains landuse types, moisture conditions, and weather scenarios. After selecting the CRP scenarios, the user needs to click on the interactive map to highlight an area of interest among all index areas. After the user has defined all the parameters, result for both peak flood damage and total economic loss are displayed in the table. Color-cods are added to river segments to visualize flood inundation and economic loss pertain to each index area. The platform is also capable of drawing river cross-sections based on user's selection of an index area.
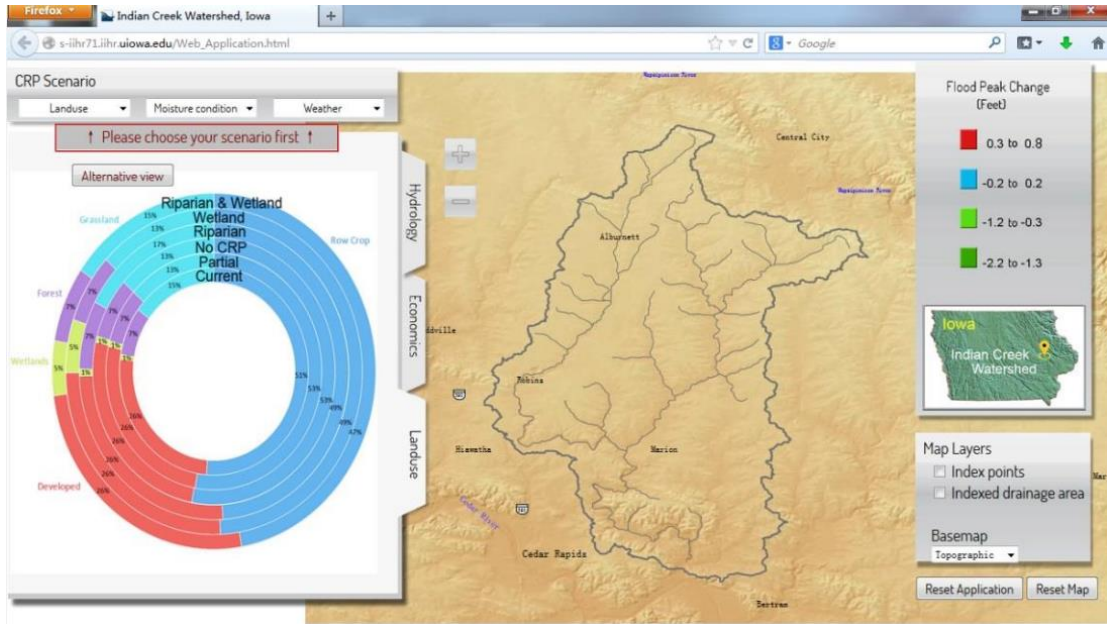
Figure 3.4 User interface for the Indian creek application

CHAPTER 4 IOWA CULVERT DSS ARCHITECTURE
4.1. Overview

As described in the previous section, the Iowa Culvert geo-portal is expected to assist culvert design and monitoring. As most modern web applications, the geo-portal operational functions of the Culvert DSS comprise a front-end and a back-end component. The concepts of front-end and back-end originated from separation of concern (SoC), which is a software design principle for dividing a computer program into different sections, each of which addresses a separate concern (Microsoft, 2015). The term "front-end" is refereeing to user's computer, while "back-end" is indicating the server in the "back". Front-end is also known as client side, the practice of producing user interactive interface using HTML, CSS and JavaScript for a website or web application. The back-end is the server-side section of a web platform, which usually consists of three parts: a server, an application, and a database. Backend are usually created using languages like Java, PHP, Ruby, Python, etc. Some platforms may use web frameworks like Ruby on Rails, Cake PHP, and Code Igniter on the back-end to optimized system structure (Long, 2012).

This chapter primarily presents the system architecture and informatics aspects of the platform. The data and models included in this platform, which are tightly connected to the scientific side of the platform, are introduced in the next chapter. Since the entire system is a single-page web application, no Model-View-Controller (MVC) or other heavy software architectural pattern (Microsoft, Model-View-Controller, 2015) is used to ensure performance and system runtime. The schematic of the Iowa Culvert geo-portal is provided in Figure 4.1.
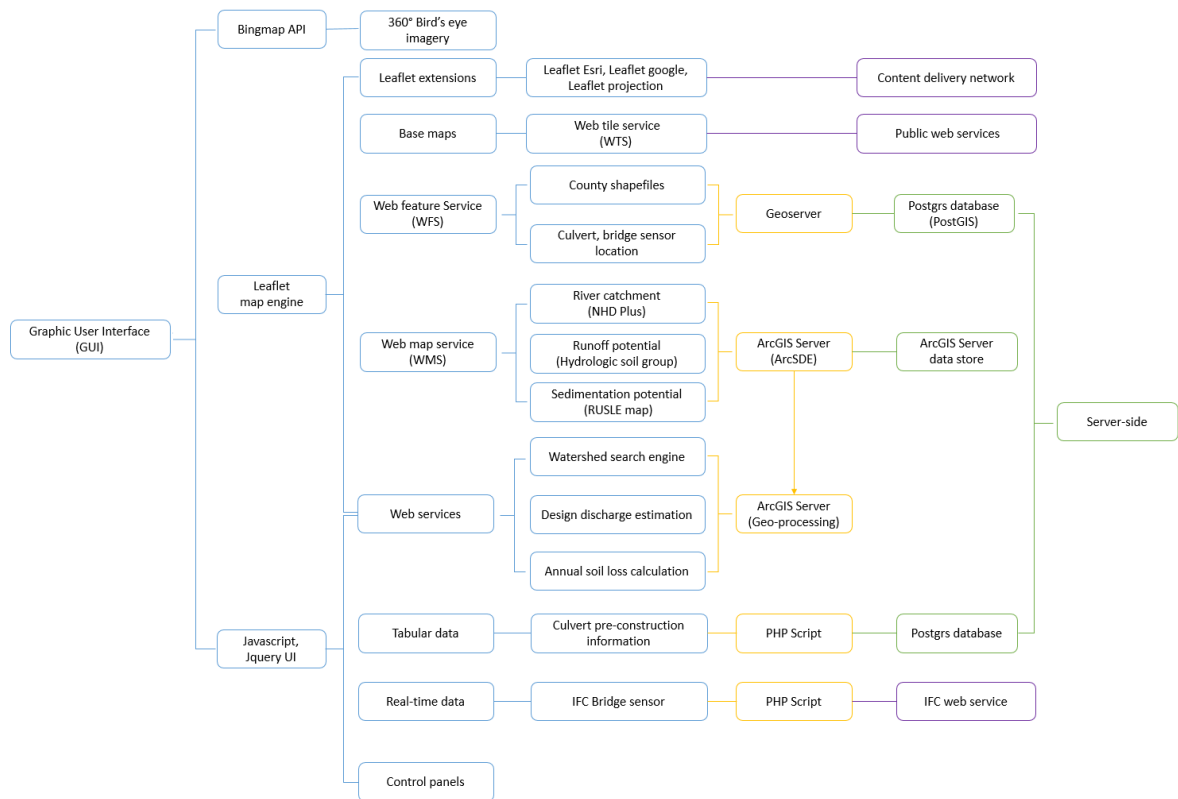
Figure 4.1 System architecture.

The front-end consists of a Graphic User Interface (GUI) and an interactive map

created using HTML (MDN, 2015), CSS (MDN, 2015), and JavaScript (MDN, 2015).

The GUIs are created for function implementation, workflow navigation, and platform

control purposes. In another word, 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

classification for different functionalities and workflows. The platform's GUIs are

programmed with static HTML and CSS. JQuery (jQuery, 2010) and generic JavaScript

are attached to the webpage to create dynamic effects and interaction with users. An

interactive map is built to visualize geographic information and spatial data. The map 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

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(Agafonkin, Leaflet Plugins, 2010) as map engines. 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, Leaflet Plugins, 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. Details of map engines will be provided in Section 4.2.2. Map services in the SDSS are materialized through Web Map Service (WMS) (OGC, 2009), Web Map Tile Service (WMTS) (OGC, OpenGIS Web Map Tile Service Implementation Standard, 2011), and Web Feature Services (WFS) (OGC, Web Feature Service , 2011). The platform provides a variety of base maps including aerial imagery, street map, topographic map, and hydrographic map. Aerial imageries acquired from a different time period create a time series for monitoring environmental, topographical, and infrastructural changes. All those map services are considered as platform data, hence are discussed in Chapter 5.

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 main database for the platform is the PostgreSQL database with PostGIS extension, 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 achieved by using middleware programs. GIS web server software is used to manage, and distribute spatial data. Besides the base maps, the platform allows 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 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. Future optimization of the platform will include the replacement of the ArcGIS server, which is responsible for geo-processing services, with custom created scripts hosted on an IIHR server.

Other than front-end and back-end on the local server, the platform also uses applications and web services on the Iowa DOT servers. These applications include the connection to IDOT SIIMS database and the integration of the Iowa DOT Iowa Culvert software.

4.2 System components

The platform is built using open source technologies (including PostGIS database, Leaflet map engine, GeoServer) that makes the system light-weighted, low cost and flexible. The prototype is currently being developed on IIHR servers. In the future, the

current prototype platform will be upgraded to industrial standards with commercialized API and licenses, so that it can be permanently transferred to the Iowa DOT server. This transfer will require usage of more enterprise level technology within the platform, including an Oracle spatial database, and an ArcGIS server. The original prototype with the latest open-source technologies will be preserved for educational and research purposes on an IIHR server.

4.2.1 Web interface (Front-end)

The Graphic User Interface (GUI) provides the user with graphical and intuitive ways to operate the platform. The web interface is a front-end JavaScript work rendered in browsers on the user's computer. The JavaScript, previously known as the ECMA Script, is a dynamic programming language used to enable browsers-control, asynchronous communication, and user-interactive effect in web pages and web applications. The syntax of ECMA script is somehow similar to Java, which is the reason why people started to call it "JavaScript". In fact, JavaScript is a front-end scripting language, while Java is an object-oriented server-side programming language. However, some JavaScript, such as Node.js, can also be used in server-side network programming with runtime environments. Like any other scripting language, JavaScript also includes extensive libraries. Each of these JavaScript libraries is developed to achieve specific functionalities.

The user interface for our platform is designed using jQuery and jQuery UI. jQuery is a cross-platform JavaScript library designed to reduce the redundancy and complexity in tradition DOM-based client-side HTML scripting. jQuery is an event-driven programming library, its syntax is very different from that of a traditional

JavaScript. The fundamental structure of jQuery is organized by jQuery "selectors",

which bind events and functions to HTML elements directly. jQuery UI is a curated set of

user interface interactions, effects, widgets, and themes built on top of the jQuery

JavaScript Library. Both jQuery and jQuery UI are free, open-source software. They are

the most popular JavaScript library in use today.

<div align="center">4.2.2 Mapping engine (Front-end)</div>

The platform uses two map engines: Leaflet and Bing map API. Leaflet is used as

the primary map engine to display base map and most of 2D features. Bing Map API is

used to display 40 degrees bird-eye's view, which is considered a 2.5-fimensional

representation for a map.

4.2.2.1 Leaflet map engine

Leaflet is a popular open-source, mobile-friendly JavaScript map engine library

designed for interactive web mapping. Compared to other modern map engines (such as

OpenLayers, ArcGIS JavaScript API, Google map), Leaflet is the most light-weight and

flexible. The library for Leaflet only weights 33 kb, containing all the features most

developers ever need for online mapping. Leaflet supports WFS, WMS, and WMTS in

geographic coordinate system, geographic features or maps in geographic projection

system, which can also be supported via certain leaflet extensions. The fundamental

Leaflet provides a basic methods to display base map, overlay, and data visualization in

browsers, while its diverse extensions provide more advanced features in web mapping.

For examples, with Google-leaflet and ESRI-leaflet extensions, Leaflet can display

Google map and ArcGIS map services; With Proj4Leaflet (Leaflet projection extension),

leaflet is able to support tiles and geo features in any projection system other than WGS

84, which is Leaflet's default system. Unlike other heavy web map engines, leaflet loads its extensions only when it is needed. Therefore, leaflet is a light-weight map engine with very fast speed. The tables of map services and leaflet extensions used by Leaflet map engine in the platform are listed in Table 4.1, 4.2, and 4.3.

Table 4.1 Base map services

Map layer name	Source, web services
Street map	ESRI, ESRI-Leaflet API
National Hydrographic Dataset	U.S. Geological Survey, USGS map server
National Elevation Dataset	U.S. Geological Survey, USGS map server
ESRI Imagery 2011	ESRI, ESRI-Leaflet API
Google Imagery 2013	Google Map, Google-Leaflet API
Iowa DOT imagery	Iowa Department of Transportation map server

Table 4.2 Map overlays

Map layer name	Source, web services
County	Iowa Geological Survey, IIHR ArcGIS map server
Hill shaded	Iowa State University, Iowa Geographic Map Server
Erosion potential	Iowa Geological Survey, IIHR ArcGIS map server
Runoff potential	SSURGO, IIHR ArcGIS map server

Table 4.3 Leaflet extensions

Extension name	Description
Esri-leaflet.js	An extension combining Leaflet with ESRI map services, ArcGIS features, and ArcGIS server features.
Leaflet-grouplayer.js	A Leaflet extension enabling layer grouping in leaflet control. Layer grouping helps to categorize map services in the platform.
Google-leaflet.js	A Leaflet extension enabling Google Map in Leaflet map engine
Leaflet_marker-rotate.js	Leaflet marker rotation extension, used in the platform to create rotated arrows to indicate flow directions.

