Development of a Decision-Support Tool for Bridge Infrastructure Adaptation in Response to Climate-Induced Flood Risk

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To my wife, Julie, and my daughters, Emma and Sarah

and

To my parents, Carol and Carl Banks, my stepmother Virginia Banks

and my Grandmother Mary Evelyn Parsons.

You have all taught me so much.

Dad and Granny, although you weren't able to

finish this with me I know you are proud.

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CHAPTER 1

Introduction

In 1979, Senator Jacob Javits (R-New York) introduced Senate Bill 104. The legislation, whose short title was “The Community Conservation Act”, attempted to establish a bank from which loans to improve and protect deteriorating urban and rural infrastructure could be obtained. Had the bill not died in committee, it would have established and funded a non-governmental bank for the purpose of providing money to United States communities for maintaining and improving deteriorating infrastructure including roads, bridges and sewers (Senate Bill 1049, 1979). Although the bill was never sent to the Senate floor for action, the problem of deteriorating infrastructure remained. The American Society of Civil Engineers’ (ASCE) “2013 Report Card for America’s Infrastructure” gives the US infrastructure a grade of “below average” or “D”. This grade is a composite based on the individual grades of the various types of infrastructure (ASCE 2013).

One of the infrastructure components assessed by ASCE is bridges. Bridges are used to span topographical and human-made features to facilitate travel on roads and railways. When a bridge fails, the immediate consequences can be disastrous. A somewhat recent example was the collapse of the I-35W bridge spanning the Mississippi River in Minneapolis, Minnesota, in August 2007. This bridge failure resulted in 13 fatalities and injuries to another 145 individuals. In addition to the tremendous tragedy from loss of life, the bridge was closed for 14 months while repairs were completed (NTSB 2008, MPR 2008). When bridges fail, in addition to the immediate and direct costs relative to loss of life and rebuilding, there are indirect costs from increased travel and transport time due to detours (Stein 2006).

Adding immediacy and complexity to the problem of bridge degradation is the phenomenon of climate change. Current climate models predict an increase in frequency and severity of precipitation events along with a concomitant increase in floods (IPCC 2007). Along with increased flooding comes the potential for increased bridge damage due to scour. Fortunately, bridges can be armored for scour and adapted to the changing climate. Given these factors, having a tool for rapidly assessing bridges under future flood scenarios and prioritizing them for adaptation is prudent especially under today's limited availability of funds for such activities.

To ensure clarity, the terms "adaptation" and "mitigation" require clarification. In this research, "adaptation" is defined as actions taken in response to climate-change induced events to minimize their impact while "mitigation" is defined as actions taken to reduce emissions that result in climate change. In short, "adaptation" is employed to deal with the consequences of climate change while "mitigation" reduces the cause of climate change. Both approaches are needed since IPCC models indicate continued emissions will only increase climate change which will in turn increase the impacts to infrastructure (IPCC, 2007). The objective of the research presented in this dissertation is to present a methodology for use by municipalities in prioritizing bridges for adaptation measures.

The dissertation is organized as three separate but interrelated manuscripts. In using this approach, basic background information regarding climate change and the need for adaptation planning is present in all three. Where possible, redundancy of this material between the three manuscripts has been minimized.

The first manuscript (Chapter 2) is a review and assessment of available tools for flood and damage modeling. The review performed for this manuscript resulted in identifying the United States' Federal Emergency Management Agency's HAZUS-MH (also known as Hazus) program as a potential tool for flood and damage modeling. The second manuscript (Chapter 3) provides details on limitations identified in Hazus when using it at sub-county levels. The final manuscript (Chapter 4) proposes a methodology for assessing and prioritizing bridges. As part of Chapter 4, the methodology is calibrated using a recent flood event, the May 2010 Davidson County (Nashville), Tennessee floods. Then, the methodology is applied to selected bridges in Pulaski County (Little Rock), Arkansas to demonstrate how a municipality might use it for prioritizing multiple bridges for adaptation planning. Chapter 5 provides a summary of research contributions from this work as well as identifying possible areas for additional research.

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CHAPTER 2

Adaptation planning for floods: A review of available tools

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2.1 INTRODUCTION

With the 1990 publication of the first assessment report by the United Nations' Intergovernmental Panel on Climate Change (IPCC), there has been increasing focus on climate change and its impacts. Of the many hazards associated with climate change, flooding presents some of the most frequent and severe consequences. Worldwide in the period from 1900 to 2013, flooding was the most frequently occurring natural disaster impacting more people than any other natural disaster. For the same period, flooding in the United States was second only to storms in impacts to people and cost of damage (EM-DAT 2013). Exacerbating this situation is that flooding can occur at any time of year and in any part of the United States (Mileti 1999).

It is becoming increasingly apparent that climate change mitigation efforts, such as reduction of greenhouse gases, will not be sufficient to stop or reverse its increasing impact on the environment (IPCC 2007). Consequently, adaptation is becoming a more prominent risk reduction strategy, making the development of effective tools to assist in adaptation planning a prudent course of action. Examples of adaptation strategies include strengthening existing infrastructure or scheduling more frequent maintenance to alleviate increased wear and tear caused by extreme weather, such as excessive heat or flooding.

Tools that model flood inundation and perform damage assessment have historically been directed at planning for disaster response or developing Flood Insurance Rate Maps. (FEMA 2008; Mudaliar 2011; FEMA 2012; Flo-2D Software 2012). This paper presents a review of currently available flood damage assessment tools and their ability to be repurposed for adaptation planning.

2.2 MODEL SELECTION CRITERIA

The review evaluated currently available flood modeling tools with consideration of their ability to perform flood modeling and damage assessment estimation. Additional consideration was given to the ease with which a municipality or other organization might both obtain and utilize such tools (Chau 1995). Criteria employed for evaluation included:

- Extent and resolution of area modeled
- Ability to perform flood hazard analysis at least at a two-dimensional (2D) level
- Presence of infrastructure damage assessment and loss estimation function
- Ability to perform or support spatial data viewing capabilities, such as geographic information systems (GIS)
- Affordability
- Technical skills required for use
- Training required/available
- Technical support
- Hardware requirements

The latter four factors are considered "organizational criteria" in the ensuing discussion and represent those that are not critical for pure damage analysis, but may become limiting in a municipality's ability to utilize the tool for adaptation planning. We next discuss each of these criteria.

2.2.1 Extent and Resolution of Area Modeled

Tools capable of covering a large area with sufficient stream detail are critical to ensure sufficient flood extent and impact definition. A favorable selection criterion is a tool that can perform estimates over a wide range of areas with the potential for high resolution.

2.2.2 Ability to Perform Flood Hazard Analysis

Flood hazard analysis includes the ability to model parameters defining a flood event with an ability to view or evaluate the potential for flooding, its extent (inundation area), and flow characteristics (Scawthorn, Blais et al. 2006). An acceptable tool should be capable of performing, at a minimum, 2D flood analysis to show both the depth and extent of a flood event.

2.2.3 Presence of Damage Estimation Function[*]

Once the flood boundaries are defined, the capability to estimate damage is essential. Damage estimation can be performed as a core function of the software or externally via export to another product. Tools that explicitly perform damage estimation, particularly those that assess damage categories (e.g., damage by building type and inundation level) are considered desirable under this criterion.

[*] Damage includes all consequences associated with a flood event such as loss of life, direct physical loss, and indirect and direct financial impact.

2.2.4 Ability to Perform or Support Spatial Data Viewing Capabilities

Research has shown that public forums with rich media use improve message clarity (Baker, Addams et al. 2005). Spatial data viewing, utilizing geographic information systems (GIS) technology, provides for a means for effective communication. Such visualization can display specific areas of flood impact and resulting damage.

2.2.5 Affordability*

Price may be a limiting factor in software selection. A favorable attribute for this criterion is a tool (inclusive of any ancillary software required) whose acquisition cost is affordable. With municipalities in mind as potential users, a purchase cost of $10,000 is considered a reasonable affordability threshold.

2.2.6 Organizational Criteria

Tools that are easy to use, sufficiently detailed to produce meaningful results and can be manipulated by someone familiar with common business software are preferred, given the wide variety of personnel who may use the product. The criterion of short duration, domestically available training minimizes personnel time away from work and ensures no unforeseen embedded cost in the product. Since problems often arise in software use, having an accessible technical support base, in any form, works to minimize disruptions. Finally, software that runs on commonly available platforms (e.g., the Intel Core 2 processor family or their AMD equivalents) allows the system to run without any special hardware or additional expense.

2.3 TOOL EVALUATION

The following presents a review of commercially available flood tools and an assessment of their ability to meet the aforementioned criteria considered desirable in supporting adaptation planning.

2.3.1 Flo-2D

Flo-2D is a software program capable of performing one-dimensional (1D) and 2D hydrodynamic analysis (simulated channel flow, unconfined overland flow and street flow over complex topography). The two-dimensional flood modeling is based on user input and various topographic features. Flo-2D does not have a size limit to the area modeled and can model grid elements as small as 100 square feet (Flo-2D, 2012). Flood damage assessment may be performed using depth-damage functionality inherent to the program, although it requires the user to develop cost tables and the polygon association for export to a GIS program (O'Brien 2009). Damage estimation is performed using GIS data comparison functions to estimate amount of damage within a given polygon based on flood extent/depth. These damage estimates are linked with the polygons' associated cost data and summed for total cost. The primary shortcoming of this approach is that the definition of data to include in cost estimates is at the discretion of the user with no standard for impact analysis. The program requires no adjunct software for flood modeling and uses extensions included with the software to allow GIS export and mapping functionality (Flo-2D 2012). The program is priced at $3,495 for a single user license. Additional capabilities for hydrodynamic modeling of riverine flooding exist through RiverFlo-2D, which can be purchased for $3,950. The developer offers on-line training at a cost ranging from $50 and $200 depending on the course taken and whether technical support is through telephone or email communication.

2.3.2 TUFLOW

TUFLOW flood modeling software may be used as a standalone application or can be integrated into other flood model software. The software consists of two numerical engines: 1) TUFLOW which does 1D/2D modeling and 2) TUFLOW FV which does three-dimensional (3D) modeling. To use TUFLOW, a GIS program, text editor, spreadsheet program and a 3D surface modeling program, such as Surface-Modeling Software (SMS) or waterRIDE is required (Aquaveo 2013; WorleyParsons 2013). As a standalone, TUFLOW uses GIS software to create data files such as 2D grid locations, topography and digital terrain models, as well as viewing model output. If the GIS cannot perform the function, separate three-dimensional surface modeling software is used to create the digital terrain models. A text editor is used to create items such as simulation control files, while the spreadsheet software is used for boundary time-series data (BMT Group LTD 2012). Pricing for TUFLOW begins at $6,000 for a single license (BMT Group LTD 2012). Data inputs for damage assessment require the user to develop depth-damage relationships and link these through a tool such as GIS with the flood data from TUFLOW. Software training is available at a cost of roughly $500 per class (BMT Group LTD 2012). TUFLOW offers technical support both through a wiki site as well as through contracted services.

2.3.3 Surface Modeling Software (SMS)

SMS (Aquaveo 2013) is a suite of software packages, comprised of SMS-TUFLOW, SMS-SRH2D and SMS-ADCIRC, that is available for a variety of applications. SMS-TUFLOW uses a graphical-user interface (GUI) with TUFLOW as the engine for modeling complex surface flows.

SMS-SRH2D is a version with higher capability for modeling stream flows and which incorporates greater ability to include in-stream structures and water returns (Aquaveo 2011). SMS-ADCIRC, is used for modeling flows in and around oceans. Of these options, SMS-TUFLOW is the most relevant product relative to the review criteria (Aquaveo 2011). The data from SMS-TUFLOW can be used by the program itself or output to GIS software. SMS-TUFLOW models hydraulic data but does not perform damage assessment for flood scenarios. An advantage of the software is its ability to model very large areas for flooding or inundation (Ballard 2012). SMS-TUFLOW costs approximately $9,000 for a single user license (Aquaveo 2011). The developer offers training at a cost of approximately $1,400 for a one-week course on 1D/2D modeling using the product.

2.3.4 XP-SWMM

XP-SWMM can be used to model a variety of hydraulic scenarios, including floodplain management (XP Solutions Inc. 2011). The software can perform 1D and 2D analysis, but requires an add-on, XP2D, to perform flood inundation analysis. As with SMS-TUFLOW, the XP2D module uses the TUFLOW engine. Although a GIS-like interface is available with the product, the data can also be integrated with external GIS programs for different modeling area sizes (XP Solutions Inc. 2012). Software training is available beginning at $1,300 for a two-day class or $350 for an online training event. A single user license, which includes XP-SWMM and up to 10,000 cells of XP-2D, is available for $3,200 (XP Solutions Inc. 2012). The tool is priced based on number of cells modeled. If a finer resolution cell is used (e.g., 100 feet by 100 feet), the area modeled will be smaller than a larger cell size (Bouchot 2012). Given this condition, the user must have some idea as to what resolution will be required as well as the size of area to be modeled.

Failing to appropriately size the modeling space may lead to results with insufficient resolution or unnecessary expenditure. As with SMS, the software has no inherent damage assessment function and would rely on integration with a secondary program to perform damage analysis (XP Solutions Inc. 2012).