4.2.2.2. Bing Map API and aerial viewpoint

Another map engine used by the platform is the Bing Map API. Although it is uncommon for one web application to use multiple Bing Map API, it is necessary for the platform to use some unique features provided by both Leaflet and Bing Map API. Bing Maps APIs is a JavaScript Library that embeds map controls and services to incorporate Bing Maps in web applications and websites. The APIs provide web services such as geocoding, route and queryable spatial data sources as well as interactive and static base maps.

Bing Maps API is one of the few map engines that is able to display 40 degrees birds'-eye view. There are two major types of imagery in aerial imagery: Overhead view and bird's-eye view. Overhead view imageries are the traditional type of 2D aerial

imagery with top-down perspective. The bird's-eye view is also termed "aerial viewpoint", which is 2.5D ("two-and-a-half-dimensional") compared to the traditional 2D aerial imagery (Ravenhill, 1986). In many cases, Bird's Eye view is also called 3/4 perspective and pseudo-3D as it attempts to "fake" three-dimensionality using graphical projections and techniques. The Bird's Eye images are angled at 40 degrees rather than being straight down. Oblique projection (Weisstein, 1860) is a type of parallel projection, which projects an image by intersecting parallel rays (projectors) from the three-dimensional source object with the drawing surface (projection plane). Using oblique projection programs, Bird's Eye images at same location but looking from different perspectives or directions are geo-referenced in Bing Map API, which grants the Bing Map abilities to display pseudo-3D topographic environment.

The rationale for using the 40 degrees Bird's eye view is to allow monitoring of culvert conditions, especially the inspection of the sediment deposits from various directions. Traditional imagery renders only 2-D information regarding the sediment deposits, while the Birds eye view enable 2.5D of the same by providing the $z-axis$ value for each point on the map. With the capability to view the culvert site from different directions, the user can choose the best perspective of sediment deposits that is typically obstructed by the culvert structure or surrounding vegetation (canopy).

4.2.3 GeoServer and ArcGIS server (Back-end)

Our platforms use both ArcGIS server (ESRI, ArcGIS for Server, 2015) and GeoServer (GeoServer, 2014) for sharing, processing and editing geospatial data. ArcGIS and GeoServer belong to web middleware category and they are similar in many ways, including their abilities to create WMS, WFS, and WMTS. ArcGIS server is capable to

host Geo-Processing services (GP) and Web Processing Service (WPS) (ESRI, A quick tour of publishing a geoprocessing service, 2015). The basic GeoServer doesn't support web services, but can host geo-processing services through the GeoServer WPS extension.

The ArcGIS server requires a paid license while the GeoServer is a free and open-source software. The current platform is still at proto-type stage. Both the GeoServer and the ArcGIS servers are in use. GeoServer is responsible for providing WFS, which includes culvert location, county shape-files. ArcGIS server is used to host geo-processing services as utility tools. Given the fact that this platform will be eventually transferred to the funding agency, the developmental plan includes two tracks: a) Iowa DOT and b) IIHR frameworks. Unlike IIHR, a research and educational institute, the Iowa Department of Transportation is required to develop applications with commercially licensed software. The Iowa DOT servers employ an enterprise version of the ArcGIS server, so their servers are oriented by ArcGIS structures. As a non-private research institute, IIHR is allowed to use open-sources scripts and software with educational licenses. The IIHR developmental track is to employ GeoServer along with other open-source software. The existing platform is being developed along the IIHR open-source track, with most of its web services created using open source software and python scripting. Given the educational and exploratory nature of the IIHR track, the platform may incorporate some other popular open source GIS technology such as Quantum GIS (QGIS) (QGIS, 2015). In future, the platform will be prepared for Iowa DOT track, all of its open-source components will be substituted with ArcGIS products.

4.2.4 PostgreSQL (Back-end & database)

The Iowa Culvert geo-platform uses PostgreSQL as back-end database to store both tabular and spatial data. PostgreSQL, often referred to as "Postgres", is an object-relational database management system (ORDBMS) with an emphasis on extensibility and standards-compliance (Postgresql, 2015). In order to store spatial information, PostGIS extension is installed on the top of Postgres. PostGIS provides spatial objects for the PostgreSQL database, allowing storage and query of information about location and mapping of various features. PostGIS is able to ingest various spatial formats, including ESRI shapefile (ESRI, ESRI Shapefile Technical Description, 1998) and Geo Tiff (OSGeo, 2014). Inside PostGIS, Spatial data are stored as three formats: EWKB, EWKT, and Canonical Forms. By using GeoServer, or data parsers created using PHP, spatial data in EWKB and EWKT formats can be converted into common spatial formats for web. Another popular program, which interprets PostGIS spatial data into web displayable formats, is the Geospatial Data Abstraction Library (GDAL). Since the GDAL is a console-based library, it is light-weighted and fast in data translation. Moreover, it can be easily ingested into other applications. Incorporating the GDAL into the platform is one of the developmental plans in future.

All vector-base spatial data in the platform are stored in the Postgres, including the culvert location, the culvert attributes, the Iowa boundary, and the county boundary. The platform uses GeoServer to connect front-end with the database. The GeoServer converts those shape-files into GeoJSON format (Geojson, 2008) and exports the data as WFS, which is the sent to the front-end leaflet map engine using JavaScript AJAX

(MDN, AJAX, 2015). Beside spatial object storage capability, PostGIS also supports

spatial query and simple geo-processing service.

As mentioned earlier, the development of the Iowa geo-portal follows two distinct tracks:

1) to accommodate the exploratory nature of the development at IIHR and 2) to

accommodate the uniformity of Iowa DOT computer framework. Similarly to the use of

the ArcGIS server, the Iowa DOT uses Oracle Spatial as the standard database. The

existing prototype platform is developed based on the IIHR track. For the future Iowa

DOT track, the Postgres will be replaced with Oracle database. For the IIHR track,

Postgres will still be used, because the performance of Postgres is better than that of

Oracle 11g in many aspects (Ramsey, 2012)

Another database used by the platform is the ArcSDE (Spatial Database Engine).

The ArcSDE works as a sub-system of the ArcGIS server. This is why details of this

database are not discussed in this thesis. In the platform, ArcSDE stores all input

information for the geo-processing services hosted on the ArcGIS server. Detail of those

geo-processing services will be presented in the data input section in the next chapter.

CHAPTER 5 IOWA CULVERT DSS IMPLEMENTATION
5.1 Data sources

5.1.1 Overview

Following the computer science aspects of the platform presented in the previous

chapter, a description of the domain specific knowledge relevant to culverts is presented

in this chapter. The later information is eventually the working knowledge that the

platform provides to users in making decisions. The domain data, information and

knowledge is generated by using direct monitored data and results of modeling (with

simpler or more complex simulations). Some of the data sources are used in their raw

format for monitoring and design purposes, while other datasets are used as input for

modeling various aspects of culvert design or assessment of the sediment accumulation at

the culvert location. Another view of the data used in the Iowa geo-platform is based on

their format, i.e., spatio-temporal time series (for hydrologic and hydraulic data),

infrastructural specifications (culvert dataset) and geographical data (such as base maps).

The data are classified as local (if they resides in a local database) or external (if they are

hosted on a remote database such as Iowa DOT SIIMS database and other third party

databases). The next section will discuss these data sources grouped around their

provenance.

5.1.2 Culvert dataset

The culvert dataset 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 properties

including culvert structure numbers, owner, type info, state code, and geometry information. All of the pre-construction data are stored in a PostgreSQL database. The database is connected to the GeoServer software 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 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. For each culvert location, the preconstruction data also include supplementary information such as sediment estimation from Revised Universal Soil Loss Equation (RUSLE) and river flow direction at the culvert location. The details of RUSLE will be discussed in Section 5.2.3. These supplementary information are derived by numerical simulations conducted prior to the populating the database and associated with the pre-construction data. Post-construction data are the information collected after the culvert is placed at a specific location. Post-construction data primarily contain information acquired during routine 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. The 2014 culvert sedimentation survey was coded into pre-construction data as attributes of culvert location, so that its information can be color-coded directly on map. The culvert sedimentation survey is named as "manager survey" on the Iowa DOT Culvert geo-portal.

The maintenance records also contain recommendations from IDOT engineers regarding the asset status. Figure 5.1 shows typical culvert maintenance information stored in the IDOT SIIMS database. Figure 5.2 shows culvert inspection records and photos available in the database. The SIIMS database is connected to the platform externally using the common FHWA number for the culvert for security concerns.
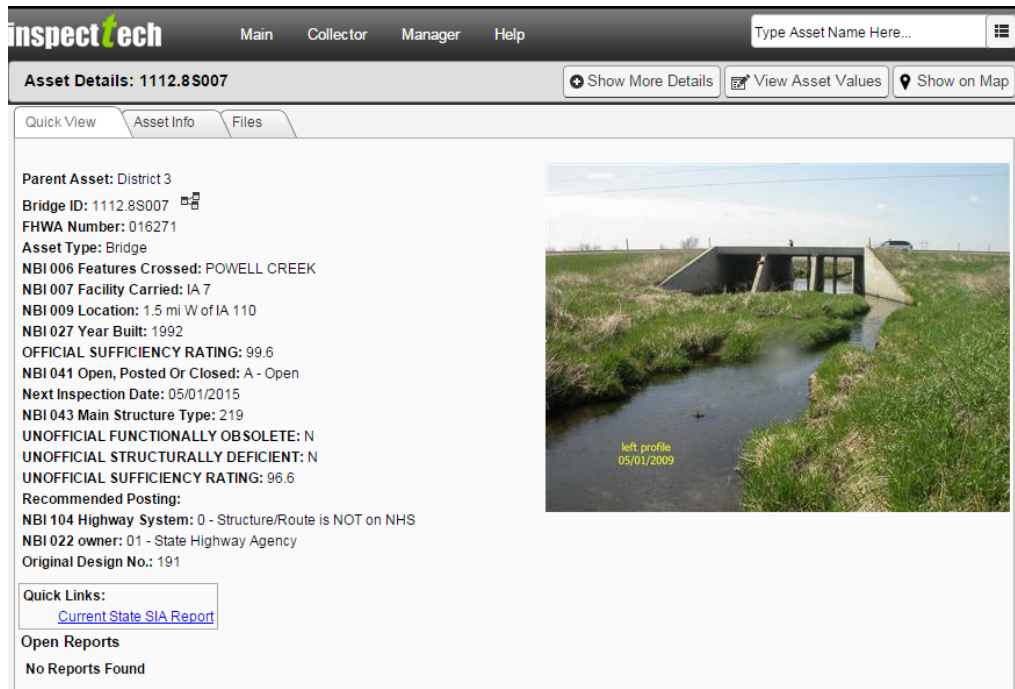
Figure 5.1 Maintenance record in the IDOT SIIMS database (SIIMS, 2015)

Currently the photos acquired from different angles during successive visits are stored in the IDOT SIIMS database. They provide useful time record of culvert aging and document the hydro-morphological changes at the culvert site. Such resources can be efficiently used to build the culvert sediment matrix described in the previous chapter. It is expected that in future, Close Range Photogrammetry technologies might be applied to support the culvert inspections such that quantitative information on the accumulated sediment volumes can be obtained from the acquired images. The mapped volumes can

be correlated with the culvert and stream geometry to provide all the needed information

for the development of the culvert sedimentation matrix.
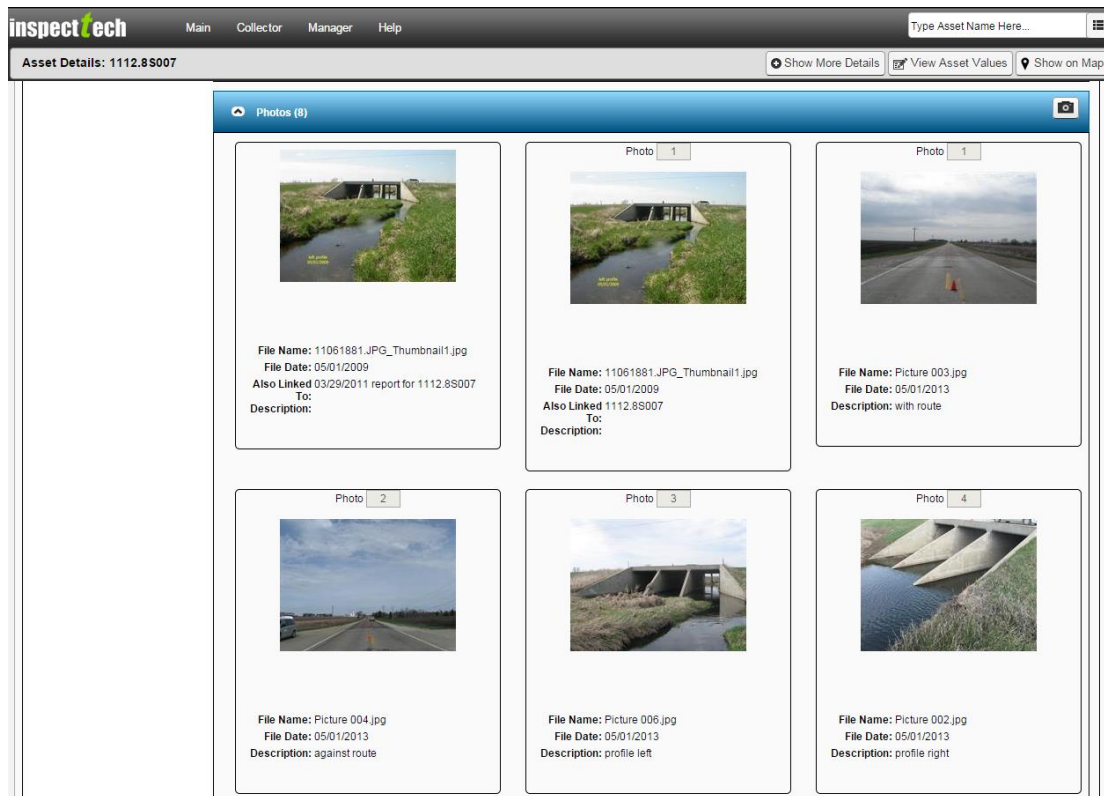
Figure 5.2 Photos taken during successive culvert inspections are stored in the IDOT
SIIMS database (SIIMS, 2015)

5.1.3 Hydrologic datasets

Culvert design and sediment management require information about the

hydrologic and hydraulic data at the culvert site. Among the most relevant hydrologic and

hydrologic data relevant to culverts are: river network and watershed information

upstream of the culvert location, as well as the runoff and sedimentation potential along

with river cross-section data, river stage, and discharges.

5.1.3.1 Hydrography

The river hydrography entails information about the river network, watershed and sub-watershed boundaries along with their hydrologic properties. The backbone of the hydrography datasets associated with the Iowa DOT Culvert platform is the National Hydrography Dataset plus Version 2.0 (McKay et al., 2012, p. 7). NHDPlus V2 is a repository of hydrography information for the entire US territory and has multiple usages, such as river network display, hydrologic information display, and model input for calculating design discharge. Beyond the information it carries, NHDPlus V2 also serves as hydrologic data structure for the platform as well as hydrologic and hydraulic models in the back-end. For example, the user can view river cross-section data that are bind to river reach in the NHDPlus river network spatially. Such spatial data structure for managing and query river-reach-related attributes is more powerful than the traditional data table and list.

The Watershed Boundary Dataset (WBD) contains the surface water components of The National Map. NHD and WBD are digital vector datasets that can be readily ingested in geographic information systems (GIS). The NHD contains surface water features such as lakes, ponds, streams, rivers, canals, dams and stream gages. The WBD defines the areal extent of surface water drainage to a set point with specification of the associated Hydrologic Units Code (HUC). NHDPlus is an updated suite of digital geospatial dataset of the original NHD. The original NHD is based on digital vector and raster datasets and was designed to support cartographic applications and surface water analysis. NHDPlus integrates selected features of the original National Hydrography Dataset (NHD), the National Watershed Boundary Dataset (WBD) and the National Elevation Dataset

(NED). The NHDPlus aims at fulfilling the same role as NHD but has a number of considerable refinements.

Currently there are two versions of NHDPlus released: NHDPlus version1 (2006) and NHDPlus version2 (2011). The NHD hydrography datasets are available at both medium resolution (1:100000-scale) and at high resolution (1:24000-scale or higher). Limited coverage is available at local resolution (1:5000-scale). The NHDPlus are developed based on medium resolution NHD at 1:100000-scale or better and 30 meter NED. NHDPlusV1, developed by the U.S.Geological Survey (USGS) and the U.S. Environmental Protection Agency (EPA) team, includes improved geometric networking, elevation-derived catchment, feature naming, "value added attributes" (VAA) and hydro-enforced digital elevation model (DEM) for a wide range of usages. NHDPlus Version 2 (NHDPlusV2) is a more structured geospatial database stemming from NHDPlusV1 successive improvement. The most notable NHD V2 improvements are:

1.   Improved 1:100K National Hydrography Dataset (NHD)

2.   Improved 30 meter National Elevation Dataset (NED)

3.   Complete National Watershed Boundary Dataset (WBD)

4.   Value added attributes to enhance stream network navigation, analysis and display

5.   An elevation-based catchment for each flowline in the stream network

6.   Catchment characteristics

7.   Headwater node areas

8.   Cumulative drainage area characteristics

9.   Flow direction, flow accumulation and elevation grids

10.   Flowline min/max elevations and slopes

11.   Flow volume and velocity estimates for each flowline in the stream network

12.   Catchment attributes and network accumulated attributes

13.   Various grids from the hydro-enforcement process including the hydro-enforced DEM.

The data model supporting the US hydrography dataset was successively improved in the transition from NHD to NHDPlusV1 and subsequently to NHDPlusV2. One of the major modifications in the new NHDPlusV2 data model is the division of the NHDPlus data structure into "core" components and "extended" components. The set of "core" data components are the direct results of integrating the three primary source datasets: the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), and the Watershed Boundary Dataset (WBD). The "extended" components of NHDPlusV1 and some new NHDPlusV2 components are the result of extending the primary source dataset to include flow estimates, catchment attributes, and accumulated catchment attributes.

On the Iowa DOT Culvert geo-platform back-end, NHDPlus is implemented through the ArcGIS server and ArcSDE (Spatial Database Engine) – a sub-system of the ArcGIS server that manages spatial data in a relational database management system (RDBMS) and prepare it for ArcGIS clients (ESRI, "Geodatabase,ArcSDE Technology , 2012). The ArcSDE adopts Relational Database Management Systems to store spatial data. The primary usage of NHDPlus hydrography dataset in the Iowa DOT Culvert geo-platform is in the watershed search engine, which will be presented in Section 5.1.3. The spatial query tool for hydrologic information on the present platform is also developed using

NHDPlus datasets. This tool provides information on watersheds or river reached based on user-defined locations.

5.1.3.2 Runoff datasets

Runoff is a variable directly influencing the amount of sediment transported and deposited in rivers. The runoff potential tool is one of Iowa DOT Culvert platform's feature that is using the hydrologic soil groups (HSGs) contained in Soil Survey Geographic database (SSURGO) dataset as indicators. The SSURGO database stores information about soil as collected by the National Cooperative Soil Survey covering most areas in the United States (NRCS, Description of SSURGO Database, 2014). HSGs classifies soils into four different groups (A, B, C, D) based on their saturated hydraulic conductivity at saturation level (NRCS, Part 630 Hydrology, 2007).

The SSURGO database contains information about the US soils, as collected by the National Cooperative Soil Survey (NCSA) over the course of a century. The information was gathered by walking over the land and observing the soil. Many soil samples were analyzed in laboratories. The maps outline areas called map units. The map units describe soils and other components that have unique properties, interpretations, and productivity. The information was collected at scales ranging from 1:12000 to 1:63360 (NRCS, 2014)

According to HSGs classification, Group A soils have low runoff potential when thoroughly wet. Water is transmitted freely through the soil. Group A soils typically have less than 10 percent clay and more than 90 percent sand or gravel and have gravel or sand textures. Group D are the soils have high runoff potential when saturated. Water movement through the soil is restricted or very restricted. Group D soils typically have

greater than 40 percent clay, less than 50 percent sand, and have clayey textures. The

Iowa DOT Culvert portal tool assumes that watersheds containing mainly Group A soil

has a low runoff potential, while watersheds containing mainly Group D soil has a high

runoff potential. The areal distribution of the soils per watersheds and the overall

watershed runoff potential characterization is based on the gridded SSURGO raster data.

Like NHDPlus, SSURGO database also contains core data and extension tables. The core

data used in this tool is the 30 meter gridded SSURGO raster (gSSURGO), which

contains "MuKeys" as database key for each cell. Using relational database structure,

attributes of soil in extension tables can be joint to the gSSURGO. The reason to use

gSSURGO instead of original vector SSURGO database is that the raster data are

rendered faster in GIS software and web platforms. Figure 5.3 shows all the data sources

used by the platform under different categories. Data pertained to hydrologic models and

other web services will be discussed separately in the next section.
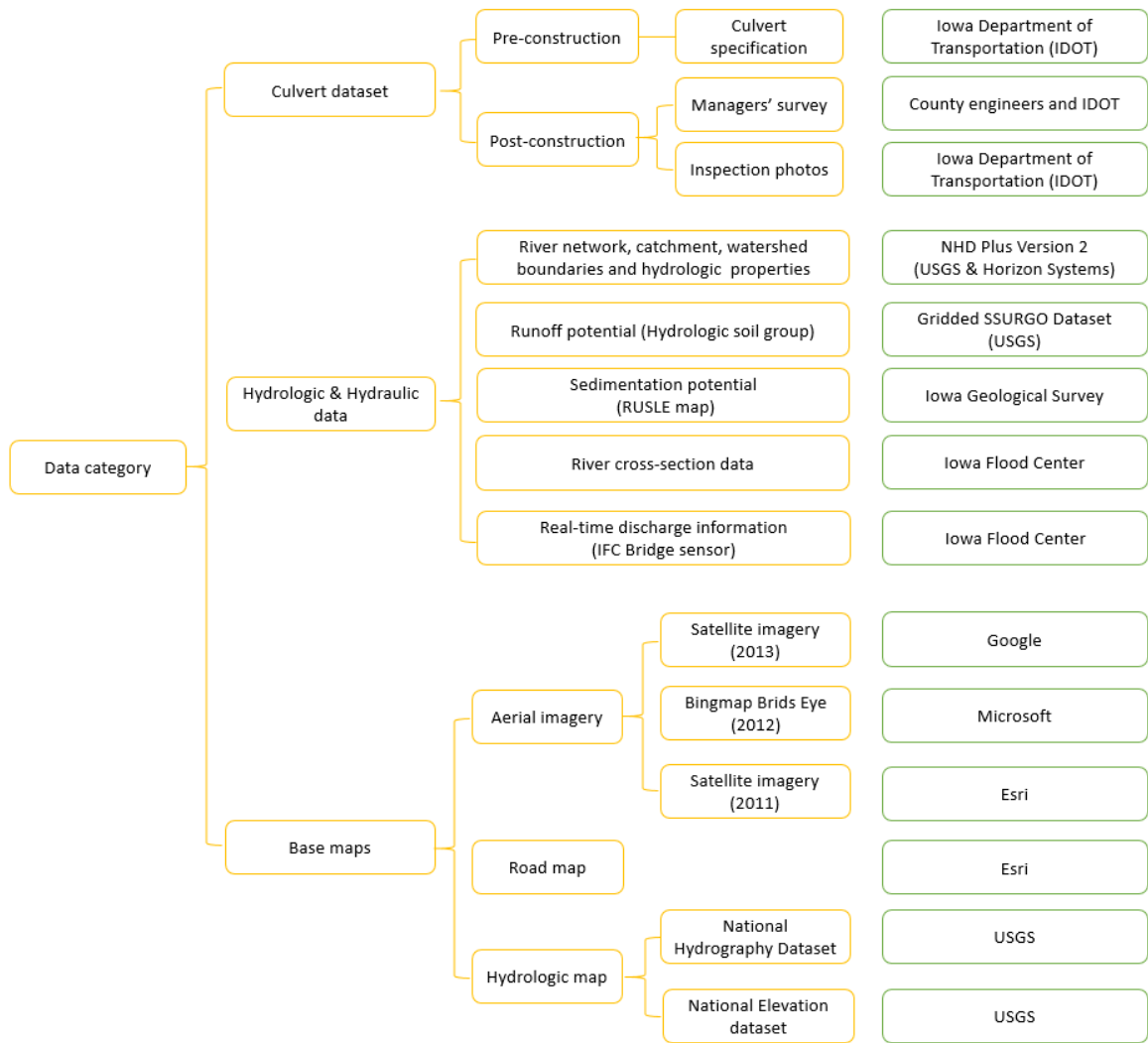
Figure 5.3 Data source of the platform

5.2 Stand-alone workflows

5.2.1 Watershed search engine

As this platform is designed to assist the culvert design process including considerations related to sedimentation potential at the culvert site, the needed models are coded into geo-processing services and published through the ArcGIS Server to perform online analysis. The needed culvert design considerations were discussed in Chapter 2

along with the current protocols used by Iowa DOT for implementation of the hydrologic

and hydraulic design. The culvert hydrologic design requires estimation of the design

discharge based on the flood frequency analysis equations that in the IDOT protocols. In

order to use these equations, the upstream drainage area of the existing or future culvert

sites needs to be calculated. The delineation of the upstream drainage area is needed for

both hydrologic considerations as well as for estimation of the sedimentation potential.

Finding the upstream drainage area is done using the watershed search workflow. The

workflow is a basic geo-processing service that finds the boundary and area of upstream

drainage basin starting from any point of interest (POI) selected within the Iowa state.

The current service is created out of the National Hydrographic Dataset (NHDPlus2)

river network using the ArcGIS toolbox and the ArcGIS Model Builder. The service

simply traces the upstream of POI via geometric network analysis tools and output the

corresponding basin as shape file. Once published, the geo-processing service takes the

user defined POI from client-side and calculates the watershed on the server. The service

returns output watershed boundary and its area as Jason object to the client-side so that

the leaflet map engine can display the boundary on base map.

The use of ArcGIS based geo-processing service demands on the ArcGIS server,

which is heavy and slow in run-time. For system optimization reasons, another approach

for the watershed search is currently explored using a front-end based watershed search,

similar with the one used in the Iowa Flood Information System (IFC, IOWA FLOOD

INFORMATION SYSTEM, 2015). The IFIS watershed search utilizes flow direction

matrix and DEM to delineate watershed boundary. The run-time of the IFIS search

engine is much faster than that of the ArcGIS-based search engine, because the IFIS

approach stores the flow directional matrix at the front-end as an independent application. This application is downloaded to users' computer once the platform is launched, and the application is executed directly in users' browsers without any server-side involvement, which is why the speed of IFIS search is faster. However, in IFIS approach, the directional matrix is a separate dataset from the NHD, therefore doesn't carry any of the NHD attributes.

5.2.2 Peak discharge estimation workflow

The design discharge calculator is a geo-processing service built on USGS Lara and USGS Eash regional regression equations. Both methods calculate annual exceedance-probability discharge based on watershed drainage areas in pre-defined hydrologic regions in Iowa. USGS Lara method distinguishes five hydrologic regions across the Iowa landscape while USGS Eash distinguishes only three hydrologic regions. The visualization of the hydrological regions according to Lara and Eash are provided in Figure 5.4. Details of the two methods were presented in the Section 2.1.2. The present section will focus on the implementation of the methods in the web-based geo-portal.