2.3.5 MIKE Flood

MIKE Flood also performs 1D and 2D flood analysis. The program utilizes aspects of three software packages: 1) MIKE 11 for river modeling, 2) MIKE URBAN for urban flows, and 3) MIKE 21 for 2D flow modeling (DHI 2011). The program has a toolbox for flood damage assessment that integrates with ArcGIS which can calculate damage per unit area in any specified currency. However, the user must supply specific depth-damage estimates for various land uses (Landrein 2011). Training is available for both urban and river applications of MIKE Flood, with each course costing $1,110 (DHI 2012). MIKE Flood license fees begin at $18,500 (Johnston 2012).

2.3.6 waterRIDE

waterRIDE offers a GIS interface as well as capability to export to other GIS platforms. It performs both 1D and 2D flood hazard analysis using TUFLOW as well as having the ability to use multiple other models (e.g., HEC-RAS, MIKE11, MIKE21, XP-SWMM). The software can use fine scale digital terrain models for the extent and resolution of area modeled (Worley-Parsons 2012). waterRIDE can also perform damage assessments by using depth-damage relationships generated from regional experience, such as insurance claims and damage research. The program extrapolates the flood model depths and extents to estimate the amount of damage to a given structure type (e.g., concrete slab construction). Infrastructure components can be modeled if the necessary data is included in the depth-damage development (Lam 2012). As with MIKE Flood, waterRIDE offers a tool with integrated flood modeling and damage estimation. waterRIDE licensing fees begin at $15,000 (Copenhaver 2012).

2.3.7 ISIS

ISIS is a group of flood modeling tools comprised of ISIS Professional, ISIS 2D and the ISIS-FAST program. ISIS Professional performs 1D modeling of flows found in settings such as open channels or estuaries. The ISIS 2D product, as the name suggests, performs two-dimensional modeling of water flow. It can be used for water management plans and flood modeling. ISIS Fast is designed to rapidly assess a variety of flooding scenarios, including tidal surge and levy breaching. Each of these products has its own GIS interface or output can be directed to other GIS applications. ISIS also offers a variety of add-ons to perform functions such as increasing the number of nodes for flooding, mapping output from the tools, and linking ISIS with TUFLOW. ISIS is supported by both a free, online user community as well as a fee-based support system (Halcrow Group 2012). Property loss estimates and infrastructure damage are based on depth-damage relationships. As of December 2011, ISIS contains only depth-damage information for the United Kingdom, so users in other locations would be required to develop data for their native area (Adams 2011). Although there is a no-cost limited version of ISIS available, the full-featured program begins with a base price of $7,680 per year for a single user license. Additionally, there is an annual support and maintenance fee starting at $1,350. Classroom training is available beginning at $400; however, course offerings are hosted in Great Britain (Halcrow Group 2012).

2.3.8 HEC-RAS

HEC-RAS is the United States Army Corps of Engineers (USACE) Hydrologic Engineering Centers' River Analysis System. It is free software that performs 1D hydrologic modeling for natural and constructed channels. No damage assessment function is provided, but flood data can be output to ArcGIS through the use of an ArcGIS shapefile or HEC-GeoRAS. Although HEC-RAS contains its own viewer for flood visualization, the HEC-GeoRAS program provides a more robust interface with ArcGIS (USACE 2012), providing a tool kit for using ArcGIS to create input files for HEC-RAS analysis as well as to use HEC-RAS output for presentation in ArcGIS (USACE 2009). Neither through HEC-RAS itself nor through the HEC-GeoRAS tool does the program provide damage analysis, however. For non-governmental users, training and support for the tool is solely the responsibility of the user. Should support in using the software be required, USACE recommends performing an online search for vendors offering this service (USACE 2012).

2.3.9 HEC-FIA

Also available from USACE is the Hydrologic Engineering Center's Flood Impact Analysis (HEC-FIA) tool. HEC-FIA differs from HEC-RAS in that it utilizes data relative to structures, crops and people to perform flood damage analysis. Flood data is provided to the system through a watershed tool, which allows the user to either create a watershed and associated attributes or import them from other HEC software (USACE 2012). Once created, an impact area is identified by the user. HEC-FIA allows the user to either develop and import their own data for structural inventories (e.g., buildings, vehicles) or import the structure data from FEMA's Hazus database for buildings. Once imported, HEC-FIA users can make both global and specific modifications to certain structural attributes such as foundation height, occupancy, structure value and content parameters (USACE 2012). Similarly, HEC-FIA allows agricultural data to be imported from Hazus with modifications for crop loss functions (USACE 2012). Of note is the loss methodology applied by HEC-FIA to structures and agriculture. For structure damage, HEC-FIA looks only at flood height to predict damage to structures. Flood depth, time of year flooding occurs, duration of inundation and drying time are used in determining agricultural damage. Additionally, the loss of life function in HEC-FIA is rather detailed. The program uses a "warning diffusion" algorithm to predict how rapidly the public is made aware of a problem based on the warning system used. Coupled with this is a mobilization function to determine how quickly personnel can evacuate to a safe zone (USACE 2012). These loss functions allow for very specific and detailed analysis of flood impacts within an area. The software runs on commonly available systems and training courses are offered by USACE at a cost of $2,350 per course (USACE 2012). Software technical support is up to the user since HEC does not list vendors for support nor is it offered from USACE (USACE 2012). However, training workshops are sometimes offered by professional associations such as the American Society of Civil Engineers.

2.3.10 ArcGIS

ESRI's ArcGIS can perform hydrologic analysis through its Spatial Analyst extension, which includes a 2D advection flood model. Hydrogeological data is used to generate groundwater flow fields which then may be used to map at-risk parcels (ESRI Inc. 2012). ArcGIS does not possess inherent damage estimation functionality and would require the user to develop and import this information for impacted areas. Additionally, the user would be required to develop damage relationships, such as depth-damage curves, to determine impact in a given area. The software has a graphical user interface and runs on commonly available PC hardware (ESRI Inc. 2012). The basic ArcGIS program begins at $1,500 with the Spatial Analyst extension costing an additional $2,500 (ESRI Inc. 2012). Training is available from ESRI for $1,000 for a two day course on hydrologic analysis using ArcGIS (ESRI Inc. 2012).

2.3.11 Hazus-MH

Developed by the Federal Emergency Management Agency (FEMA), Hazus-MH tool performs flood hazard and flood damage analysis along with damage analysis for hurricanes and earthquakes (FEMA 2012). Although Hazus-MH itself is free, it does require ESRI's ArcGIS and Spatial Analyst software which, as previously mentioned, costs $1,500 and $2,500, respectively (ESRI Inc. 2012). Packaged within the Hazus-MH software is a 2D flood modeling tool, an inventory of land use and estimated values by U.S. census tract, data on critical infrastructure such as bridges, depth-damage curves for various occupancy and building types, and algorithms to predict both direct and indirect losses from flooding (FEMA 2009). Hazus-MH also has capabilities to utilize output from more robust flood models such as HEC-RAS for use in the damage analysis. Training is available online through ESRI as well as offered to government users through FEMA's Emergency Management Institute (EMI). Tuition for Hazus training at EMI is free but travel costs are not covered except for government personnel (EMI 2013). Approximately ten classes are offered online through ESRI for Hazus-MH at roughly $30 per course (ESRI Inc. 2012). Technical support is available through the Hazus-MH webpage and the FEMA Map Information Exchange toll-free line (FEMA 2012).

2.3.12 Summary of Tool Analysis

A summary of the characteristics of the aforementioned tools relative to the evaluation criteria for flood adaptation planning is provided in Table 1. All tools surveyed possessed similar capabilities for modeling flood extent and depth as well as hardware required to run the programs. The assessment criterion that provided the greatest differentiation between tools was the presence of a inherent damage assessment function with only four of the tools evaluated possessing this capability. Beyond having an damage assessment capability built in, the remaining categories provided only modest differentiation between the tools.

The four tools evaluated that had damage assessment capabilities included HEC-FIA, waterRIDE, MIKE-Flood and Hazus-MH. MIKE-Flood and waterRIDE were removed from further consideration due to pricing above the set $10,000 limit of the affordability criterion. HEC-FIA was further excluded due to an absence of technical support and the need for robust technical skills required for use. Of all the tools evaluated, only FEMA's Hazus-MH fulfilled all assessment criteria.

	Extent and Resolution of Area Modeled	Ability to perform flood hazard analysis at least at a 2D level	Presence of infrastructure damage assessment and loss estimation function	Ability to perform/support spatial data viewing (e.g., GIS)	Affordability	Technical skills required for use	Training required/available	Technical Support	Hardware Requirements
FLO-2D	●	●		●	●	●	●	●	●
TUFLOW	●	●			●	●	●	●	●
SMS	●	●		●	●	●	●	●	●
XP-SWMM	●	●		●	●	●	●	●	●
MIKE Flood	●	●	●	●		●	●	●	●
waterRIDE	●	●	●	●		●	●	●	●
ISIS	●	●		●	●	●		●	●
HEC-RAS	●				●	●	●	●	●
HEC-FIA	●	●	●	●	●		●		●
ArcGIS	●	●		●	●	●	●	●	●
Hazus-MH	●	●	●	●	●	●	●	●	●

Table 1: Assessment of Tools Relative to Evaluation Criteria

2.4 FINDINGS AND IMPLICATIONS

A variety of flood modeling and impact assessment tools were evaluated for potential re-purposing in flood adaptation planning. Evaluation criteria considered both technical abilities to perform flood modeling and damage assessment analysis as well as additional factors which might limit a municipality’s ability to actually utilize the tool (e.g., training, software and hardware requirements, etc.).

While a number of products are available that could be used to model floods and corresponding impacts, Hazus-MH was identified as the best option for flood and damage estimation for municipalities. Hazus-MH is able to model, within its resident capabilities, flood scenarios in terms of their area and extent, damage estimation and provides GIS mapping of flood inundation areas and damaged areas to support visual communication of results. Moreover, the software is affordable, both in terms of acquisition cost as well as training and technical support.

Hazus-MH provides the user with a number of useful inherent functionalities and inventories. Hazus-MH provides the user the option of modeling flooding using built-in return periods for flood events (e.g., 100-yr, 250-yr, 500-yr) using digital elevation models and national data as well as the capability to read output from hydrodynamic models such as HEC-RAS. The depth-damage functions supplied with Hazus-MH come from a variety of reputable sources such as USACE and the US Federal Insurance Administration (Scawthorn, Blais et al. 2006). Coupled with this are pre-loaded inventories of building types, economic data, life-line utility data and agricultural data from sources such as the US Census Bureau, Dun and Bradstreet and the US Department of Agriculture. In addition to a depth-damage function and an inventory of businesses and buildings for a given census area, Hazus-MH also comes with the ability to perform direct and indirect economic loss estimates as well as displaced person estimates for a flood event (FEMA 2009).

In summary, Hazus-MH comes with multiple options for modeling flooding and includes valuable data for a community to utilize in flood planning and damage assessments. Additional research is required to determine effective incorporation of Hazus into adaptation planning.

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CHAPTER 3

Scale and Resolution Considerations in the Application of HAZUS-MH 2.1 to Flood Risk Assessments

Banks, J., J. Camp, et al. "Scale and Resolution Considerations in the Application of HAZUS-MH 2.1 to Flood Risk Assessments." Natural Hazards Review **0**(0): 04014025. American Society of Civil Engineers, reprinted with permission of ASCE

3.1 INTRODUCTION

HAZUS-MH, also referred to as Hazus, is a tool developed by the U.S. Federal Emergency Management Agency (FEMA) for performing earthquake, hurricane and flood hazard modeling and damage assessment (FEMA 2012). Hazus is intended for use as a standardized methodology for community mitigation and recovery planning through development and modeling of plausible disaster scenarios and determining the economic and community impacts of the modeled events (FEMA 2013).

Given its intended purpose, it is important to understand the limitations of applying Hazus in order to facilitate relevant application. Of particular interest in this work is the scope and application of the Hazus flood modeling component. Some prior studies have been performed in which Hazus flood predictions have been compared to modeled flood events. Ding, et. al. (2008), compared Hazus models using 10-year, 100-year, and 500-year floods with the White Oak Bayou watershed of Harris County, Texas. Empirical hydrology and hydraulics data were used in comparison with Hazus' predicted flood. The study found that Hazus analysis utilizing digital elevation models (DEM's) with increased resolution and detailed hydrology and hydraulic data better represented the flood plain. In related research, Qiu et. al. (2010) observed that drainage threshold and region size were important factors in determining agreement between Hazus flood models and FEMA Q3 flood maps. These papers are important in demonstrating ways in which Hazus' predictive ability may be increased; however, they did not compare the Hazus data to an actual flood event. The focus of this research is to build on the work conducted by Ding and her associates by comparing Hazus' flood model performance to a well-characterized flood event.