Both USGS Lara and USGS Eash methods are created as geo-processing services through the ArcGIS server, the ArcGIS toolbox, and the ArcGIS Model Builder. USGS Lara method and basic version of USGS Eash method need the upstream drainage area from a POI as input. Using python scripting and ArcPy (i.e., Arc tool box python API), the upstream drainage area delineated by the watershed search engine can be divided in hydrologic regions conforming to the USGS Lara or USGS Eash methods. The delineation is done using intersect tools in ArcPy library. Numerical values of each divided upstream drainage areas 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 in the respective regression

equations corresponding to the hydrologic regions their divided area lies. For better

estimation, USGS Eash method has a three-parameter version, it takes main channel

slope (MCS) and DML (Des Moines Lobe). Figure 5.4 presents the hydrologic regions

defined by the Eash methods. The hydrologic regions in the Lara method is presented in

Figure 2.2.
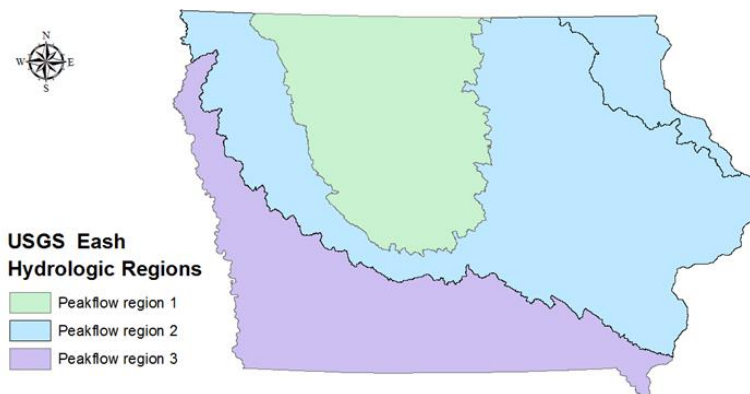
Figure 5.4 The Iowa hydrologic regions as defined by the USGS methods for estimating
the Flood-Frequency Discharges for Streams: Eash regions (Eash, 2001)

5.2.3 Sedimentation estimation workflows

This workflow facilitates the estimation of the amount of sediment generated in

the upstream area of the watershed from the culvert (or, in general, from any point of

interest) and transported at the culvert site as runoff. The sediment generation is

estimated based on the Revised Universal Soil Loss Equation – RUSLE (NRCS, 2012),

while sediment transport analysis requires calculation of sediment delivery ratio at the

desired location. The delivery ratio is calculated using Spatially Explicit Delivery MODel – SEDMOD (Glenn et al., 2006).

USLE, a predecessor of RUSLE, is an empirical model developed in 1930s and released in the early 1960s by the U.S. Department of Agriculture (USDA) Soil Conservation Service. Its current name is USDA Natural Resources Conservation Service (USDA-NRCS). The method was empirically derived based on large amount of soil erosion data acquired over extensive areas of the US. Currently, RUSLE has been extensively used for conservation planning purposes both in the US and worldwide. The soil loss is estimated in the Iowa DOT Culvert platform via geo-processing services connected to RUSLE. The web services operate on ArcGIS server using drainage area as source of sediment and 10-meter RUSLE grid as input. A conservative estimation is made by assuming that all soil loss within the watershed leaves the drainage area at the downstream POI. Consequently, an addition of the soil loss cell values within the watershed boundary upstream from the POI is made by the web services. This assumption is more reasonable for long-term sediment estimation whereby it is expected a more global mobility of the sediment over the drainage area.

RUSLE model estimates soil loss using following parameters (NRCS, 2012):

$$A = R * K * (LS) * C * P \text{ (5.1)}$$

A : Computed Average Annual Soil Loss

R : Rainfall-Runoff Erosivity Factor

K : Soil Erodibility Factor

L : Slope Length Factor

S : Slope Steepness Factor

C : Land Cover-Management Factor

P : Conservation Practice

The estimation of the delivery ratios with SEDMOD is calculated for each watershed cell with consideration of six sediment transport parameters. The parameters are derived using information on the local elevation, vegetation cover, and soil properties. SEDMOD is deeply integrated within Arc/Info, a widely used geographic information system, using a menu interface and Arc/Info's programming language (ESRI, Understanding GIS—The ARC/INFO method, 1999). Figure 5.5 illustrates the how RUSLE and SEDMOD are combined to estimate sediment production at river locations of interest (Glenn et al., 2006).
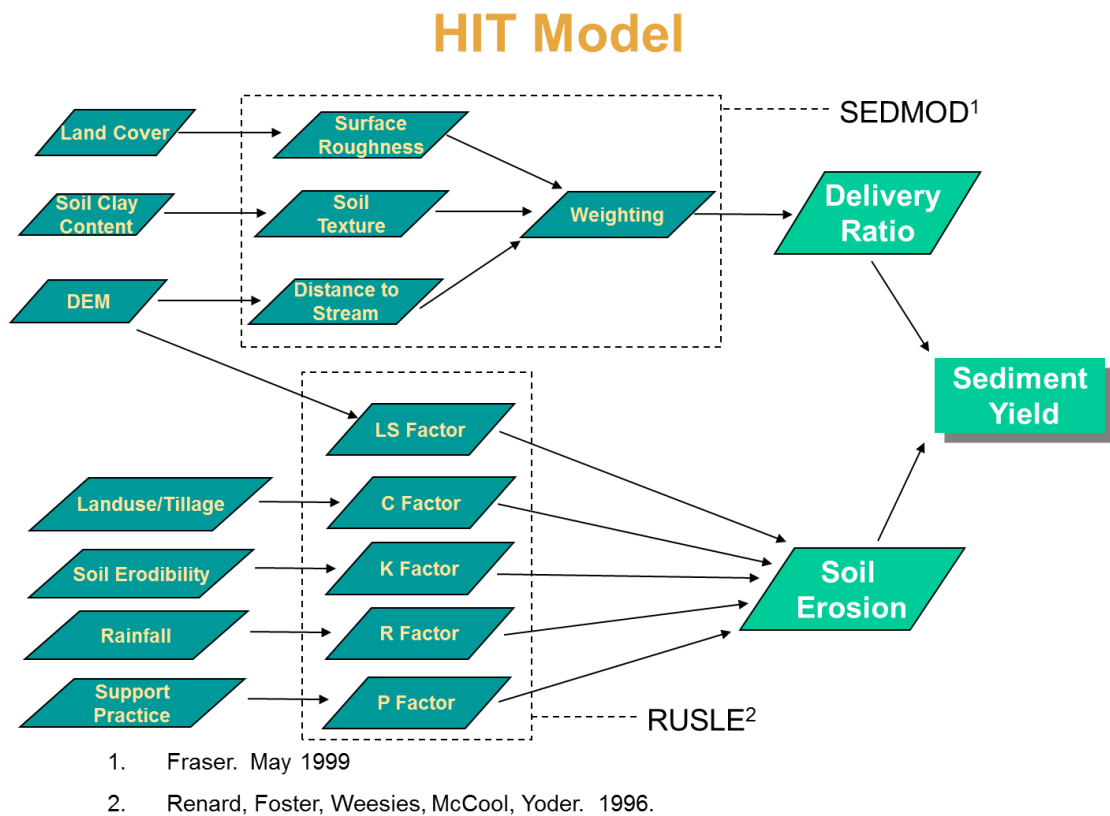
HIT Model

Figure 5.5 HIT Model combines RUSLE and SEDMOD for estimation of the sediment delivery ratio (Glenn et al., 2006)

A similar model to the HIT model will be adopted for the Iowa DOT Culvert platform for sediment accumulation estimation. Soil inputs for the SEDMOD are fetched from the SSURGO data stored in the Arc SDE database. Soil erosion is a pre-processed using RUSLE model and stored in the Arc SDE database as raster data. Supplementary web services including Esri-Leaflet geocoding and watershed information tool are also embedded into the platform to help user query information in different ways. A visual schematic of the interconnection between the models described above is provided in Figure 5.6.
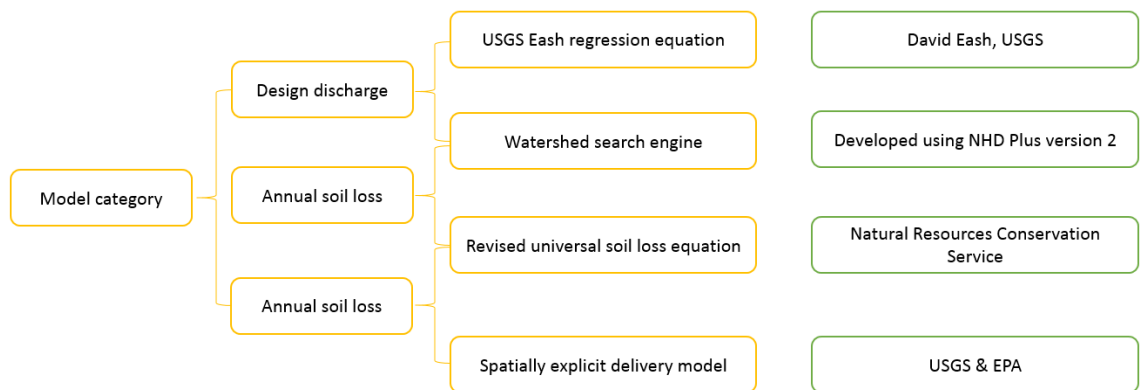
Figure 5.6 Summary of the linkages between the models used in the Iowa DOT Culvert platform.

5.3 Assembling workflows clusters

The combined use of the above presented database, web mapping, and GIS technologies produces a web-based geoportal that conveniently integrates data from various sources, couples them with models, and allows the user to interact with the platform through user friendly interfaces. The interfaces are stripped by the information that is inferred from implicit assumptions and straightforward calculation to provide a

simple and user-friendly appearance of the platform to the users. Having in mind that the final product has to support the culvert design and monitoring activities, the stand-alone workflows are presented below from this perspective. Both sets of workflows were designed having in mind that the platform users are engineers that have limited computer programming background, so the backend scripts and algorithms are hidden during the interaction with the platform.

5.3.1 Culvert design workflow cluster

This cluster combines the culvert data repository, and regional hydrologic analysis with universal soil loss models to provide a useful support during the culvert design with inclusion of sedimentation aspects of the culvert operations. The platform also provides geo-processing tools that facilitate the derivation of useful empirical relationships between the degree of sediment accumulation and culvert and stream geometry.

The usage of the workflows in the design cluster are phased as follows:

(1) Identify a point of interest (POI) to place a new multi-box culvert or to evaluate the status of an existing culvert with the purpose to inform the design of a new culvert in its proximity

(2) Estimate design discharge and annual soil loss based on stream and basin characteristics via the hydrologic web services

(3) Estimate culvert geometry and inlet and outlet controls

(4) Combine runoff and sedimentation potential to estimate the potential degree of threat of sedimentation formation at the site under consideration (POI).

The geographic location of POI is selected by pointing the desired location on the web-based map, this instantaneously triggers geocoding through the mapping engine and connecting the point with river network and the road map at that location. Exceedance-probability discharges for the design discharge are obtained using the USGS Eash regression equation. This procedure is compliant with the current discharge determination protocols in the Iowa Bridge Backwater Design Software Version 2.0, which is the currently authorized culvert design software for Iowa culverts. Annual soil loss is calculated based on the drainage area upstream of the POI using RUSLE. Using the sediment production provided by the RUSLE, the SEDMOD calculates the sediment delivery ratio to determine the final sediment reaching the culvert site. The runoff potential is indicated by the type of hydrologic soil group derived from the SSURGO dataset, which exhibits potential amount of runoff generated on each parcel of land based on soil type. The sedimentation potential is represented as a color coded map resulted from the RUSLE analysis. Both runoff and sedimentation potential are web map services (WMS) designed to provide users with the hydrologic and hydraulic properties relevant to culverts. Figure 5.7 visualizes the culvert design workflow cluster.
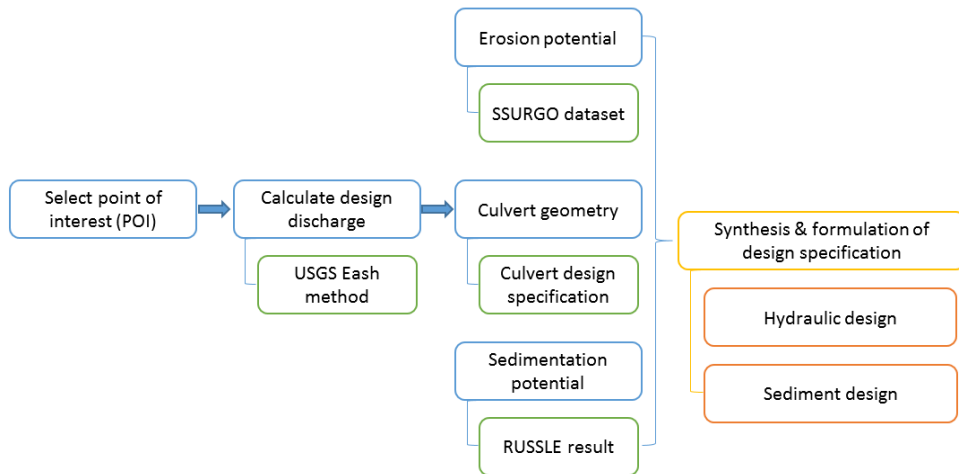
Figure 5.7 Flow diagram of culvert design workflow cluster.

5.3.2 Culvert monitoring workflow cluster

This cluster is assembled with aspects of culvert monitoring in mind. Specifically, the workflow should assist the agencies maintenance personnel to query comprehensive culvert information and inspect culvert physical status through high quality aerial imageries taken in different years. The phasing of the workflow is as follows:

(1)   Identify a culvert of interest using culvert search tool provided by the platform

(2)   Select culvert location

(3)   Quantify sediment accumulation at site using the GIS-based analysis tool.

Following step 1, the culvert searching tool access to the culvert metadata (by specifying structural code, geocoding and the river on which the culvert is located). After locating the culvert of interest, the system automatically display an inspection window for the selected site. The window contains basic information about culvert design and

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geometry, and a 360° Bird's Eye imagery which covers the site from all directions (if available). Users can access additional site information by taking advantage of the availability of ortho-rectified aerial imagery from 2011 to 2013 stored in Iowa DOT SIIMS database.

The Iowa DOT Culvert platform offers a choice of background basemaps including high resolution topographic maps derived from national elevation dataset, watershed and river information from national hydrographic dataset, and 1 meter Lidar hill shaded maps, which provide the user with a 2.5 dimension view of the culvert geometry and surrounding terrain. The quantification of culvert sedimentation status (step 3) is attained directly on display window using geo-referencing techniques and geo-processing services developed on ArcGIS server software. The user delineates the polyline boundary of sediment in the culvert inspection window with the overlay of 360° Bird's Eye imagery. The map engine estimates the geo-coordinates of the polyline vertices and imports the results into geo-processing service for area calculation. If required, the geo-processing service is capable of roughly estimate sediment volume using area and elevation information in the regional digital elevation model.

All numerical and textual information are retrieved from the specialized IDOT culvert database, while the graphical information coming from various web map services (WMS). Currently, the Iowa DOT Culvert platform will also ingest selected content from the SIIMS database, which is the main Iowa DOT database for bridges, but also includes culverts. The value of SIIMS database is that it is continuously updated after culvert construction, therefore being a useful source of information on the dynamic of the geo-morphological processes for the geographical area where they reside. SIIMS is a product

widely used across the US; hence, it makes the construct of the Iowa DOT Culvert

platform usable in other settings across the nation. Figure 5.8 visualizes the culvert

design workflow cluster.
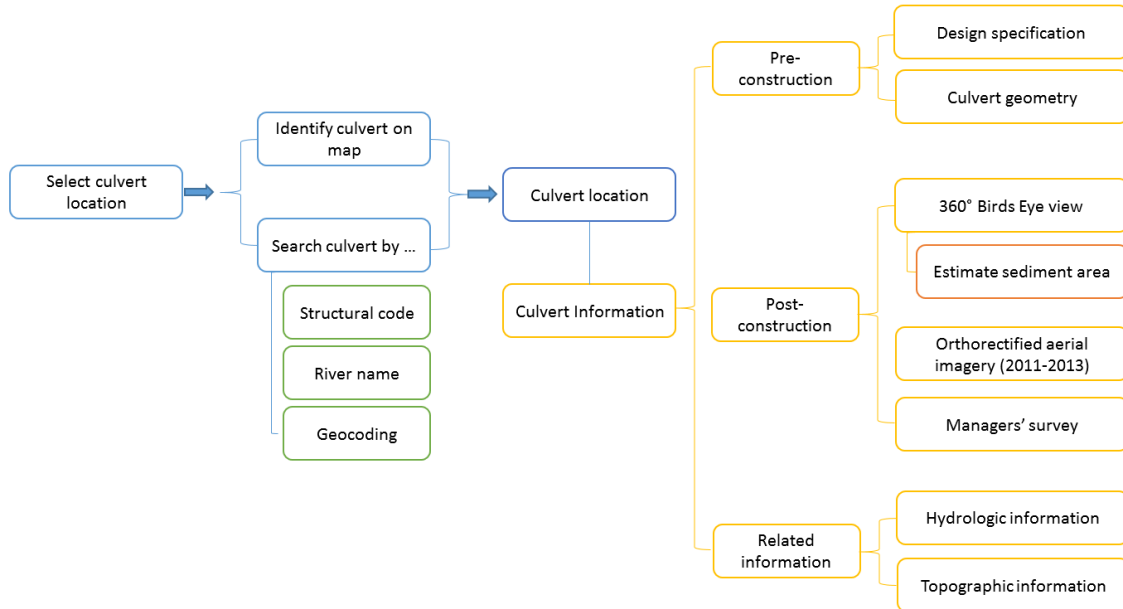
Figure 5.8 Flow diagram of culvert monitoring workflow cluster

5.4 GUIs for workflow execution

5.4.1 General platform GUI

The GUI of the platform comprises interactive web maps and control panels. The

web map visualizes spatial data, including culvert location, various base maps, and

modeling results as spatial (geo-referenced) distributions. The control panel provides user

tools and functions to run analysis, query data, and control the web maps. Figure 5.9

presents the general arrangement of the Iowa DOT Culvert platform.

Figure 5.9 Platform user interface
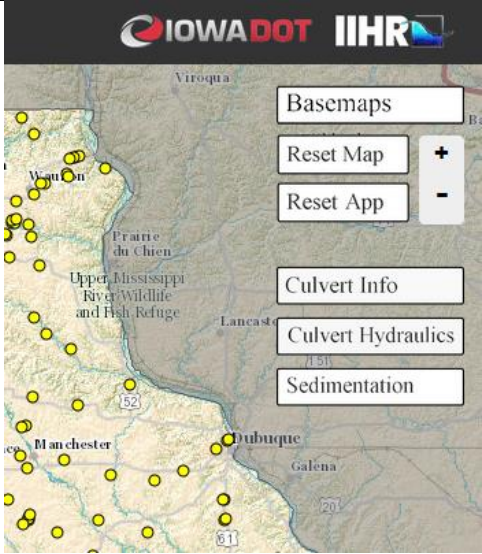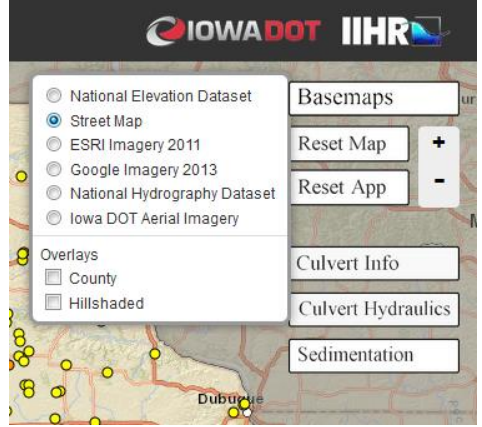
Culverts are displayed as colored dots on the basemaps. Color-coding on culvert location indicates the number of boxes and sediment characteristics.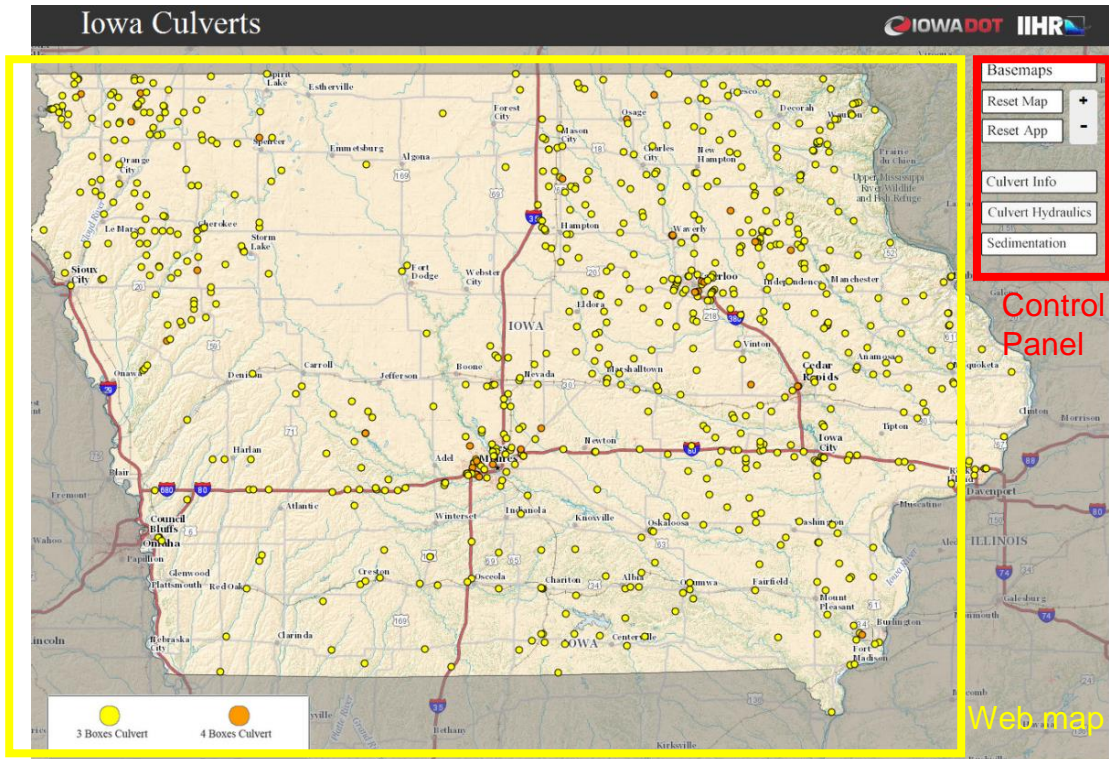 All culvert location points are clickable, i.e., user can click on a culvert site of interest to view detailed information about the culvert. On the upper-right is the platform control section. The GUIs are associated with "tools" and "workflows". Tools are simple services returning results after the user solicits one of these tools. Workflows are combination of tools that lead to a problem-solving situation such as design of a culvert or monitoring operation.

5.4.2 GUIs stand-alone workflows

The intent, computer front- and back-end of the tools were described in the previous chapter. Herein, only the GUI (the look and feel of the tools) are presented for

completeness. Table 5.1 provides details on the tools included in the Iowa DOT Culvert platform.

Table 5.1 GUIs and descriptions for the Iowa DOT Culvert platform tools.