The event used for this study was flooding in the Davidson County, Tennessee, area that occurred in May 2010. At that time, Davidson County (Nashville) was subjected to flooding from what is estimated to be a 1,000-year rainfall event when over 13 inches of rain fell over a two-day period during what was characterized as "abnormally dry" middle Tennessee spring. Compounding the rapid rainfall was the rainfall pattern. The U.S. Army Corps of Engineers (USACE) operates an extensive number of flood control dams on the Cumberland River system, the predominant water body flowing through Davidson County. Although it is part of a dammed and man-managed river system, the rains of the May 2010 event fell on downstream areas which severely limited flood control capacity due to time of year and storm area concentration. Together, these factors combined to create a significant flood event in Davidson County (USACE 2010).

3.2 HAZUS SOFTWARE

Hazus performs flood modeling and damage assessments characterized as a Level 1, 2 or 3 analyses. A Level 1 analysis utilizes basic hydrology concepts built into the program and a localized digital elevation model (DEM) to determine flood depth and extent combined with local census data to approximate economic losses. Hazus models floods by using various parameters such as flood return frequency, discharge parameters, and ground elevation to generate flood depth and extent. Scawthorn, et. al. (2006) provides a discussion and summary of flood modeling functionality. However, in brief, the return frequency and discharge parameters for Level 1 analysis are provided with Hazus, while ground elevation is imported through a DEM. These parameters are then used to estimate flood depth, flood elevation, and flow velocity to perform flood impact analysis using basic overland flow analysis (FEMA, 2012b). Level 2 analysis may use a combination of Level 1 modeling and analysis capabilities in addition to user supplied data relative to flood parameters and/or property/building content values. Although there is no definitive delineation between Level 2 and 3 analysis, Level 3 is generally characterized as having a larger number of user-provided input parameters, such as flood data, user-defined facilities, building inventories, and depth-damage relationships, supplied or modified to fit the situation being modeled by the user (ESRI Inc. 2007). Hazus also has provisions for incorporating output from more advanced flood models, such as the U.S. Army Corps of Engineers Hydrologic Engineering Centers' River Analysis System (HEC-RAS), to improve the accuracy of the flood impact for Level 2 and 3 analysis (FEMA, 2012c).

The flood loss estimation method used by Hazus considers direct physical damage and induced damage on items contained in Hazus' inventory. This is accomplished through the use of depth-damage curves which associate a depth of flooding to the percent damage sustained by a structure. The depth-damage relationships contained within Hazus are based on curves developed by the USACE, the Federal Insurance and Mitigation Administration and the USACE Institute for Water Resources. Note that HAZUS-MH, version 2.1, service pack 2, was used for this paper.

3.3 THE 2010 FLOOD IN DAVIDSON COUNTY

Empirical data on the extent of flooding and associated damages from the 2010 flood in Davidson County, Tennessee, was obtained from two primary sources. The Metropolitan Government of Nashville and Davidson County conducted a physical survey and assessment of flood impacted areas including high water marks on residences. Based upon the high water mark, a residence was assigned a damage level ranging from 0-4 (see Table 1). The US Army Corps of Engineers (USACE) Nashville District provided flood depth grids from a HEC-RAS model calibrated to high water marks following the event (Figure 1).

Damage Rank	Amount of Damage	Description
0	Extremely minimal	
1	Minimal	Waterline anywhere on the structure (involvement in flood)
2	Moderate	Waterline above floor elevation (water just invading home, maybe damage to mechanical units)
3	Major	Waterline 2 to 6 feet above floor elevation
4	Severe	Waterline greater than 6 feet above floor elevation

Table 1: Damage Ranking and Criteria for Physical Damage Survey used by Nashville Metro Government

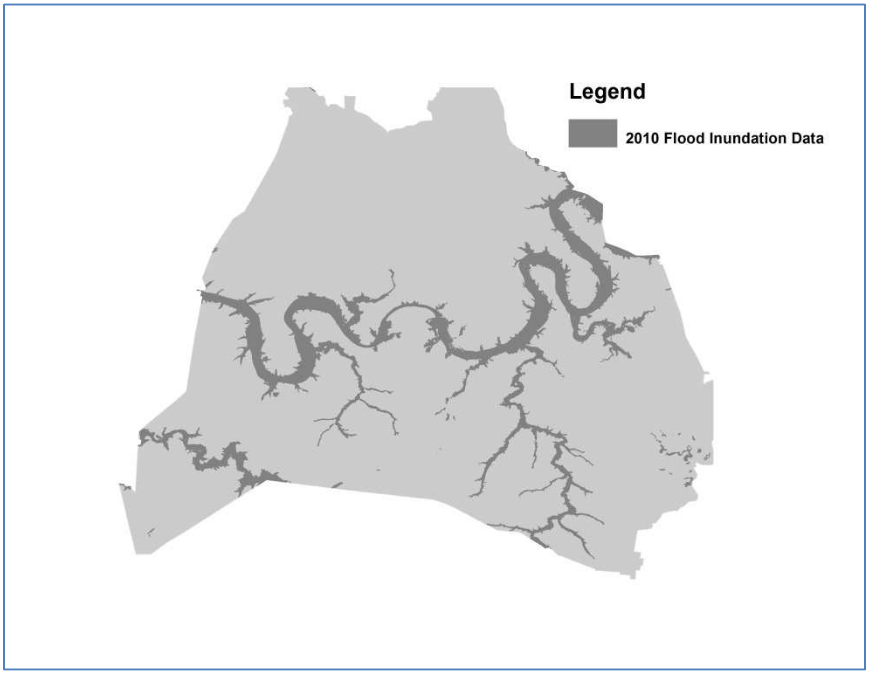

Figure 1: Davidson County Tennessee 2010 Flood Areas from US Army Corps of Engineers (46.08 mi2 flood surface area)

3.4 COMPARISON OF HAZUS FLOOD MODELS TO ACTUAL EVENT

Iterative flood models were run to determine which of Hazus' predicted floods (based upon return period) provided the best estimation of the 2010 Davidson County flooding. Model simulations were performed using a two-square mile drainage area, flood return periods of 100-, 500- and 1,000-years, and DEM's obtained from the U.S. Geological Survey (USGS) for the region with 1 and 1/3 arc-second cell size resolution (1 arc-second ≅ 30 meters and 1/3 arc-second ≅ 10 meters). A two-square mile drainage area was used in all scenarios for consistency. By contrast, the range of return periods were used to create floods of increasing impact, while the DEM resolutions were varied to evaluate the influence of increased DEM resolution similar to the work of Ding et al., 2008.

Variations within each DEM type were noted for the estimated flood surface areas. For the 1 arc-second DEM, there is approximately three square miles of surface area difference between the 100-year return period flood and both the 500- and 1,000-year return period floods and only a 0.5 square-mile flood surface area difference between the 500 and 1,000 year return periods. Similarly for the 1/3 arc-second DEM, there is approximately a seven square-mile difference between the 100-year return period and both the 500- and 1000-year return period, while there is essentially no difference in flood surface area between the 500- and 1000-year return periods. Results similar to those observed by Ding et. al. (2008) are seen here in that increased DEM resolution results in improved flood prediction. Overall, the combination of the 1/3 arc-second DEM with the 1000-year return period resulted in the greatest agreement with actual flood events observed in 2010. The modeling results are summarized in Table 2.

Flood Return Period (Years)	Estimated Flood Surface Area (square miles) 1 Arc-second DEM	As % of Observed Surface Area (46.08 mi^2)	Estimated Flood Surface Area (square miles) 1/3 Arc-second DEM	As % of Observed Surface Area (46.08 mi^2)
100	34.76	75%	33.53	73%
500	37.28	81%	40.16	87%
1000	37.78	81%	40.17	87%

Table 2: County-Wide Summary of Flood Inundation Areas at Varying Levels of DEM Resolution and Flood Return Periods

While Hazus was able to reasonably approximate flood location and surface area for the entire county, differences in specific inundation patterns were noted in several smaller areas of the county. Areas A, B and C (Figure 2) denote general locations within the study area where these differences were observed. Figures 3, 4 and 5, address each area, respectively, in greater detail.

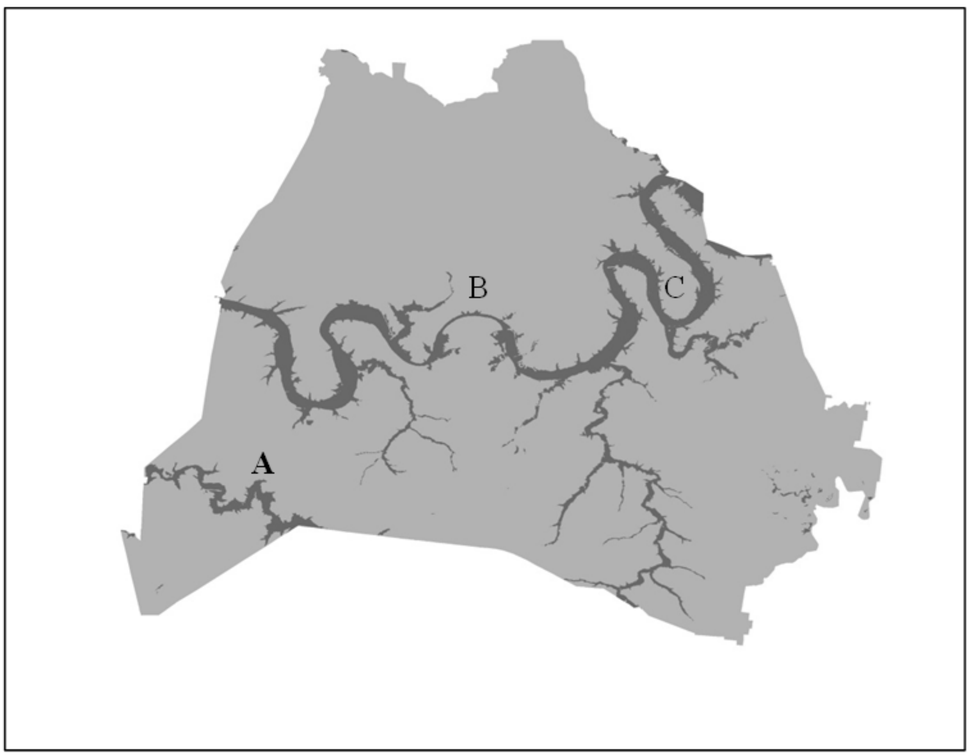

Figure 2: Selected Areas of Difference

Area A demonstrated notably less predicted inundation than was observed during the 2010 flood (Figure 3). The cross-hatched area representing the 2010 flood shows an actual flood surface area of 4.48 square miles, while 3.00 square miles of flood surface area were predicted by the 1/3 arc-second DEM and 1000-year return period model.

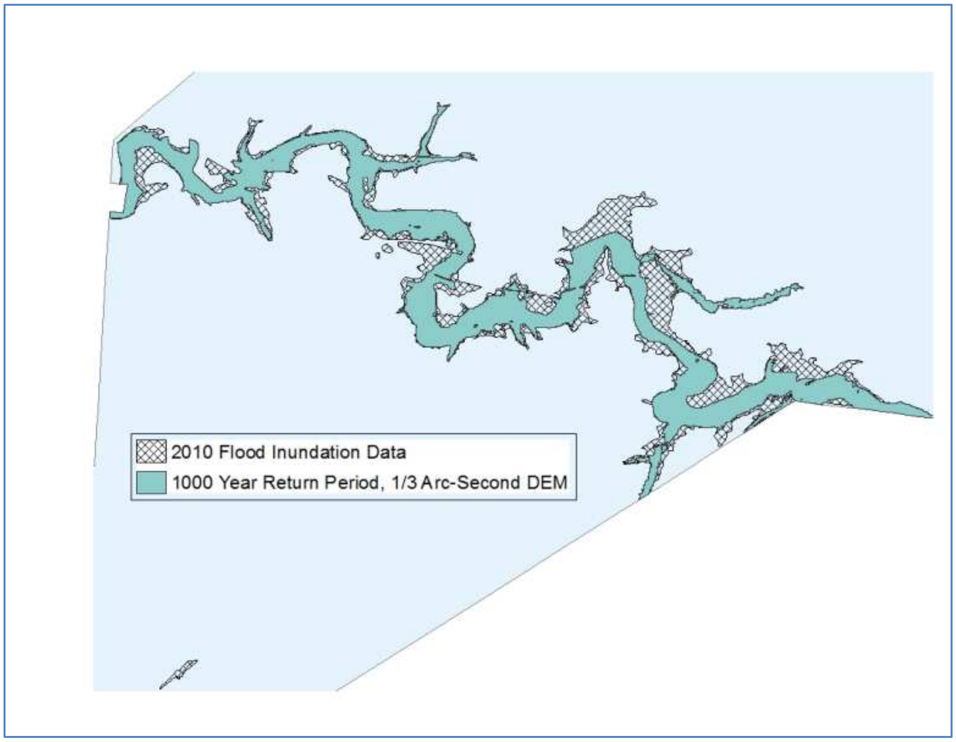

Figure 3: Area A Difference in Inundation Area

Similarly, the predicted inundation pattern for Area B is markedly different than the observed pattern (Figure 4). Hazus estimated 3.66 square miles of inundation in Area B whereas only 3.08 square miles were observed.