GUI	Descriptions
	Control panel can be divided into two sections: i) Map control tools ii) Platform tools The map controls contains buttons for changing, resetting, and manipulating the web maps. The platform tools include web services and modelling tools for culvert design and monitoring.
Map tool 	"**Basemaps**" tab provides user options to switch basemap and overlays. "**Rest Map**" tab restores default map view, which zooms to the entire state of Iowa. "**Rest App**" tab reloads the webpage and restore everything inside the platform.
Culvert info tool	
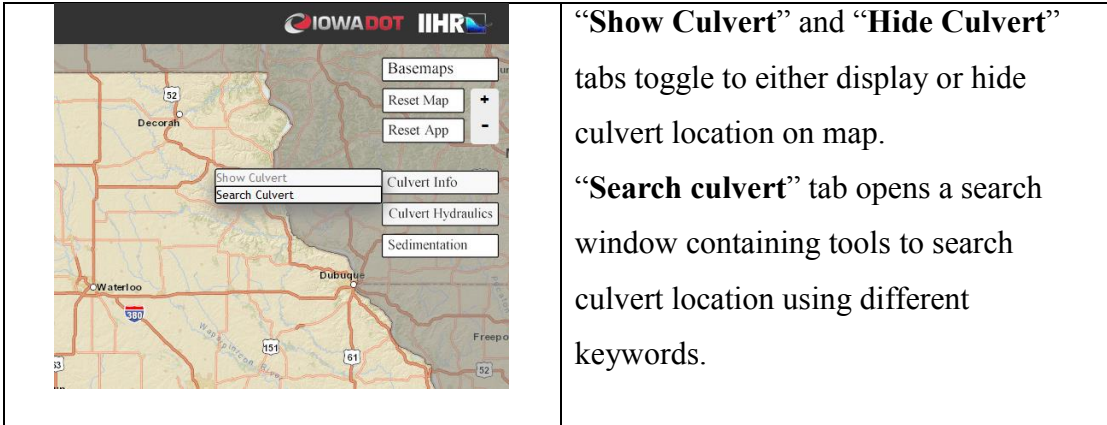
	"**Show Culvert**" and "**Hide Culvert**" tabs toggle to either display or hide culvert location on map. "**Search culvert**" tab opens a search window containing tools to search culvert location using different keywords.
Culvert Search tool 	There are two ways user can select a site: i) select from map and ii) select through culvert search. The culvert search contains a text input search bar and a dropdown menu with specifications for the search. The search window is dynamically generated and fully draggable in the browser window.
	In the culvert search window, three search specifications are provided. The user can search culvert by its structure code (FHWA code), river and road where the culvert is located.
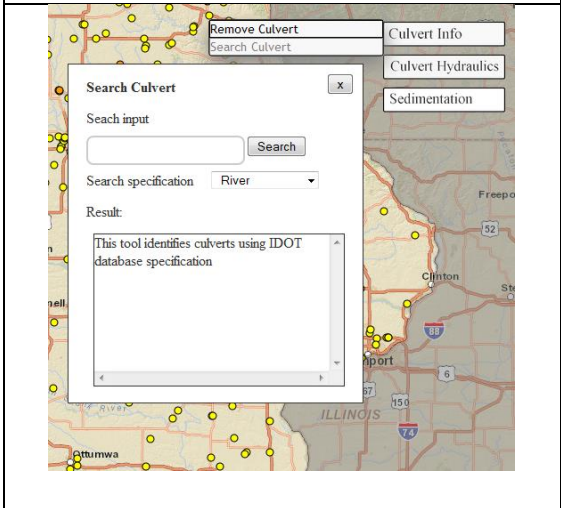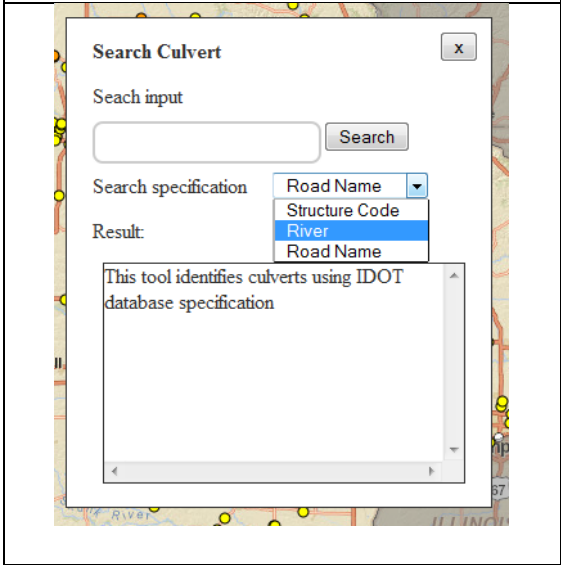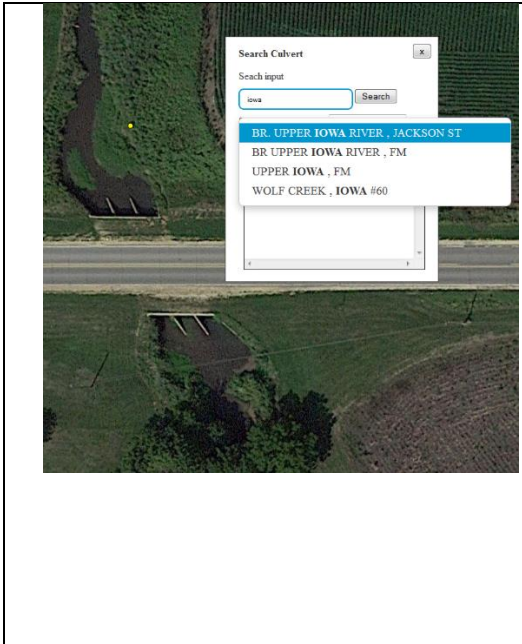
	Once the search specification is set, user can type keyword in the text box to find any multi-box culvert inside Iowa. The Keyword can be complete or incomplete, the text box has the autocomplete feature, which can recognize segments of the wording for search specifications (e.g., river, road, and culvert structure code).
Culvert hydraulic toolset	The culvert hydraulic tab contains the following tools:
	• River catchments (NHD) • Runoff Potential • Search Watershed • Calculate Discharge • Estimate Culvert size (in development) "**River catchments (NHD)**" is the WMS of NHD watershed boundary dataset: the tools returns the catchment area for each specified stream. "**Runoff potential**" is WMS for hydrologic soil group maps in SSURGO dataset.
Search watershed tool	
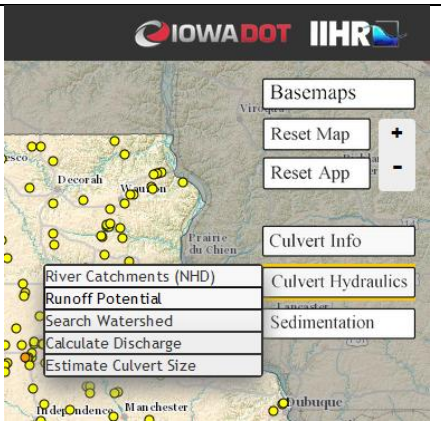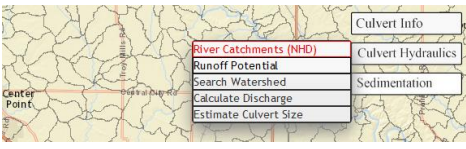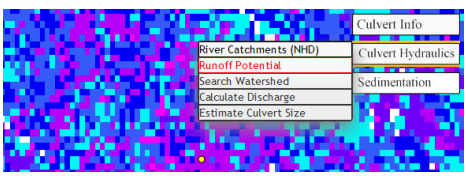
	Search Watershed search engine identifies the extent of drainage area upstream from any POI. The tool offers two options: i) Trace local catchments (provides local watershed characterstics and information), and ii) Trace to headwater from chosen POI (traces the maximum extent of the drainage area unstream from the POI).
	In "Trace to headwater from point of interest", the user sets a location on the map by dropping a pin.
	After the tracing is finalized, quantitative results of the search are displayed in the "Result" window. The color of watershed boundary can be changed using the "Display color" drop down menue inside the window.
Calculate discharge tool	
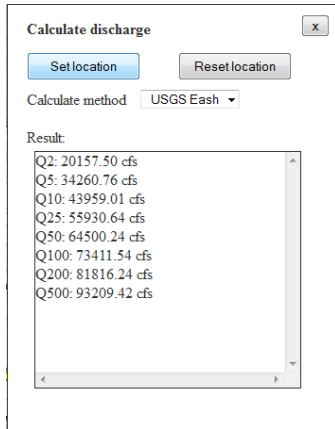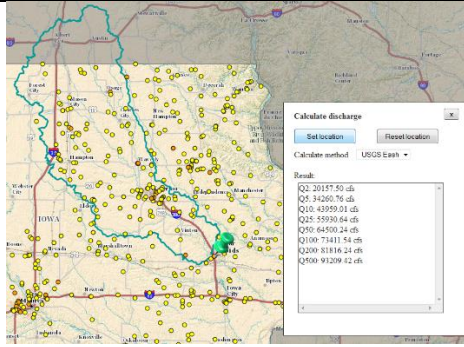
	Calculate discharge tool estimates the design discharge using USGS Eash method. The tool is similar to the "Search watershed tool", but produce it also provides probability of exceedance for different return periods (i.e. 2, 5, 10, 25, 50, 100, 200, and 500 years). Through the dropdown menu, user can also switch to othe options for the probability estimation.
Sedimentation toolset	Sedimentation tab contains tools and web services for culvert sedimentation analysis. It includes: • Current Situation • Erosion Potential • Sedimentation Potential • Sedimentation Potential analysis • Site inspection
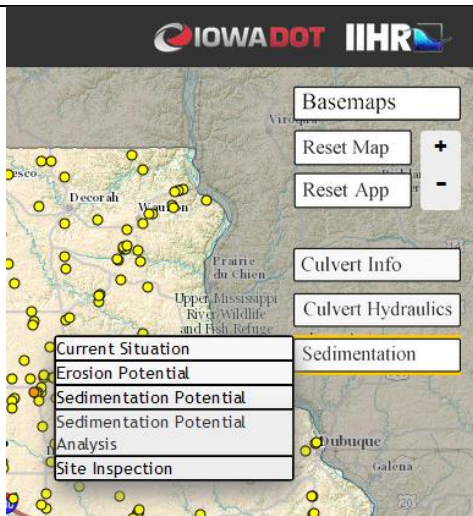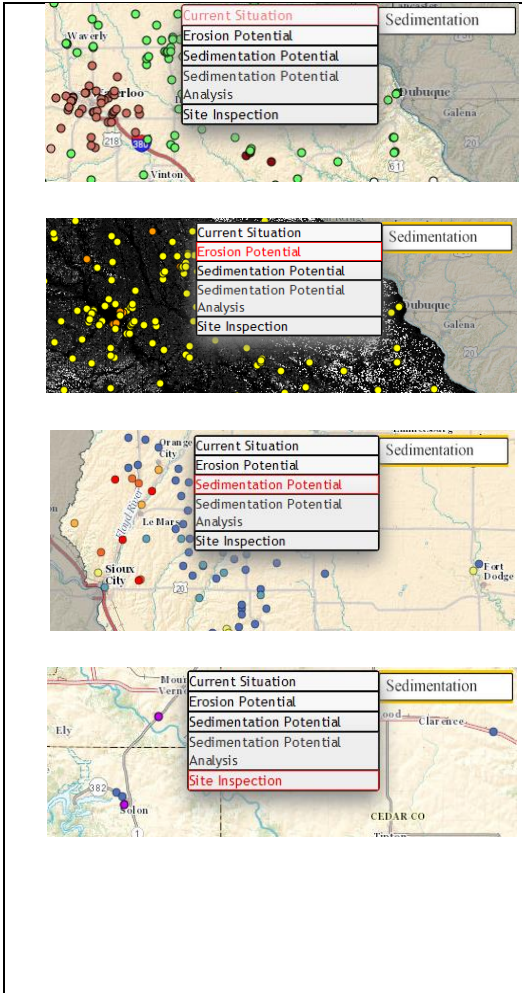
	"**Current Situation**" creates color-coding on culvert location to reflect the degree of sediment blockage based on a 2014 survey of the Iowa DOT and county engineers. "**Erosion Potential**" is the WMS of the RUSLE modelling output. "**Sedimentation Potential**" associates colors to culvert locations commensurate with the degree of soil loss upstream each culvert site. The color code is based on the scaled magnitude output by RUSLE and SEDMOD. "**Site Inspection**" tool displays up to five culvert locations chosen for comparison of field inspections. The chosen sites are colored in "purple".
Sedimentation Potential Analysis tool	"**Sedimentation Potential Analysis**" tool estimates the annual soil loss in the drainage area upstream the culvert. This tool is similar to the watershed search tool. In order to produce estimation, user needs to set a POI or select a culvert site. After selection, the tool delineates the upstream watershed boundary and shows the annual soil loss corresponding to the identified drainage area (in tons/acre/year).
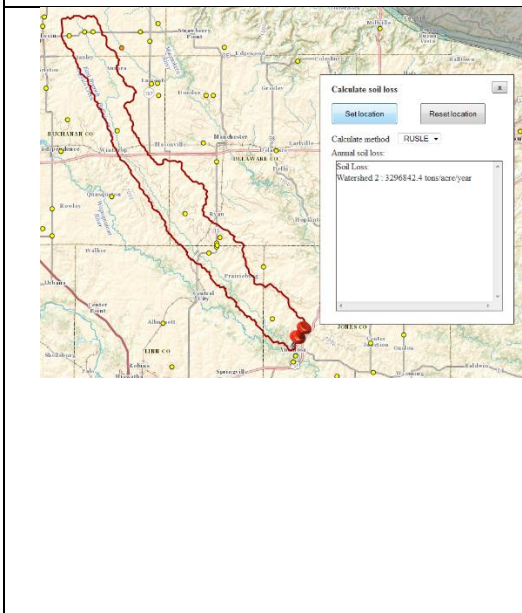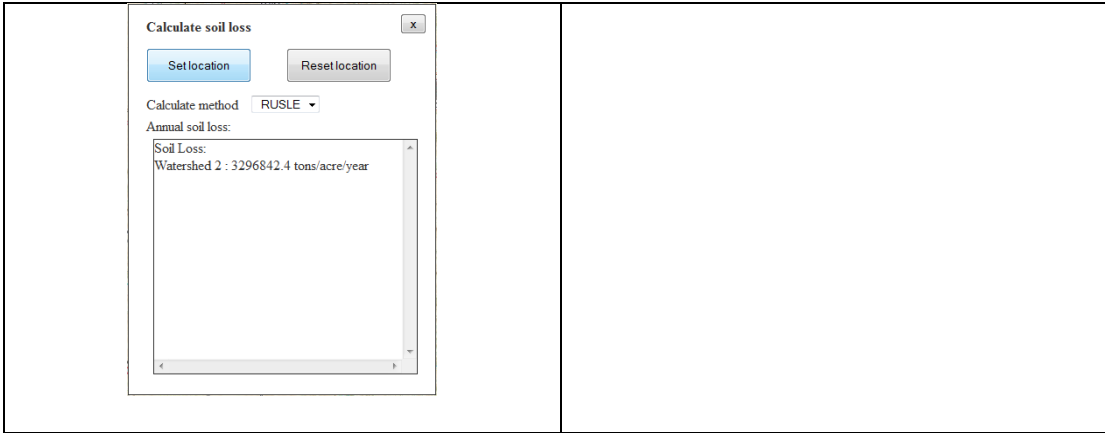
5.4.3 GUIs for workflow clusters

The tools presented above can be grouped in various way to accomplish specific tasks. Provided below is a grouping of the tools corresponding to routine operations conducted during the design and monitoring of the culverts.

5.4.3.1 Culvert design and sediment analysis

As mentioned before, culvert design involves hydrologic analysis and hydraulic design. Hydrologic analysis is mainly peak discharge determination, while the hydraulic design contributes to culvert sizing. The tools developed so far are not covering all the design and sedimentation analysis yet. Further work as described in the end of this thesis is needed to attain a more comprehensive decision support system for multiple purposes related to culverts. The combination of tools used in the hydraulic design grouped based on their functionality is displayed in Figure 5.10 and 5.11.

USER WEB INTERFACE	DESCRIPTION
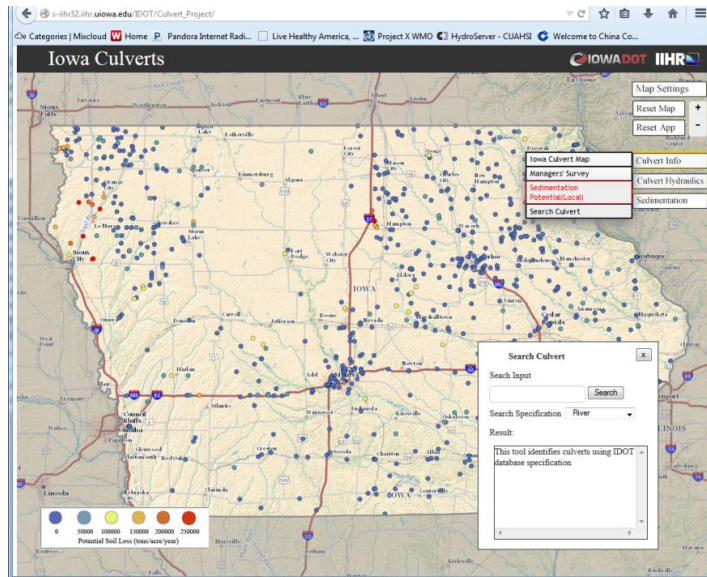
Tools:
a) culvert mapping
b) culvert sedimentation
*   potential*
c) search culvert

This geo-portal function maps all the multi-box culverts (2, 3, and 4) contained in the IDOT database. Culverts can be also searched using specifications contained in IDOT database (e.g., by river or road name, ID, geometric specifications, etc). This geo-portal feature also provides the potential for soil loss at each culvert estimated with NRCS's Revised Universal Soil Loss Equation (RUSLE) model. The tools are illustrated in the image at left.