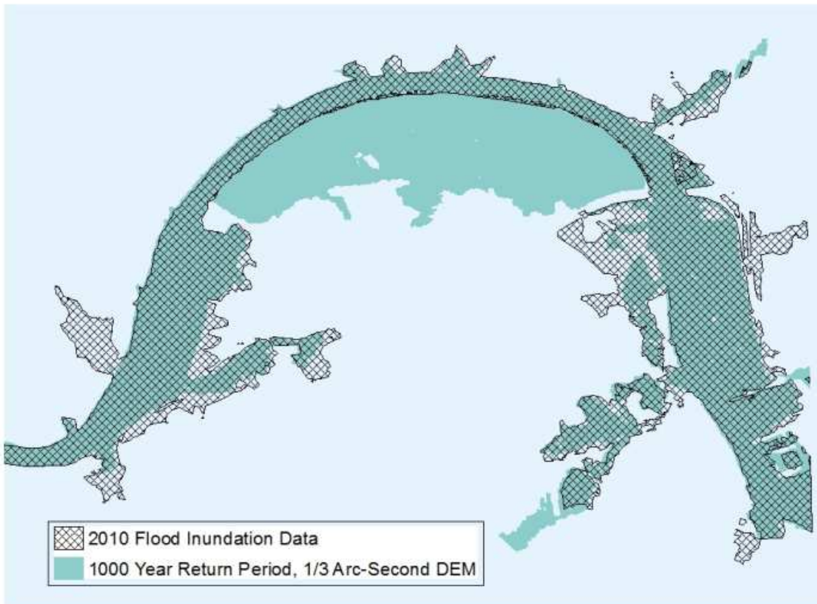

Figure 4: Area B Difference in Inundation

Area C showed the greatest variation between observed and predicted values (Figure 5). The 2010 flood produced 13.16 square miles of flood surface area in this region; in contrast, Hazus estimated almost 50% less flood surface area at 5.92 square miles.

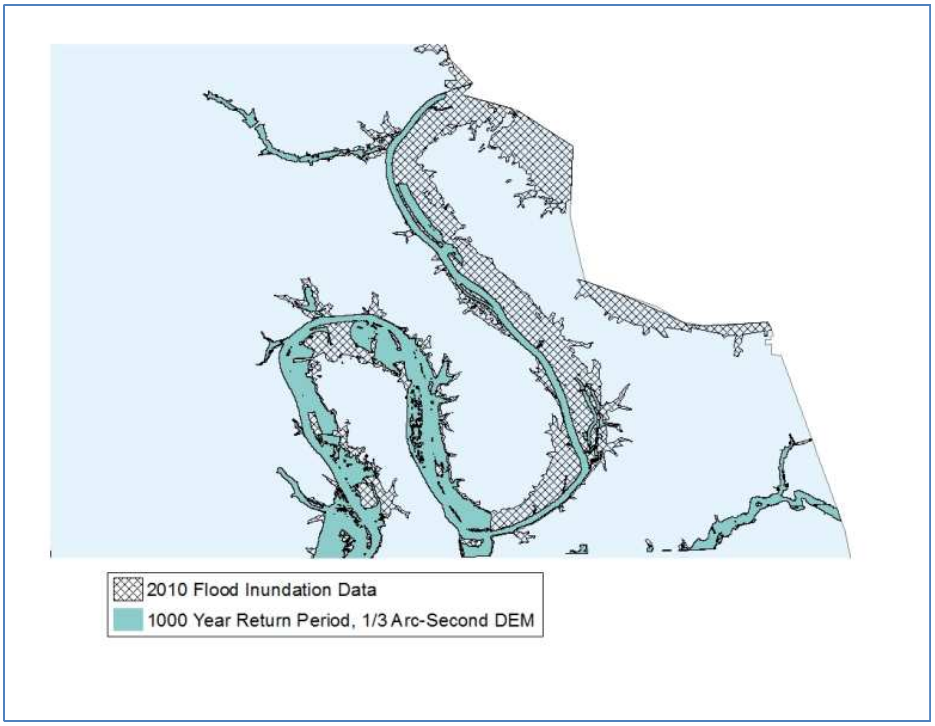

Figure 5: Area C Difference in Inundation

Analysis was also conducted for specific sub-county areas to determine if using higher resolution DEMs improved agreement between Hazus predictions and observed data. Selection of these areas of study was based on the fact that their watersheds were contained entirely within Davidson County. To determine the extent of DEM required for a model, Hazus creates a shapefile area defining the boundary of watersheds that contribute to the hydrology of the study area. The DEM requirements are then based on the shape of the watershed polygon. If the DEM does not include the area of the watershed polygon, the program will not develop stream networks or perform further analysis (HAZUS Help Desk 2013). Since available LiDAR data only covered the interior of Davidson County, this selection technique only allowed the use of DEM data with a 1/9 arc-second grid (1/9 arc-second ≅ 3 meters) for two specific areas (USGS 2006). A 0.25 square mile drainage area (the smallest drainage area allowed by Hazus), precipitation event return periods of 100-, 500- and 1,000- years, and DEM's of 1, 1/3 and 1/9 arc-second (LiDAR) resolution were considered as model parameters for each of these areas. Figure 6 shows the locations of the watersheds selected for additional study using the LiDAR data, hereafter referred to as North Area and South Area.

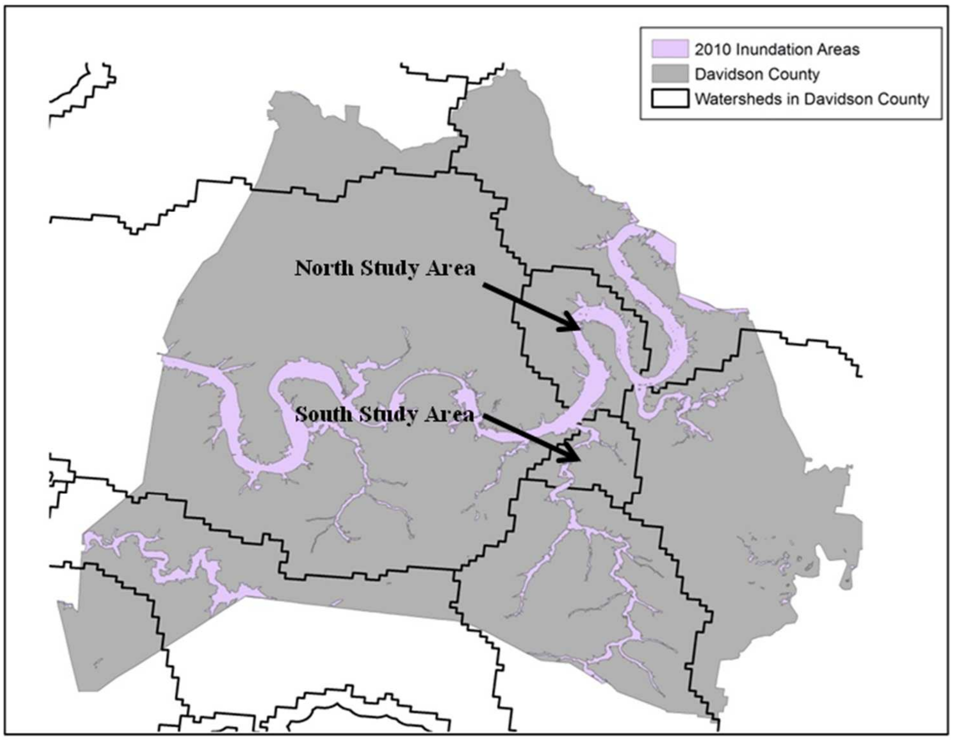

Figure 6: Hazus-Defined Watersheds Intersecting Davidson County, Tennessee

Modeling for the North Area was attempted using the 1, 1/3 and 1/9 (LiDAR) arc-second DEM resolutions and for 100-, 500-, and 1000-year return periods. Figure 7 presents the North Area and the stream network developed by Hazus.

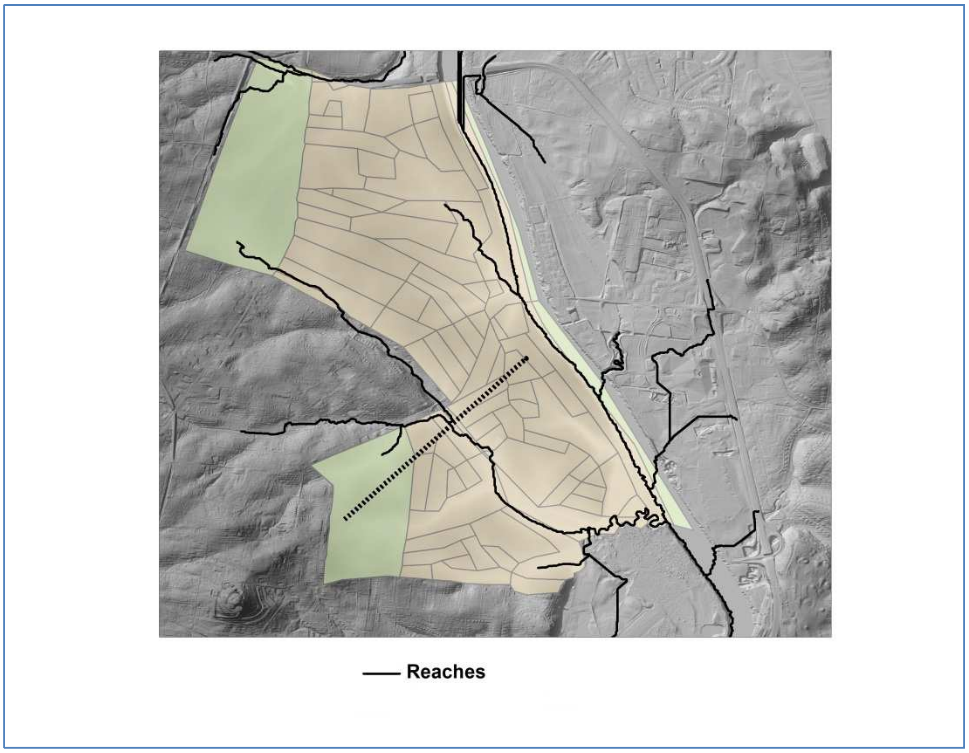

Figure 7: North Area with Stream Network
(The dashed line indicates the break point where Hazus failed to perform hydraulic analysis.)

Although stream development proved successful for the North Area at all DEM resolutions, hydrology calculations were problematic. Depending on the return period, Hazus failed to compute portions of the hydrology. For the 100-year return period, hydraulic analysis was successful for the lower reaches of the study area, while for the 500- and 1000-year return period hydraulic analysis was successful for the upper reaches of the study area (see Figure 7 and 8). The program's inability to complete hydraulic calculations for this study area precluded comparison with the observed 2010 flood.

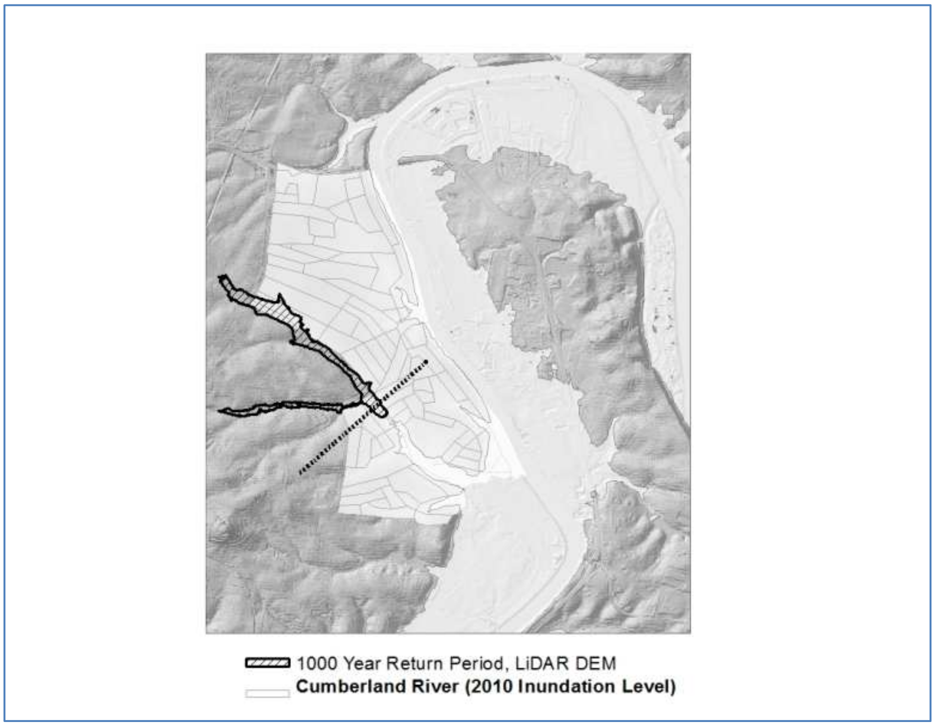

Figure 8: Modeled Area and 2010 Inundation
(The dashed line indicates the break point where Hazus failed to perform hydraulic analysis.)

As with the North Area, the South Area modeling was attempted using the 1, 1/3 and 1/9 (LiDAR) arc-second DEM resolutions and for 100-, 500-, and 1000-year return periods. Hazus was able to develop flood maps for the 1 and 1/3 arc-second DEMs for all return periods, but experienced problems when the LiDAR DEM was used, as two center reaches covering the interior portion of the study area could not develop hydraulics (Figure 9).

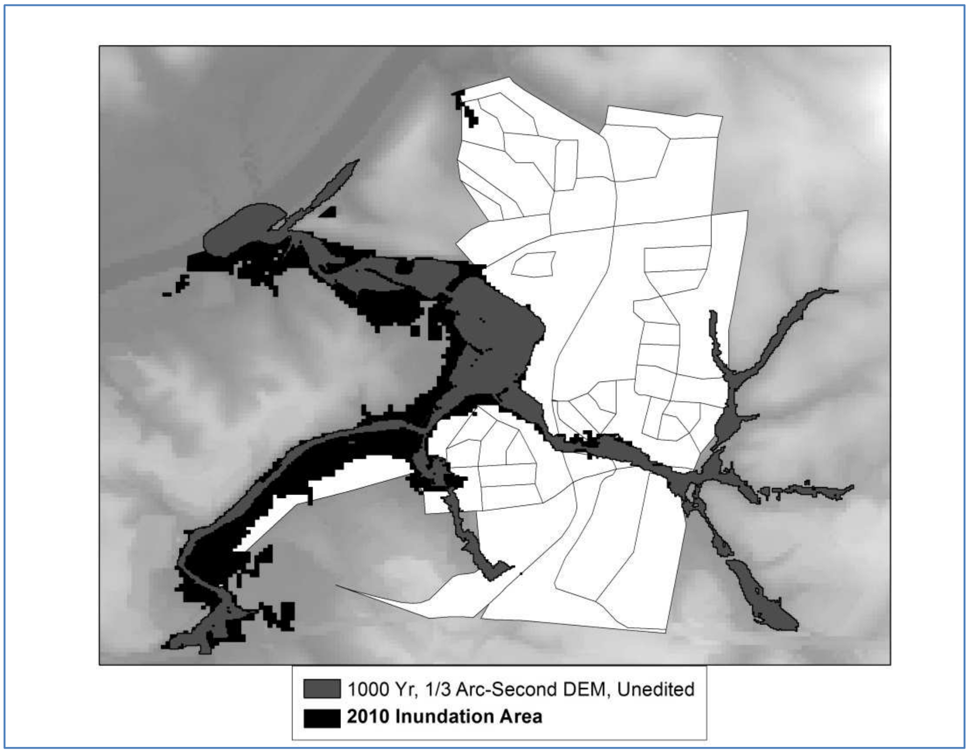

Figure 9: Raw Predicted Flood Area

The raw predicted flood areas for the South Area ranged from a low of 0.42 square miles using the 1 arc-second DEM and 100-year return period to a high of 0.5 square miles using the 1/3 arc-second DEM and 1000-year return period (Figure 9). As was the case with the county-wide flood model, the 1000-year return period and 1/3 arc-second DEM most closely approximated the observed flood area of 0.68 square miles (Table 3).

Flood Return Period (Years)	Estimated Flood Surface Area (square miles) 1 Arc-second DEM	As % of Observed Surface Area (0.68 mi^2)	Estimated Flood Surface Area (square miles) 1/3 Arc-second DEM	As % of Observed Surface Area (0.68 mi^2)
100	0.42	62%	0.45	66%
500	0.47	69%	0.48	71%
1000	0.48	71%	0.50	74%

Table 3: Raw Flood Areas for South Area Using 1 and 1/3 Arc-Second DEMs

3.5 DISCUSSION OF FLOOD MODELING

Although a significant portion of the actual flood was predicted by Hazus, very little variation in flood surface area was seen between the 500- and 1000-year return periods for both the 1 and 1/3 arc-second DEM models. Hazus utilizes flood-frequency regression equations for each region to develop flow for each modeled reach which are in turn used to predict flood extent. These flood-frequency equations are provided up to the 500-year return period after which Hazus uses a Log Pearson Type III distribution to interpolate values for longer return periods (HAZUS Help Desk 2013). Given the similarity of the predicted flood surface areas between the 500- and 1000- year return periods in both DEM resolutions this suggests possible limitations with the regression equations or the approach used by Hazus for return periods greater than 500 years. Because of this possible error, care should be exercised when modeling flood return periods greater than 500 years. Also, the authors fully recognize that terrain is a major factor in development of an inundation area and should be considered when comparing extent of flooding for various return periods.

As previously discussed, Hazus using a 1/3 arc-second DEM and a 1000-year flood return period developed a flood prediction at the county level that approximated 87% of the flood surface area observed in the 2010 floods. At a sub-county level, however, Hazus produced more notable variation between predicted and observed flood areas (Table 4). Not only are the percent differences in inundation level quite large, but there is not a consistent trend of Hazus in under or over predicting the flood surface area. This suggests that down-scaling the use of Hazus to sub-county levels should proceed with considerable caution.

Study Area	Predicted Flood Area 1/3 Arc-Second DEM 1000 Year Return Period (square miles)	2010 Flood Area (square miles)	% Difference (Predicted/Observed)
A	3.00	4.48	34%
B	3.66	3.08	118%
C	5.92	13.16	55%

Table 4: Summary of Predicted and Observed Flood Surfaces for Sub-County Areas

Hazus uses the DEM to identify reaches, provide topographic parameters to regression equations used for hydrologic analysis, and to provide parameters during hydraulic analysis and flood depth grid generation (FEMA 2009). Results from the 1000-year return period using a 1 arc-second DEM suggest that this would lead to modeling improvements, as when applied to Area A, Hazus estimated 2.49 square miles of flood surface area compared with a 3 square mile surface area estimate using the 1/3 arc-second DEM. Increasing resolution from a 1 arc-second DEM to a 1/3 arc-second DEM improved agreement between predicted and observed by 10%. Although increasing DEM resolution increases accuracy, the maximum benefit from using high resolution DEMs, such as LiDAR, appears to be limited. The dates of DEM data should be taken into consideration also to ensure the most current data is used. As was previously noted, Hazus determines DEM coverage requirement by analyzing all watersheds that intersect a study area. Although LiDAR data was available for all of Davidson County, it was not sufficiently large enough to cover the watershed extents intersecting the county. Figure 10 presents the view of the required DEM (reqDEMpolygon) as determined by Hazus, the extent of the available LiDAR data, and the Area A boundary. As is shown, the available LiDAR data is insufficient when compared to the required DEM polygon used by Hazus.

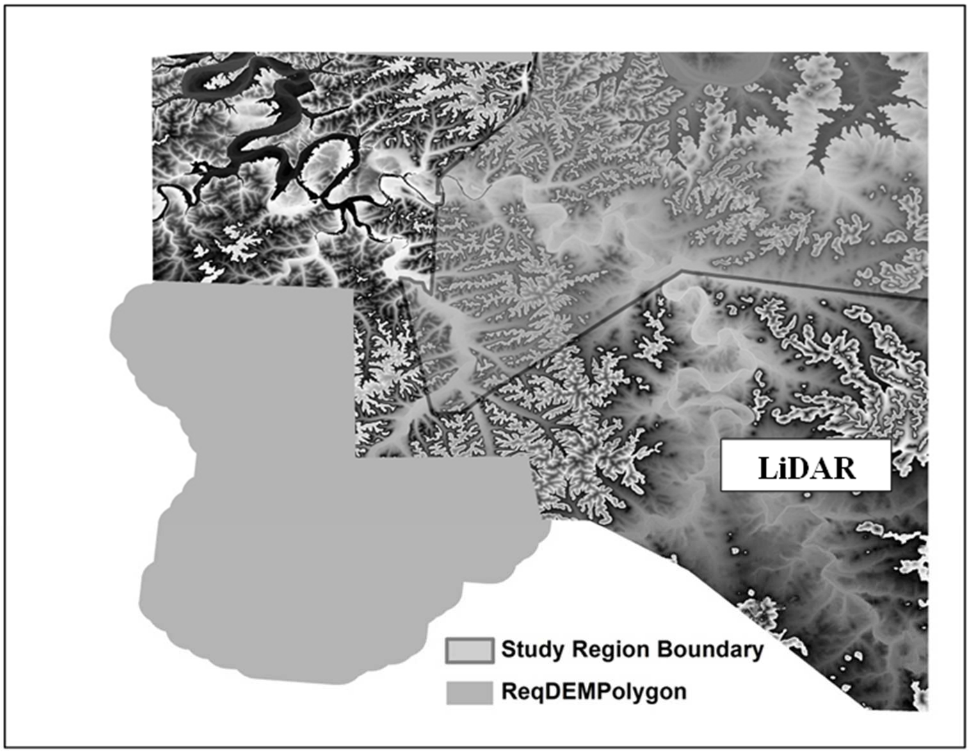

Figure 10: Required DEM for Area A

Area B demonstrates errors that can be attributed to the age of the DEM data. A review of the metadata associated with the 1/3 arc-second DEM available from the USGS Seamless Server indicated that the initial photography from which the DEM was derived occurred before 1975. Moreover, the DEM was last inspected in the year 2000. In 2004, the USACE in conjunction with Nashville Metro Water Services constructed a flood control levee in this area. This levee was designed with a 99% probability of containing a 100-year return period flood and a 76%

probability of containing a 500-year return period flood (USACE 2012). Since the levee was constructed after the DEM was created, those topographical changes were absent from Hazus' calculations at the 1/3 arc-second level. As is demonstrated from mapping of the observed flood data, the levee reduced inundation in Area B (Figure 4).

Area C is located directly downstream of the Old Hickory Dam, which is used for hydroelectric generation and navigation control. During the 2010 flood, the Dam was used to control flooding (USACE 2010). Hazus applies regional regression equations for unregulated streams to calculate discharge values for use in predicting flood height (FEMA 2009). Since the Cumberland River is a managed stream this likely led to the discrepancy between observed flood areas and those predicted by Hazus in Area C (Figure 5).

Relative to the sub-areas in which LiDAR was used, the North Area did not yield usable results. However, the South Area demonstrated a maximum of 74% agreement between the predicted and observed surface area in comparing the 2010 flood event with the 1/3 arc-second DEM and 1000-year flood return period. Although data suggested predicted and observed flood surface areas were similar, the distribution of the flooded area differed in the models compared to the 2010 event. The Hazus model predicted a significant portion of the flood occurring in the area to the east of the observed flood surface (Figure 9). Removing those areas outside of the study boundary decreased agreement between predicted and observed to no more than 60% (Figure 11). Summary of surface area estimates for 1 and 1/3 arc-second DEMs compared with the 2010 flood are provided in Table 5.

Flood Return Period (Years)	Estimated Flood Surface Area (square miles) 1 Arc-second DEM	As % of Observed Surface Area (0.68 mi^2)	Estimated Flood Surface Area (square miles) 1/3 Arc-second DEM	As % of Observed Surface Area (0.68 mi^2)
100	0.34	50%	0.37	54%
500	0.38	56%	0.39	57%
1000	0.39	57%	0.41	60%

Table 5: Edited Flood Areas for South Area Using 1 and 1/3 Arc-Second DEMs

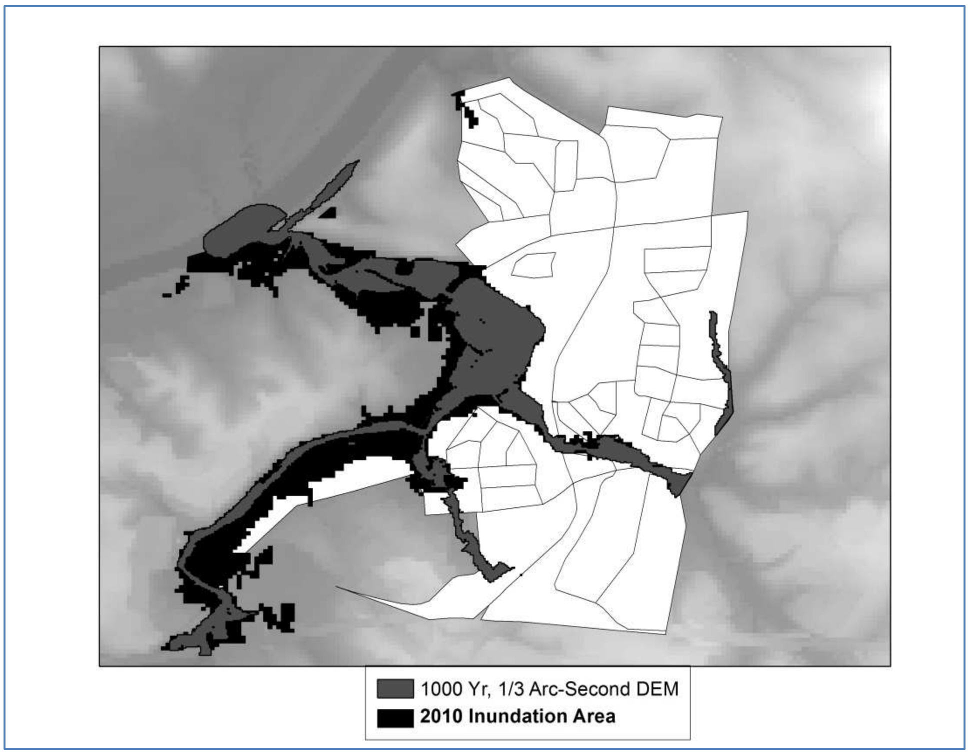

Figure 11: Edited Predicted Flood Area

For hydraulics, Hazus utilizes a number of estimations to determine flow and subsequent flood surface elevations (FEMA 2009). In a Level 1 analysis, Hazus relies entirely on the generation of a synthetic stream network through analysis of the DEM and the drainage area. Even though a high resolution DEM was used, if areas adjacent to, but not included in, the study region contribute to the flow, discontinuous streams may develop (FEMA 2009). An example of discontinuous flow is noted in the South Area. Although it did not impact 1 and 1/3 arc-second DEM models to perform hydrology estimations, the discontinuous stream network may have impacted the ability to accurately predict the hydraulics of the reaches (Figure 12).