Figure 5.10 Web interface for culvert design.

USER WEB INTERFACE	DESCRIPTION
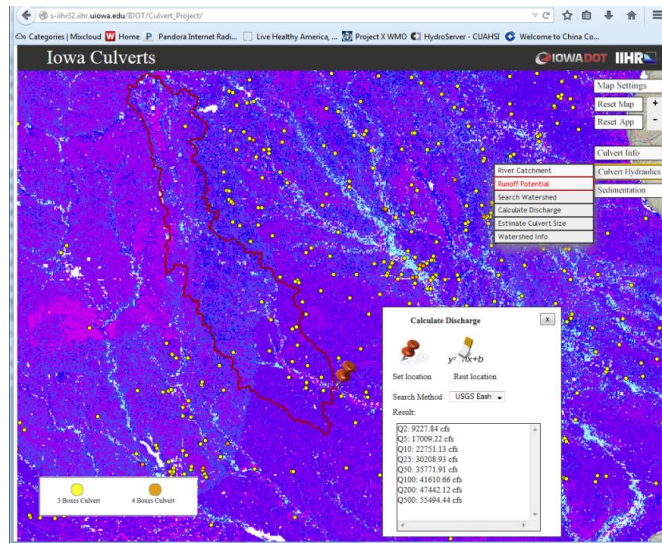
Tools:
a) river catchment delineation
b) runoff potential
c)calculate discharge at culvert
d) culvert sizing (using IDOT software)
e) watershed info

These tools are based on the National Hydrographic Dataset (NHD) web maps. NHD contains quantitative data on river network geometry, characteristics of any size drainage area (or HUCs), DEM and soil specifications for the selected basins. The NHD dataset combined with USGS's StreamStats provides all the hydraulic data needed data in gages and ungagged basins. Culvert sizing is done on the fly using the IDOT culvert sizing software.

Figure 5.11 Hydrologic analysis in the platform.

Sediment analysis in the platform are mainly based on the RUSLE, and the SEDMOD web services. The web execution of sediment analysis shares similarities with the hydrologic analysis, as it requires watershed search as well. Sediment analysis can be used on estimating sedimentation potential on existing culvert, as well as future site location. For existing culverts, part of sediment analysis functionalities are also covered in the culvert information window, where the user can delineate sediment deposit volume on bird's eye view. The web execution of sediment analysis is demonstrated in Figure 5.12.

USER WEB INTERFACE	DESCRIPTION
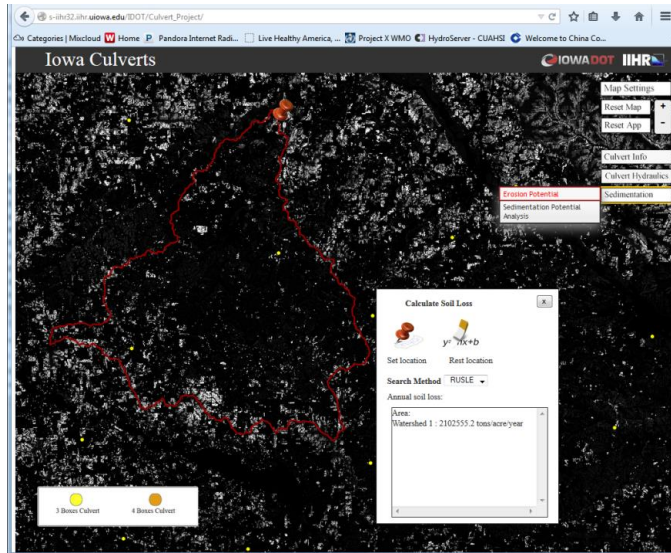
Tools:
a) erosion potential maps
b) sedimentation analysis

This tools use the RUSLE model to estimates on the fly rates of soil erosion caused by rainfall and associated overland flows over drainage areas defined by the user. RUSLE is widely used for soil erosion assessment. The factors used in the estimation of the erosion include: rainfall-runoff erosivity, soil erodibility, slope length and steepness, cover and management practices in the selected drainage area. The pre-calculated maps and the dynamic RUSLE runs enabled by the geo-portal provide excellent tools for assessing the analysis of sedimentation at any culvert site.

Figure 5.12 Sediment analysis in the platform.

5.4.3.2 Culvert monitoring

The culvert monitoring is in an initial stage of development. However, for completeness of this thesis work, the features developed so far are illustrated below. The capabilities for online and archiving the field observations developed so far are shown in Figure 5.13.

USER WEB INTERFACE	DESCRIPTION
	Tools: ***a) aerial (Bird's eye) views*** ***b) culvert geometry*** ***c) mapping of sediment deposits*** Selecting any culvert site on the map or in the culvert search feature described above, opens a new window with the aerial photograph of the culvert site (in most of the cases the 360°Bird's eye views). This feature allows observing from an oblique angle the upstream and downstream culvert vicinity including the extent of the sedimentation deposits. A special feature of the tool allows identification in real coordinates of any point or surface on the photograph allowing for sediment deposit mapping.

Figure 5.13 Culvert information window.

CHAPTER 6 CONCLUSION

The Decision Support Systems developed through the present effort demonstrate their potential to directly improve the efficiency and sustainability of the decision-making through several means. The main merits of these systems are highlighted below. Firstly, the developed geo-platforms bring together data from a variety of disciplines (infrastructure management, hydrology, hydraulics) that can be easily processed to fill gaps in information and knowledge and facilitate the translation of science in action with the participation of both scientists and practitioners. Decision-makers in water resources spend a significant amount of time not only with searching the useful data on multiple sources but also with basic information technology tasks (e.g. file conversion, web queries, software packages, etc.) and data conversion tasks (e.g. unit manipulations, spatial and temporal integration and interpolation, etc.). The developed platform demonstrates that it is possible to garner a set of hydrologic datasets classes from local and remote data sources for a variety of data formats, and to perform basic conversions and processing of hydrologic data in space and time. These systems can store both available data and new data as soon as it is produced in an automated manner without human intervention.

Secondly, we demonstrate how the Hydroinformatics products can improve the operational science needed for efficient and effective decision making. The information services provided by these systems allow the establishment of an iterative dialogue between the information users and producers (i.e.,design and field engineers) through an open and transparent cyber platform. The availability of data in one centralized place (even if virtual and geo-graphically distributed) enables timely production of information

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based on the synthesis, and interpretation of data from various domains and disciplines. Furthermore, these systems enable wide-access to data and information represented in a format customized for various user categories (including the general public). They facilitate efficient and timely stakeholder engagement through traditional forms (joining local watershed groups, attending training courses or public meetings) as well as through more contemporary technologies (web collaboratory, mobile devices, and online social networking tools). Collectively, these forms of involvement inject local (site) knowledge into the decision-making process.

The successful development of the workflows presented in this thesis is based on an extensive number of components developed by the global Hydroinformatics community. The software package created by this community project removes the burden of learning and interpreting diverse file formats from the data end user and then assembling them for further use. The level of technical difficulty and the amount of effort required to develop the customized workflows from scratch is not within the capabilities and resources typically available to local investigators. Nevertheless, the experience of the Iowa research group illustrates that the training materials written by the developers provide sufficient instruction to guide a user with little computer skills for implementing basic workflows for visualization and data downloading. However, customized workflows require computer proficiency and a considerable amount of effort.

The prototype implementations described in the paper illustrate that the translation of the theoretical concepts regarding integrative management approaches to practical application is achievable using community-developed products. Given the uniform and

scalable nature of the Hydroinformatics components assembled through this effort, the

workflows presented herein are transferable to other users and other watersheds.

Furthermore, these implementations point toward new, and unprecedented perspectives

on the stresses that currently threated watershed resources and comprehensive approaches

to educate and engage decision-makers and relevant stakeholders. These end-to-end

engineering systems are poised to create a new paradigm for watershed science and

management, enabling interdisciplinary teams to collaboratively understand and manage

complex watershed issues to achieve long-term sustainability.

CHAPTER 7 FURTHER DEVELOPMENTS

The prototype platform is currently operational and running on the IIHR server. Many futures and functions are still being developed on the prototype platform, some of the existing features need to be optimized in terms of performance and runtime. Since the platform is developed for the Iowa DOT, the final production-level platform will be delivered to the Iowa DOT server. As Iowa DOT has a distinct regulations and rules for web development, the final platform for Iowa DOT will have to be compatible with Iowa DOT technologies and licenses, while preserving the functions of the current prototype. Therefore, developmental plan for this project is split into two tracks: The IIHR track and the Iowa DOT track. Table 3.4 summaries the current platform components and features to be developed. Table 3.5 entails details of the two developmental tracks for future development.

Table 7.1 Existing tools and tools to be developed

Existing tools	Future implementation
Web Map and map services • Leaflet • Bing Map API	SIIMS Database connection and integration
Hydrologic modes to determine peak discharge	River-width estimation
Sediment estimation using RUSLE	IA Culvert design software integration
Spatial database (PostGIS based)	Iowa DOT web services and resources

Base map and WMS of RUSLE and runoff potential	

Table 7.2 Comparison between two tracks

Component or feature	IIHR Track (prototype)	Iowa DOT Track (Production level)
Map engine	Leaflet and Bing Map API	ArcGIS JavaScript API
	Bing Map API has both consumer license and business license. Consumer license for educational use on public or Non-Profit website is free. The IIHR is an educational and Non-Profit research institute, which qualifies for free use. Iowa DOT wants to host the platform on private networks, which requires buying costly business license. This will incur unnecessary cost for the DOT, hence the Bing Map application is abandoned for the Iowa DOT track.	
Spatial database	PostGIS and ArcSDE	Oracle Spatial and ArcSDE
	PostGIS is an open-source spatial database, and it is free. Governmental agencies has strict rules regarding open-source technologies. To avoid further complexities, PostGIS is replaced with Oracle Spatial	

	database, which is adopted by the Iowa DOT as default database.	
Application server	ArcGIS server and GeoServer	ArcGIS server only
Web service scripting	Python and QGIS tools	Python and ArcPy
	The Iowa DOT is concerned on open-source technologies, like GeoServer and QGIS. While the department does have full license of the Arc products. Consequently, all open-source GIS technologies in the prototypes are switched into the Arc product.	

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Table A.1 List of engineers who received the sediment server request

IDOT Garage

Eng. Dept	Name	Area (Garage)	County
IDOT	Aarm m. Dahl	Greenfield Garage	Adair County
IDOT	Dave Lundgnist	Corning-Adams	Adams County
IDOT	foglesong	centerville	Appanoose and Wayne Counties
IDOT	Gene Schmelzer	Urbana / Newhall	Benton County
IDOT	Jeff Vander Zwaag	Boone	Boone County
IDOT	Phil Heinlen	Carroll , Rockwell, Sac City	Carroll and Sac Counties
IDOT	Dan Meyer, Trent Sorgenfrey	Tipton	Cedar County
IDOT	Pete Audoua	Mason City	Gerro Gordo County
IDOT	Matt McCann	Osceola	Clarke County
IDOT	Roger Burns	N/A	Clayton County
IDOT	Dick Banowetz	DeWitt	Clinton County
IDOT	Nick Paardekooper	DeSoto	Dallas County
IDOT	Smith	Leon	Decatur and Wayne Counties
IDOT	Bob Porter	West Burlington	Donnellson County
IDOT	Roger Vigdal	Spirit Lake	Dickinson County
IDOT	Jim Hanson	Williamsburg	Iowa County
IDOT	Terry Zimmerman	Coralville	Johnson County
IDOT	Brad Steinhart	Sigourney	Keokuk County
IDOT	Crozier	Chariton	Lucas and Wayne Counties
IDOT	Mike Kingery	Knoxville	Marion County
IDOT	Mark Stephens	Marshalltown	Marshall County
IDOT	Norman (Sam) Thomas	N/A	Mills County
IDOT	Ron Gleiser	Dnawn	Monona County
IDOT	Jay Ridlen	Albia & Ottumwa & Bloomfield	Monroe, Wapello, Davis, VanBuren, Appanoose
IDOT	Bobbie White	Carlisle	Polk County
IDOT	Eric Lack	Des Moines North shop	Polk County
IDOT	Tobey Clyde	Dnuenpnvt	Scott County
IDOT	Ron Lauer	Creston	Union County

	Scott Wilson /		
IDOT	Todd Netley	Martensdale	Warren County
IDOT	John Lyle	N/A	Washington County
IDOT	Todd Cogdill	Sioux city Hamilton & Leeds Garag	Woodbury County
IDOT	Pete Andore	Hanlontown	Worth County
IDOT	Brad Steinhart	Oskaloosa	Mahaska and Marion County
IDOT GOA	Gary Pickett	Newton	Jasper County
IDOT GOA	Russ Frisch	Allison & Waverly	Butler County & Bremer County
IDOT GOA	David Brisbois	Avoca	Pottawattamie County
IDOT GOA	Tony Arrick	Council Bluffs	Pottawattamie
IDOT GOA	Dixie Nelson	Denison & Grove &	Crawford County & Ida County & Woodbury County
IDOT GOA	Rick Johnson	Sidney	Fremont