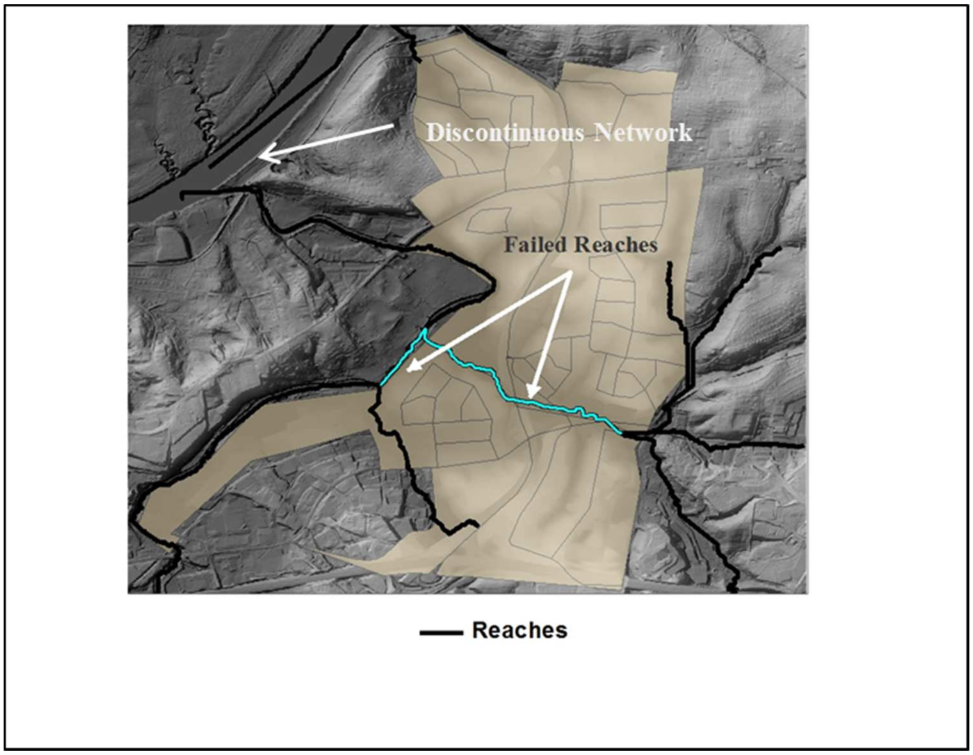

Figure 12: Stream Network and Reach Hydraulic Problems

Hazus defines the study area flood plain, the up and the downstream limits of the flood surface, and creates a centerline for the flood when performing hydraulics and flood surface estimation. From this process, Hazus applies several algorithms to define the flood surface (FEMA 2009). Problems with failed reaches were encountered when hydraulic analysis was performed on both the North and South Areas. In the North Area, reaches failed floodplain delineation for all

DEM resolutions and return periods while in the South Area reaches only failed for the LiDAR DEM. A review of Hazus scenario hydraulic logs (flHydraulicsLog) indicated that the reaches failed in both scenarios because the centerline did not intersect the cross-sections at the endpoints of the reaches. When brought to the attention of the Hazus Help Desk it was concluded that the problems are due to program coding and cannot be resolved by the user (HAZUS Help Desk 2013). Hazus users are encouraged to review the “flHydraulicsLog.txt” file when reaches fail hydraulics to determine whether this is the cause (FEMA 2009). This error may be limited to small scale application since it did not occur on the county-wide models.

3.6 COUNTY- LEVEL DAMAGE ESTIMATION USING HAZUS

An additional study was performed to compare Hazus-estimated damage and what was observed from the 2010 floods. This analysis was accomplished by contrasting Hazus-estimated damage for residential structures with the results of a survey of residential damage found in the aftermath of the 2010 floods.

Total loss by census block was calculated by Hazus based on the 1/3 arc-second DEM and a 1000-year flood return period. Hazus utilizes depth-damage relationships to assign percent damage to the average property value for a census block and does not estimate damage to specific structures. This method of estimation is expedient but may lead to discrepancies when modeled damage is compared to actual damage. Utilizing Hazus’ functionality that allows users to define structures and values for an area may provide improved accuracy when comparing modeled to actual damage (FEMA 2009). Figure 13 provides the Hazus-predicted damage areas, with lighter areas depicting where the least damage occurred and the darker areas associated with greater loss.

Hazus loss predictions range from a total by census block of $743,000 to $17,408,000, depending on the location.

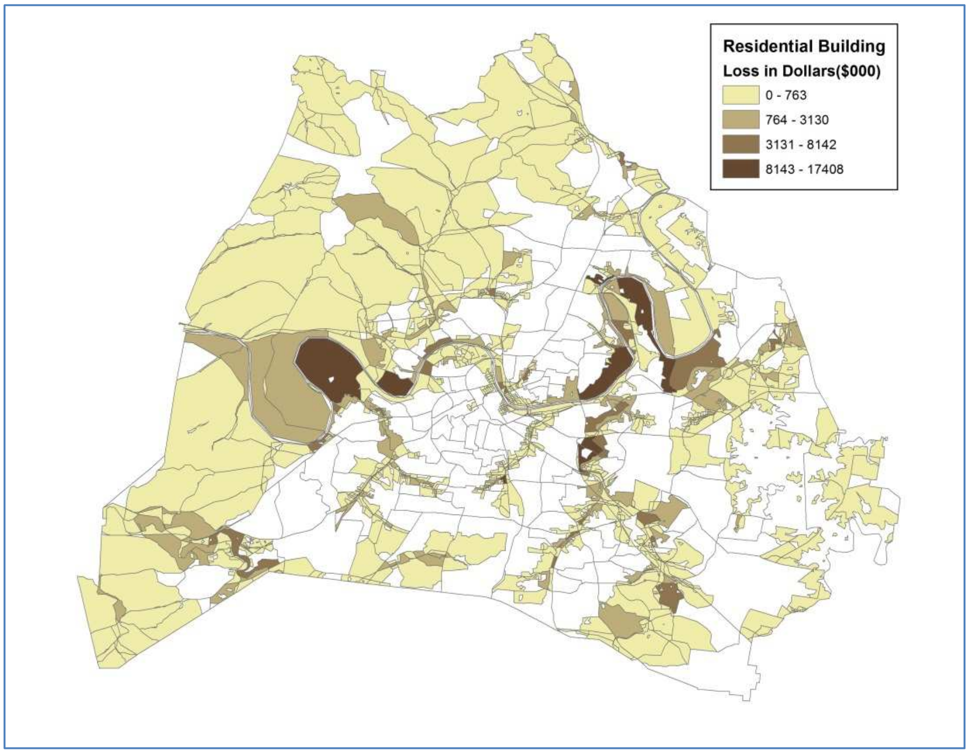

Figure 13: Hazus-Projected Losses

A physical survey of damaged structures was conducted by Metro Nashville Government in the areas impacted by flooding. Surveyors used a standardized damage rating of 0 through 4, with 0 being little or no damage and 4 being severely damaged (Table 1). All damage levels within each parcel were summed to represent the magnitude of the sustained damage. The results are shown in Figure 14.

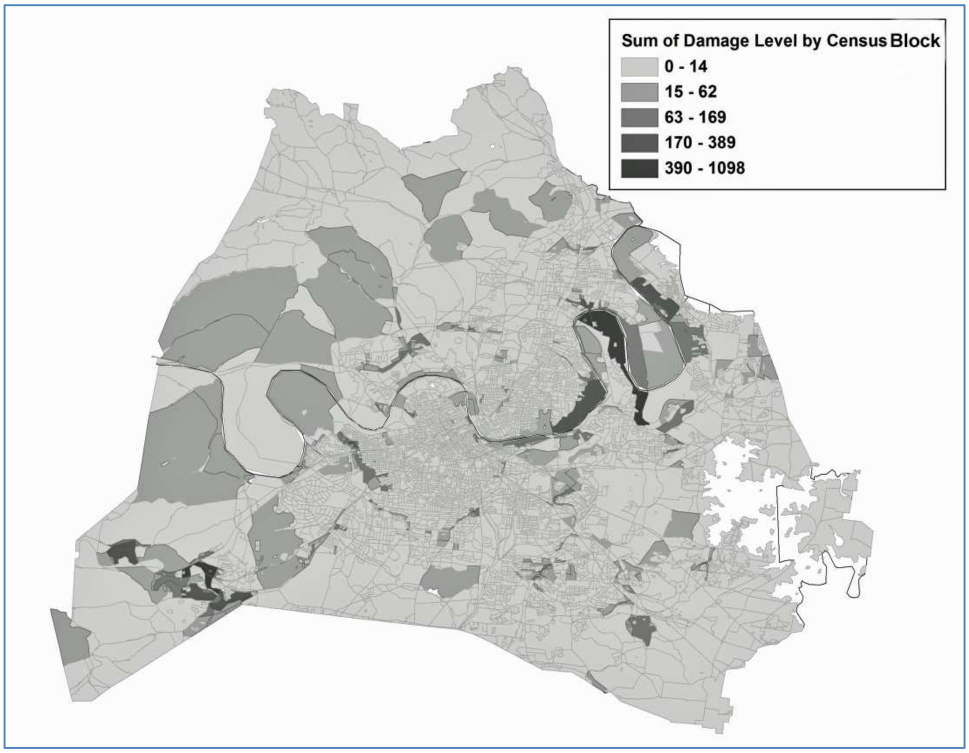

Figure 14: Sum of Observed Damage Levels by Census Block

3.7 DISCUSSION OF COUNTY-LEVEL DAMAGE ESTIMATION

A direct comparison of estimated damage between Hazus and the 2010 flood was not possible since the evaluation outputs were expressed in different terms (i.e., monetary loss vs. qualitative levels). To overcome this limitation, Pearson's Product Moment Coefficient (Pearson's *r*), which measures the strength of a linear relationship between two variables, was utilized. The values of Pearson's *r* range from -1 to 1, with -1 indicating a strong negative linear relationship, 1 indicating a strong positive linear relationship, and 0 indicating no relationship between the variables (Mendenhall, Beaver et al. 2013). Results of the Pearson's *r* calculation on these data sets indicated a value of $r = 0.45$ (n=114). This indicates a moderate, positive correlation between the Hazus-predicted damage magnitude by census block and the observed damage levels by census block. This correlation was found to be significant at the p=0.005 level with a calculated t value of 4.27 (df = 112) and $t_{0.005}$ of 2.576.

An analysis of damage was also undertaken in North and South Areas. The North Area's incomplete flood delineation provided a very limited flood impact area and a concomitant reduction in flood damage. Significant variation was noted in the distribution of the damage when the 1000-year, 1/3 arc-second model was compared to the 2010 observed damage (Figure 15). Of the census blocks in the study area, Hazus only estimated damage in 26 blocks while observations from the 2010 flood showed some level of damage in 83 blocks. As was previously indicated, significant portions of the North Area failed hydraulic analysis thereby providing only a limited area of flood impact when compared to the 2010 flood.

Figure 15: North Area Observed Damage (Left) and Predicted Damage (Right)

For the South Area, Hazus predicted 14 census blocks with some degree of residential structure damage using the 1000-year, 1/3 arc-second DEM model. The observed values for the area indicated that 10 census blocks had sustained some level of residential damage during the 2010 flood. However, when the census blocks identified by Hazus were compared with the blocks that sustained damage in 2010, there was coincidence of damage between only two census blocks (Figure 16). Therefore, although Hazus correctly identified the general area of impact, the distribution of damage was not the same.

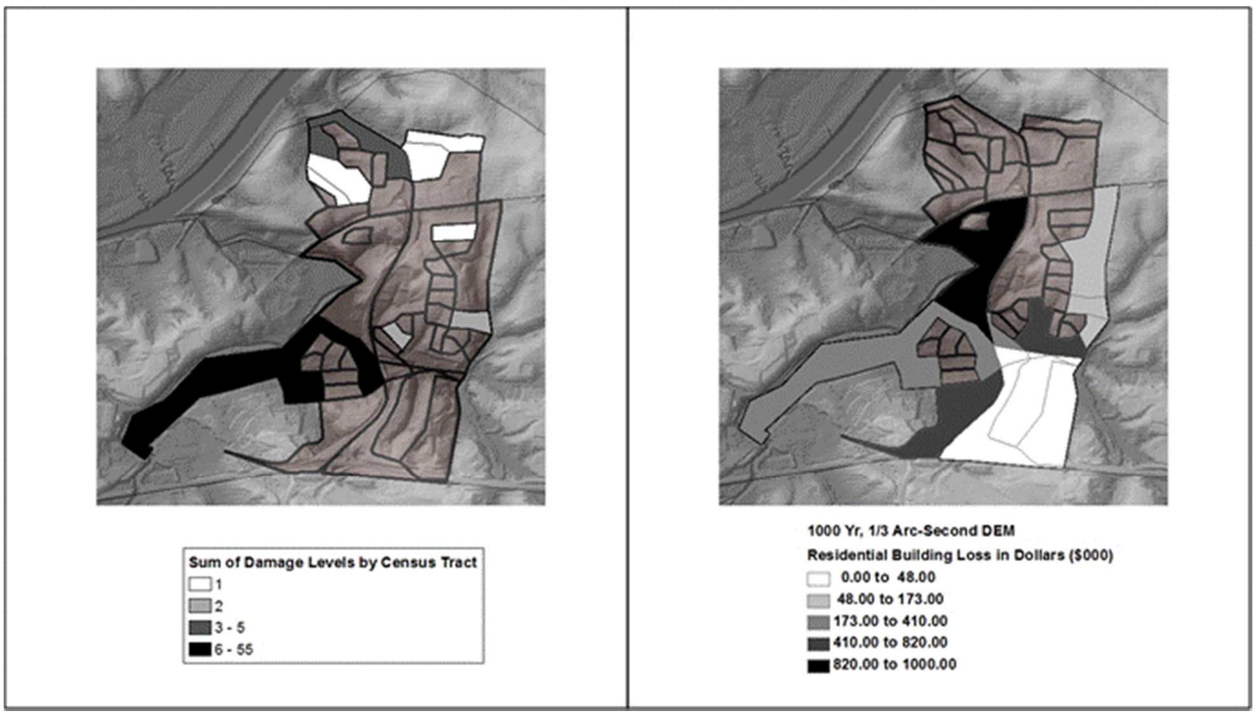

Figure 16: South Area Observed Damage (Left) and Predicted Damage (Right)

3.8 ISSUES IMPACTING AGREEMENT OF HAZUS AND OBSERVED FLOOD DATA

A number of factors impact the ability of Hazus to accurately predict the area and magnitude of impact from a flood event. DEM resolution, age of DEM data, and flood prediction equations all contribute to improving the predictive ability of Hazus when compared to actual events.

Increasing DEM resolution provides greater accuracy in stream development and flood estimation. Therefore, using a DEM with the highest available resolution is prudent (Ding, White et al. 2008; Qiu, Wu et al. 2010). The main limitation of using higher resolution DEM's is in ensuring that the selected DEM has sufficient coverage of the required watershed area as determined by Hazus. A possible solution to this problem is to use ArcGIS's "Mosaic" function to combine high and low resolution DEM's into a single file that covers the polygon required by Hazus (HAZUS Help Desk 2013). This approach was attempted, but the resulting file took more than 24 hours of computer processing time to develop and was still not usable by Hazus. Although research is continuing into why this occurred, a review of forums indicated that the mosaic function has had problems in past versions of ArcGIS (ESRI 2006) and at present, Hazus does not work with more recent versions of ArcGIS.

Improvement in Hazus' predictive ability could be accomplished by using historic flood events for calibration, including use of well-calibrated, higher-level hydrologic model representations of those flood events (e.g., HEC-RAS) for the area under study. If Hazus appears to over or under estimate inundation areas routinely, then adjustments can be made (e.g., correction factor) when utilizing the software for predictive modeling and mitigation planning purposes. In the current study, Hazus routinely underestimated the inundation area at the county level by 13-25% with the higher resolution DEM providing better results. Following that rule of thumb, the most accurate elevation data available was LiDAR, but limited coverage for the area of interest constrained its use to only a few sub-basins within the county. If available, LiDAR offers the potential to provide the greatest agreement between Hazus modeling and the "real world" situation, but LiDAR is costly and often paid for by local municipalities as opposed to having availability through national data sources such as USGS.

3.9 CONCLUSIONS

Results of this study suggest that Hazus, even when employing Level 1 data, may be used at a county level as a screening tool in determining areas of flood impact and estimates of loss. When considering the total surface area of floods, the higher resolution DEM's provided better agreement with the observed flood event, and both the Level 1 and 2 analysis provided agreement between predicted areas of greatest impact. At the county level, the location and relative magnitude of flood damage, as a function of cost, predicted by Hazus corresponded to those areas of Davidson County that experienced higher residential damages during the 2010 floods. However, Hazus experienced significant problems completing hydraulic modeling when areas smaller than a county were attempted. Because of these problems, it is recommended that Hazus be used primarily for larger, county level estimations as a screening tool to identify high impact areas that may require further analysis using some other, more advanced hydrologic analysis.

The cost, availability and ease of use of Hazus provides significant incentive for applying the tool when studying flooding and its impacts (Banks, Camp et al. 2014). Although this study indicates several problems with the program, Hazus demonstrates value at predicting reasonable estimates of flooding and flood damage when applied at county levels even for extreme events. Further research is needed in integrating Hazus into an overall flood damage estimation approach for sub-county areas due to the limitations identified in this paper. Using Hazus' more advanced analysis abilities, more accurate flood estimates could be imported to the program from other hydrologic modeling tools (e.g., USACE's HEC-RAS and HEC-FIA) to possibly improve hydraulic models in small watershed areas.

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CHAPTER 4

A Screening Method for Bridge Scour Estimation and Flood Adaptation Planning Utilizing HAZUS-MH 2.1 and HEC-18

4.1 INTRODUCTION

The 2013 Report Card for the Nation's Infrastructure, published by the American Society of Civil Engineers, estimates that more than 10% of the over 607,000 bridges in the United States are structurally deficient. To correct these deficiencies, it is estimated that $120 billion will need to be invested over the next 15 years (American Society of Civil Engineers 2013). Engendering a further sense of urgency for prioritizing and addressing bridge integrity is the impact of projected climate change and associated weather events. The most recent assessment report published by the Physical Science Basis of the Intergovernmental Panel on Climate Change's (IPCC) concludes that the frequency of heavy precipitation events is increasing along with a concomitant increase in severe flooding (IPCC 2013). These factors, coupled with scour being the leading cause of bridge damage, demonstrates a need to develop screening methods for assessing and prioritizing bridges most deserving of adaptation measures to address future flood scenarios (Khelifa, Garrow et al. 2013).

Traditional approaches for determining bridge scour involve engineering and field analysis. The United States Department of Transportation (USDOT), Hydraulic Engineering Circular 18 (HEC-18), "Evaluating Scour at Bridges", offers guidance for analyzing scour. HEC-18 recommends a procedure that includes review of the structure design as well as a physical bridge inspection to include channel conditions and both surface and sub-surface bridge structures

(US DOT 2012). Significant limitations of this approach include labor (e.g., engineers, technicians) and specialized resources (e.g., remote cameras, SCUBA equipment) to perform the inspection. Additionally, assessment of the bridge determines its status at time of inspection and does not consider impact from future flood events.

Given the current extent of bridge deterioration and the increasing impacts of climate change, developing screening tools for assessing bridge scour under future flood conditions is needed. Of the tools available to satisfy this need, the HAZUS-MH program, also known as Hazus, developed by the US Federal Emergency Management Agency (FEMA), coupled with the HEC-18 equations, offer a potential solution (Banks, Camp et al. 2014). Hazus has the ability to model a variety of flood return periods, estimate the direct and indirect economic impacts of an event, and provide spatial viewing of damage and its associated monetary value at the census block level. A shortcoming of Hazus is its assumption that bridges are point locations and are destroyed under complete inundation. This “all-or-nothing” damage function offers minimal predictive ability, thus the need for the current research.

This paper describes a methodology for utilizing Hazus coupled with HEC-18 scour equations as a screening tool for estimating damage from future flood events and presents a process for its use for adaptation planning. Of the scour types covered in HEC-18, contraction, pier and abutment scour were considered in developing this methodology, utilizing the most basic equations presented in HEC-18. Flood conditions for this research are generated using Hazus’ native flood modeling functionality while aggradation/degradation scour is not considered due to the complexity required in modeling stream bed behavior. It should be noted that more involved flood modeling and intricate engineering analysis could be performed to arrive at similar conclusions; however, Hazus was developed to be a tool for local municipalities to perform low-cost hazard mitigation planning and it is this audience that the authors have in mind in development of this methodology with costs and accessibility being key factors in the suggested approach.

4.2 SCOUR ANALYSIS

4.2.1 HEC-18 Overview

HEC-18 is designed to assist engineers in designing scour-resistant bridges as well as assessing scour for existing bridges. The document presents the types of scour impacting bridges, calculations for estimating scour, and guidance for conducting bridge evaluations. The main types of scour covered by HEC-18 include aggradation and degradation of channels, as well as contraction, pier and abutment scour (US DOT 2012). Although bridge scour for both riverine and tidal waterways are covered in HEC-18, only riverine scour is addressed in this paper.

4.2.1.1 Contraction Scour

Contraction scour occurs where a stream conveyance channel contracts. For bridges, the bank or bridge abutments may contract or restrict the flow area of a stream under the bridge. This type of scour may occur as either clear water or live bed scour. In clear water scour, bed material is transported only from the contracted section; however, in live bed scour, flow velocity is sufficient to transport bed material from upstream into the contracted section. The initial step for calculating contraction scour is to determine the critical velocities for the material sizes comprising the stream bed to ascertain whether clear water or live bed scour is occurring:

$$V_c = K_u y^{1/6} D^{1/3} \qquad [1]$$

where V_c is the critical velocity (feet/second) at which transport begins to occur, y is the average depth (feet) of flow upstream of the bridge, and D is the average diameter (feet) of the particle size of concern. K_u is a correction factor for English units (11.17). If the velocity in the stream is less than V_c, then clear water scour is present. If stream velocity is equal to or greater than V_c, then live bed scour exists for the given particle size. Of note is that since stream beds consist of varying particle sizes, during the same flood event some particles may transported while others are not. Once determination is made as to which type of scour is occurring, the respective equations for clear water (see Equation 2) or live bed scour (see Equation 3) are applied:

$$y_2 = \left[\frac{K_u Q^2}{D_m^{2/3} W^2}\right]^{3/7} \qquad [2]$$

In Equation 2, y_2 is equilibrium depth (feet) in the contracted section after contraction scour, D_m is diameter (feet) of the smallest non-transportable particle in the bed material, W is the width (feet) of the bed at the contraction, K_u is the correction a factor for English units (0.0077), and Q is the discharge through the bridge in cubic feet per second (CFS). It is important to note that D_m can be assumed to be 1.25 times the median diameter of the bed material.

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{6/7} \left(\frac{W_1}{W_2}\right)^{k_1} \qquad [3]$$

In Equation 3, y_2 is equilibrium depth (feet) in the contracted section after contraction scour, y_1 is average depth in upstream main channel (feet), Q_1 is the flow in the upstream channel (CFS), Q_2 is the flow in contracted channel (CFS), W_1 is the width of the upstream channel (feet), W_2 is the width (feet) in the contracted section minus pier widths, and k_1 is a variable determined using the ratio of the shear velocity to the fall velocity of the particle. As a note, shear velocity is estimated by taking the square root of the product of gravitational acceleration, depth in upstream section and slope while fall velocity is estimated using equations developed by the University of Illinois Hydrolab (Parker 2004). As previously noted, clear water scour takes place only in the contracted section; therefore variables describing conditions only during contraction appear in Equation 2, while Equation 3 contains variables representing both the upstream area and contraction since scour is occurring in both areas (US DOT 2012).

4.2.1.2 Pier Scour

Piers in the flood area which support the bridge decking structure are also susceptible to scour. In HEC-18, the equation for pier scour takes into account pier geometry and flow, and may be used for both clear water and live bed conditions:

$$\frac{y_s}{y_1} = 2.0k_1k_2k_3\left(\frac{a}{y_1}\right)^{0.65} Fr_1^{0.43} \qquad [4]$$

where y_s is scour depth (feet) y_1 is flow depth directly upstream from the pier (feet), k_1 is a dimensionless value based on pier nose geometry, k_2 is a dimensionless variable to correct flow angle of attack, k_3 is a dimensionless correction variable for bed condition, a is pier width (feet), and Fr_1 is the Froude number upstream from the pier. The Froude numbers used in pier scour estimation are derived using Equation 5:

$$Fr = \frac{V_1}{(gy_1)^{0.5}} \qquad [5]$$

where V_1 is velocity (feet per second) directly upstream of pier, g is the acceleration of gravity (32.2 f/s^2) and y_1 is flow depth directly upstream.