County

Eng. Dept	Name	Area (County Seat)	County
Cedar County	Rob Fangmana	N/A	Cedar County
Black Hawk County	Ryan Brennan	N/A	Black Hawk County
O'brien County	Tom Snyder	N/A	O'brien County
Montgomery County	Brad Skinner	N/A	Montgomery County
Emmet County	Alex Ewen	N/A	Emmet County
Crawford County	Paul Assman	N/A	Crawford County
Washington County	Jacob Thorius	N/A	Washington
Linn County	Steve Gannon	N/A	Linn County
Plymouth County	Thomas Rohe	N/A	Plymouth County
Grundy County	G Mauer	N/A	Grundy County
Winneshiek County	Lee Bjerke	N/A	Winneshiek County
Buchanan County	Brian Keierleber	N/A	Buchanan County
Lee County	Ernie Steffensmeier	N/A	Lee County

Pocahontas County	Jack Moellering	N/A	Pocahontas County

| Eng. Dept	Name	County
Cedar County	Rob Fangmana	Cedar County
Black Hawk County	Ryan Brennan	Black Hawk County
O'brien County	Tom Snyder	O'brien County
Montgomery County	Brad Skinner	Montgomery County
Emmet County	Alex Ewen	Emmet County
Crawford County	Paul Assman	Crawford County
Washington County	Jacob Thorius	Washington
Linn County	Steve Gannon	Linn County
Plymouth County	Thomas Rohe	Plymouth County
Grundy County	G Mauer	Grundy County
Winneshiek County	Lee Bjerke	Winneshiek County
Buchanan County	Brian Keierleber	Buchanan County
Lee County	Ernie Steffensmeier	Lee County
Pocahontas County	Jack Moellering	Pocahontas County
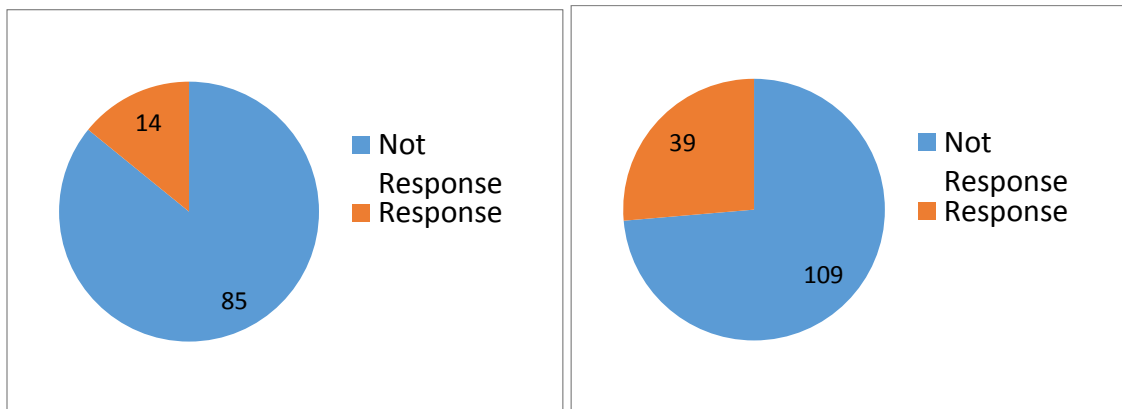
Figure A.1 Survey respondent in 2009 (left) and 2013 (right)

APPENDIX B.   CULVERT DESIGN

Table B.1 Constant for inlet control design equations (Mays, 2011)

Chart[a] no.	Shape and material	Nomograph scale	Inlet edge description	Equation form[b]	Unsubmerged		Submerged	
					K	M	C	Y
1	Circular concrete	1	Square edge w/headwall	1	0.0098	2.0	0.0398	0.67
		2	Groove and w/headwall		.0078	2.0	.0292	.74
		3	Groove and projecting		.0045	2.0	.0317	.69
2	Circular CMP	1	Headwall	1	.0078	2.0	.0379	.69
		2	Mitered to slope		.0210	1.33	.0463	.75
		3	Projecting		.0340	1.50	.0553	.54
3	Circular	A	Beveled ring, 45° bevels	1	.0018	2.50	.0300	.74
		B	Beveled ring, 33.7° bevels		.0018	2.50	.0243	.83
8	Rectangular box	1	30° to 75° wingwall flares	1	.026	1.0	.0385	.81
		2	90° and 15° wingwall flares		.061	0.75	.0400	.80
		3	0° wingwall flares		.061	0.75	.0423	.82
9	Rectangular box	1	45° wingwall flare $d = 0.0430$	2	.510	.667	.0309	.80
		2	18° to 33.7° wingwall flare $d = 0.0830$		.486	.667	.0249	.83
10	Rectangular box	1	90° headwall w/3/4" chamfers	2	.515	.667	.0375	.79
		2	90° headwall w/45° bevels		.495	.667	.0314	.82
		3	90° headwall w/33.7° bevels		.486	.667	.0252	.865
11	Rectangular box	1	3/4" chamfers; 45° skewed headwall	2	.522	.667	.0402	.73
		2	3/4" chamfers; 30° skewed headwall		.533	.667	.0425	.705
		3	3/4" chamfers; 15° skewed headwall		.545	.667	.04505	.68
			45° bevels; 10°–45° skewed headwall		.498	.667	.0327	.75
12	Rectangular box 3/4" chamfers	1	45° non-offset wing wall flares	2	.497	.667	.0339	.805
		2	18.4° non-offset wingwall flares		.493	.667	.0361	.806
		3	18.4° non-offset wingwall flares 30° skewed barrel		.495	.667	.0386	.71
13	Rectangular box Top bevels	1	45° wingwall flares — offset	2	.495	.667	.0302	.835
		2	33.7° wingwall flares — offset		.493	.667	.0252	.881
		3	18.4° wingwall flares — offset		.497	.667	.0227	.887
16–19	CM boxes	1	90° headwall	1	.0083	2.0	.0379	.69
		2	Thick wall projecting		.0145	1.75	.0419	.64
		3	Thin wall projecting		.0340	1.5	.0496	.57
29	Horizontal ellipse concrete	1	Square edge with headwall	1	.0100	2.0	.0398	.67
		2	Groove end with headwall		.0018	2.5	.0292	.74
		3	Groove end projecting		.0045	2.0	.0317	.69
30	Vertical ellipse concrete	1	Square edge with headwall	1	.0100	2.0	.0398	.67
		2	Groove end with headwall		.0018	2.5	.0292	.74
		3	Groove end projecting		.0095	2.0	.0317	.69
34	Pipe arch 18" corner radius CM	1	90° headwall	1	.0083	2.0	.0379	.69
		2	Mitered to slope		.0300	1.0	.0463	.75
		3	Projecting		.0340	1.5	.0496	.57
35	Pipe arch 18" corner radius CM	1	Projecting	1	.0296	1.5	.0487	.55
		2	No. bevels		.0087	2.0	.0361	.66
		3	33.7° bevels		.0030	2.0	.0264	.75
36	Pipe arch 31" corner radius CM	1	Projecting	1	.0296	1.5	.0487	.55
			No. bevels		.0087	2.0	.0361	.66
			33.7° bevels		.0030	2.0	.0264	.75

(Table B.1 continues)

Chart[a] no.	Shape and material	Nomograph scale	Inlet edge description	Unsubmerged Equation form[b]	K	M	Submerged C	Y
40–42	Arch CM	1	90° headwall	1	.0083	2.0	.0379	.69
		2	Mitered to slope		.0300	1.0	.0463	.75
		3	Thin wall projecting		.0340	1.5	.0496	.57
55	Circular	1	Smooth tapered inlet throat	2	.534	.555	.0196	.89
		2	Rough tapered inlet throat		.519	.64	.0289	.90
56	Elliptical Inlet face	1	Tapered inlet—beveled edges	2	.536	.622	.0368	.83
		2	Tapered inlet—square edges		.5035	.719	.0478	.80
		3	Tapered inlet—thin edge projecting		.547	.80	.0598	.75
57	Rectangular	1	Tapered inlet throat	2	.475	.667	.0179	.97
58	Rectangular concrete	1	Side tapered—less favorable edges	2	.56	.667	.0466	.85
		2	Side tapered—more favorable edges		.56	.667	.3978	.87
59	Rectangular concrete	1	Slope tapered—less favorable edges	2	.50	.667	.0466	.65
			Slope tapered—more favorable edges		.50	.667	.0378	.71

[a] Chart number in Normann et al. (1985)
[b] Form 1 is equation (16.2.2)
Form 2 is equation (16.2.3)

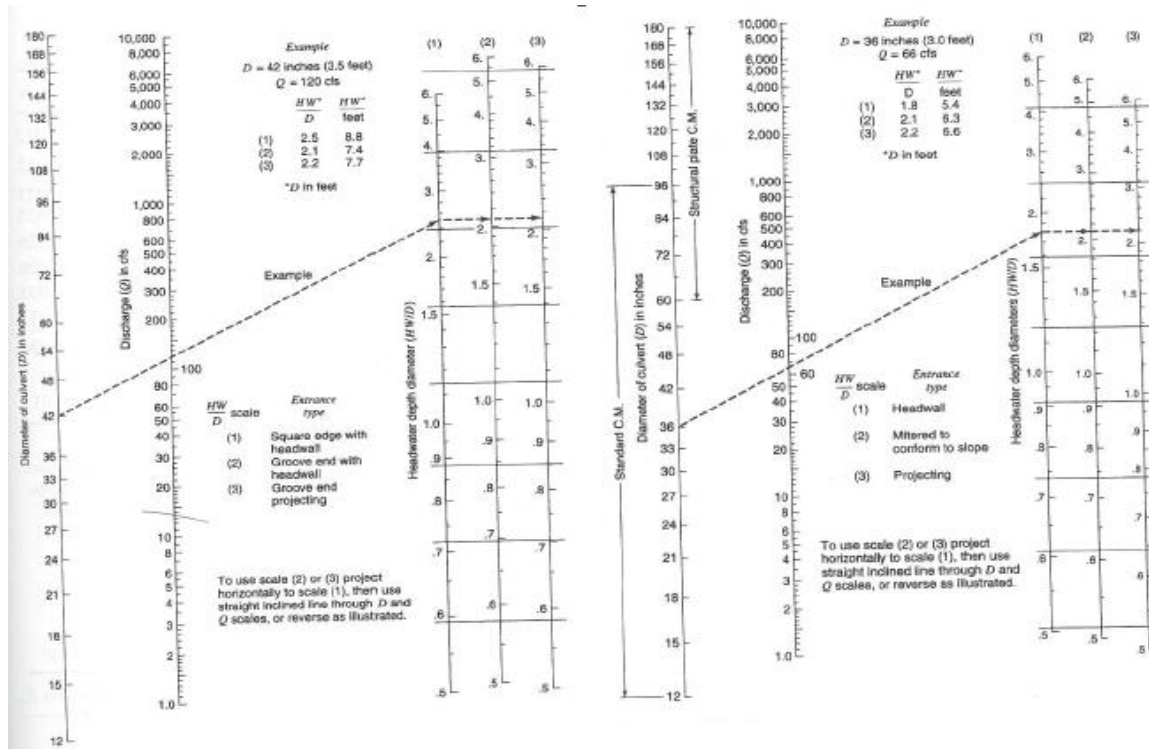*Source:* Normann et al. (1985).

Figure B.1 Headwater depth for concrete (left) and CM (right) pipe culvert with inlet control (Normann, J. M., Houghtalen, R. J., and Johnson, W. J., 1985)

APPENDIX C.   FLOOD FREQUENCY EQUATION

Selected Information for the USGS Lara (1987) (IowaDOT, Iowa Bridge Backwater Software Users Manual, 2010)

The information in this appendix is taken from Method for Estimating the Magnitude and Frequency of Floods at Ungaged Sites on Unregulated Rural Streams in Iowa, U.S. Geological Survey, Water- Resources Investigation Report 87-4132, In cooperation with the Iowa Department of Transportation, Highway Division, Highway Research Board, Iowa City, Iowa, by Oscar G. Lara, 1987. You are encouraged to reference the actual report for more detailed information.

Regional flood-frequency equations (A: the drainage area in square miles)

Table C.1 List of equations in the USGS Lara Method

Hydrologic region	Standard Error
1 (19 stations)	(percent)
Equation	
62 .02 A 211Q	61
60 .05 A 502Q	37
60 .010 A 757Q	28
57 .025 A 140,1Q	24
60 .050 A 500,1Q	21
60 .0100 A 880,1Q	24

USGS Regression Equations – Eash 2001 (IowaDOT, Iowa Bridge Backwater Software Users Manual, 2010)

The information in this appendix is taken from, Techniques For Estimating Flood-Frequency Discharges for Streams in Iowa, U.S. Geological Survey, Water-Resources Investigations Report 00-4233, D. Eash, 2001. You can download a copy of the report, in PDS format, over the Internet from the web site:

http://ia.water.usgs.gov/reports/WRIR_00-4233.html.

SEE. Standard error of estimate; SEP, average standard error of prediction; EYR, equivalent years of record; Q. peak discharge, in cubic feet per second for recurrence interval, in years, indicated as subscript; DA, drainage area, in square miles; MCS, main-channel slope, in feet per mile; DML, Des Moines Lobe, ratio of basin area within Des Moines Lobe landform region to total area of basin.

Table C.2 List of equations in the USGS Eash Method

Flood-frequency equations for Region 1, one-variable equations Estimation equation	SEE (percent)	SEP (percent)	EYR (years)
$Q_2=33.8DA^{0.656}$	35.3	41.4	4.2

Q5=60.8DA0.65 8	32.0	39.4	5.8
Q10=80.1DA0.6 60	31.1	39.0	7.7
Q25=105DA0.66 3	31.3	39.2	10.1
Q50=123DA0.66 6	32.0	39.8	11.5
Q100=141DA0.6 69	33.1	40.5	12.5
Q200=159DA0.6 72	34.5	41.4	13.2
Q500=183DA0.6 76	36.5	42.7	13.7