Values of k_1 are used to account for frictional and turbulent forces created by varying pier nose geometries. These values, presented in Table 1, are from HEC-18 and vary between 1.1 for square nose piers (poor hydrodynamic properties and increased resistance) and 0.9 for sharp nose piers (good hydrodynamic properties and decreased resistance). Values of k_2 are derived as follows:

$$k_2 = \left(\cos\theta + \frac{L}{a}\sin\theta\right)^{0.65} \qquad [6]$$

Table 7.1. Correction Factor, K_1, for Pier Nose Shape.	
Shape of Pier Nose	K_1
(a) Square nose	1.1
(b) Round nose	1.0
(c) Circular cylinder	1.0
(d) Group of cylinders	1.0
(e) Sharp nose	0.9

Table 1: Correction Factor for Pier Nose Shape(US DOT 2012)

where θ is the angle of attack of the stream to the pier, L is the length of the pier (feet), and a is pier width (feet). Values of k_3 take into account dunes that can develop in stream beds which impact pier scour. k_3 values vary between 1.1 for clear water and small dunes to 1.3 for large dunes. All calculations for pier scour described in this paper used a k_3 value of 1.1. This was selected since all streams under consideration were smaller and less prone to medium and large dune formation (US DOT 2012).

4.2.1.3 Abutment Scour

Bridge abutments and roadway approaches may be subject to scour from a variety of processes, including contraction scour, stream overtopping, local scour and channel migration. HEC-18 offers an equation to estimate abutment scour which accounts for abutment geometry, angle of flow to abutment, flow area and flow obstructed by the abutment:

$$\frac{y_s}{y_a} = 2.27K_1K_2\left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1 \qquad [7]$$

where y_s is scour depth (feet), y_a is flow depth directly upstream from pier (feet), K_1 is a dimensionless value based on abutment shape, and L′ is the length of obstructed active flow (feet). K_2 is a dimensionless variable to correct flow angle of attack, calculated using Equation 8, with values of θ less than 90 if embankment points downstream and values greater than 90 if embankment points upstream:

$$K_2 = \left({}^{\theta}/_{90}\right)^{0.13} \qquad [8]$$

The Froude number for abutment scour is calculated differently than the one used for pier scour:

$$Fr = \frac{Q_e A_e}{(g y_a)^{0.5}} \quad [9]$$

where Q_e is the flow obstructed by the abutment/approach embankment (cubic feet/second), A_e is the flow area obstructed by the abutment/approach embankment (square feet), g is the acceleration due to gravity (32.2 f/s^2), and y_a is the depth of flow on the floodplain (feet) (US DOT 2012).

4.2.2 Estimating Scour Damage

The following methodology provides a three-step process for estimating the monetary value of scour damage from a future event. The initial step involves gathering the data required to solve the HEC-18 equations. The second step calculates scour for a given future flood event and uses the resulting data to determine a scour factor. The final step applies the scour factor to an estimate of bridge construction cost to provide a monetary estimate of flood damage.

4.2.2.1 Data Gathering - Hazus

Hazus was originally developed by FEMA as a tool to be used by communities for earthquake disaster planning and later expanded to include planning for hurricanes and floods (FEMA 2012). The program requires ArcGIS with the Spatial Analyst tool pack and has the ability to model floods through native functionality as well as to import flood data, such as that generated by the US Army Corps of Engineers (USACE) HEC-RAS program (FEMA 2009). Scawthorne, et. al. provides a summary of Hazus flood modeling capability (Scawthorn, Blais et al. 2006). In addition to software functionality provided with Hazus, all native functionality of ArcGIS and the

Spatial Analysis tool pack are available for use. Version 2.1, service pack 3 of Hazus was utilized to generate the data for this research.

Salient features of Hazus and ArcGIS used in scour equations are the raster cell-as-depth feature, digital elevation models (DEM), flood frequency model data, and ArcGIS length estimation tools. Upon completion of a flood model, Hazus outputs a raster layer representing the flood and its extent. When Hazus creates this image, the values assigned to the raster cells are equivalent to the flood depth in feet (ESRI Inc. 2007). This feature allows the user to access the ArcGIS information tool to obtain estimated flood depths for use in the HEC-18 equations. Similarly, the values of the topography raster cells created by Hazus from the DEM provide elevation, measured in feet above sea level (FEMA 2009). These values are also accessed using the ArcGIS Information tool and are helpful in determining stream slope. The flood model, in addition to creating raster imagery, retains the calculations to determine flood extent and depth in the flHydraulicslog.txt file stored by Hazus in each scenario sub-directory for each study region directory. This file is important since it contains the volumetric flow for each reach, in CFS, which is used in the HEC-18 equations.

Several other variables used in scour estimation are calculated from data obtained via Hazus and ArcGIS. Output of the Hazus flood model includes an ArcGIS shape file showing flood extent and shape. Using this shape file and ArcGIS measurement tools, the width of the flood is determined, which is used in calculating the channel flow area. Slope of a given reach is calculated by determining the elevation upstream and downstream of the bridge and then measuring the distance (feet) through the stream bed between the two points. This value is then divided by the distance (feet) between the two elevation points to determine the river slope. Similarly, the velocity of a given section is determined by dividing the volumetric flow rate, in CFS, by the flood's cross-sectional area, in square feet.

4.2.2.2 Data Gathering - Other Sources

In addition to flood model outputs from Hazus, several other data sources are utilized. These include the US National Bridge Inventory (NBI), Google Earth™, direct observation, and the United States Geological Survey (USGS) stream gauge network. The NBI provides data relative to total bridge structure length and width. All elevations for decking, approaches and normal stream depth may be obtained using Google Earth™ or direct field observation of the bridge under analysis. Non-flood stream depth as well as stream bed elevation can be estimated from USGS stream gauge data, if available, direct field observation, or extrapolated using Google Earth™ elevation.

4.2.2.3 Scour Calculations – Design and Future Floods

Determining the damage for a future flood event is accomplished by solving the HEC-18 equations for two flood conditions. The first flood condition represents scour that would occur from an event for which the bridge was designed, while the second flood condition represents scour from a future flood event. The scour estimate for which the bridge is designed acts as the reference value of acceptable scour, hereafter known as "base scour value". The flood return period from which to calculate the base scour value may be chosen from actual bridge design documentation, if available, or from current design standards. If a structure is known to have existing scour problems or is nearing the end of service, a short flood return period (e.g., 5 or 10 years) may be appropriate to represent the reduced life expectancy. After computing the base scour value, the user chooses a return period for a future flood, creates a second flood model, and calculates the estimated scour from the future event.

As noted earlier, contraction scour can occur as live bed or clear water scour, depending on particle size of the stream bed material. To address this consideration, contraction scour is calculated for three particle sizes representing gravel, sand and clay. Selection of particle size values is based on the median value for the gravel and sand particle ranges, while clay is based on the upper cutoff for the size range as described by the USDOT (US DOT 2006). For each size range, critical velocity calculations (Equation 1) are applied to determine if the particle experiences clear water (Equation 2) or live bed (Equation 3) contraction scour for the given flood conditions. To facilitate uniformity of calculation, all conveyance channels are treated as triangular, open flow channels, with the triangle base defined as the width of the water surface upstream from the bridge and the flood depth at centerline being the triangle height (Bengston 2010).

4.2.2.4 Scour Factor

From the scour values obtained for the base value and future event, a scour factor is calculated. This factor is used in estimating the damage from the future flood event and involves three steps. The first step consists of establishing the fraction of additional scour from the future event compared to the base scour value:

$$\left|\left(1 - \frac{Base\ Scour\ Value}{Future\ Scour\ Value}\right)\right| \qquad [10]$$

This scour ratio is calculated for pier, left and right abutment, and the three particle sizes considered for contraction. The term “base scour value” indicates the predicted scour for the given bridge element for the designed flood return period while the “future scour value” represents the predicted scour for the future flood return period. The absolute value of the quantity is used in the calculation since Hazus may return future flood levels that may be less than base flood levels. Analysis of this phenomenon, the scour equations, and equation input data did not readily identify the cause of this anomaly; however, it is theorized that the flood prediction algorithm native to the Hazus application is responsible. If no scour is predicted for either the base or future case, a value of zero is used.

Equal weighting is used for the three types of scour considered. Since contraction and abutment scour include multiple elements, these values are combined prior to weighting. For contraction scour, 33% of the scour value for each particle size is summed to develop the contraction scour value, while 50% of each abutment scour is summed to develop the aggregate abutment scour value. Equations 11a and 11b provide the calculation for contraction and abutment scour ratio, respectively.

$$Contraction\ Scour\ Ratio = 0.33CS_g + 0.33CS_s + 0.33CS_c \quad [11a]$$

$$Abutment\ Scour\ Ratio = 0.5LA + 0.5RA \quad [11b]$$

For Equation 11a, subscript g, s and c represent contraction scour ratio (CS) of gravel, sand and clay, respectively, while in Equation 11b, LA and RA represent the left and right abutment scour ratios, respectively. Note that Equation 11a consists of contraction scour calculated for three particle types. Traditional use of scour equations requires analysis of the composition of the stream bed to establish particle sizes present and their distribution. Once this analysis is complete, a single fiftieth percentile diameter particle (D_{50}) value for the stream bed is used in the clear-water scour calculation. In recognition of the varied composition of stream beds, this methodology calculates contraction scour for the median diameter particle of the three major types of transportable bed material, gravel, sand and clay as defined in the HEC-18 publication (US DOT 2012). The values obtained are then used to calculate base scour to future scour ratios for each particle. The final contraction scour value is obtained by summing one third of each particle type scour value and dividing by three. This approach assumes an equal distribution of gravel, sand and clay particles. The final scour factor (SF) is calculated as follows:

$$Scour\ Factor = \frac{(0.33\ Pier\ Ratio + 0.33\ Contraction\ Ratio + 0.33\ Abutment\ Ratio)}{3} \quad [12]$$

4.2.2.5 Monetizing Damage

Estimating bridge damage begins by calculating the total replacement value of the bridge using data from the NBI and USDOT. The total bridge surface area (square meters), is obtained by multiplying the structure length (NBI - Field 49, in meters) by the bridge width (NBI - Field 52, in meters) (US DOT 2012). The bridge area is then multiplied by average new bridge construction estimates from the USDOT, which in 2012, were $1,803 per square meter for National Highway System (NHS) bridges and $1,783 per square meter for non-NHS bridges (US DOT 2012). The scour factor is multiplied by the construction cost to estimate the damage, in dollars, for a given flood. To adjust the USDOT bridge cost reference value for periods of study prior to or after 2012, the present value of money formula may be used. The equation for the future value of a lump sum is shown in Equation 13, while Equation 14 shows the past value of a lump sum:

$$FV = PV(1 + i)^N \quad [13]$$

$$PV = \frac{FV}{(1+i)^N} \quad [14]$$

where FV is future value, PV is present value, i is the interest rate and N is the number of compounding periods (Finkler 2003).

4.3 METHOD VALIDATION

To determine the efficacy of the developed methodology in estimating scour damage, eight bridges which incurred damage from a May 2010 flood event in Davidson County (Nashville, TN) were selected as a case study. This flood resulted from the area experiencing between 17 and 18 inches of rainfall within 36 hours. This historic precipitation event resulted in flood return periods in the area ranging from 70 to 500 years, depending on the stream in question(USACE 2010). As part of the bridge repair and recovery effort, the Metropolitan Government of Nashville and Davidson County compiled information on costs from flood damage on these bridges.

4.3.1 Return Period Selection

For the purposes of this case study, a flood return period of 100 years was chosen as the design flood for the bridges. The return period was based on the age of the bridges, available data and prevailing design standards in Tennessee (TDOT 2012). To approximate the flood experienced in 2010, a future flood return period of 320 years was used. This value represents the average of flood return periods experienced across the area during the 2010 flood event. The average was used since neither rainfall nor flood return period was homogenous across the area and only a few larger streams had actual gauge data.

4.3.2 Scour Calculation and Damage Monetization

Table 2 provides a summary of scour results and the calculated scour factor for each bridge. The results indicate a range of conditions as having been experienced by the selected bridges. None of the bridges were expected to experience scour for the gravel particle size, while six of the eight experienced scour only for clay bed materials. In three instances, bridges were predicted to experience no contraction scour at all. Pier scour was observed across all bridges modeled with the exception of two structures which had no piers. Similarly, abutment scour was consistently observed across all structures. Of note is one bridge's abutment was not estimated to have any scour. This was due to the Hazus flood model predicting no flood waters in that area. Figure 1 shows the location of the bridges within Davidson County as well as their position relative to the 2010 flood.

			Contraction			Abutment		
	Return Period	**Pier**	**Gravel**	**Sand**	**Clay**	**Left**	**Right**	**Scour Factor**
Bellevue Rd at Flat Creek	100	0	0	1.92	1.94	3.77	3.25	0.0254
	320	0	0	2.58	2.6	4.03	3.46	
Harding Pl at Richland Creek	100	0	0	0	3.54	2.23	2.53	0.0153
	320	0	0	0	4.94	2.33	2.66	
Old Harding Rd at Harpeth River	100	20.41	0	72.81	83.12	6.98	0	0.0190
	320	22.7	0	78.48	89.6	7.34	0	
McCrory Lane at Harpeth River	100	13.45	0	0	25.29	3.24	4.51	0.0300
	320	15.98	0	0	28.86	3.07	4.13	
Antioch Pike at Mill Creek	100	16.19	0	0	16.39	9.97	12.61	0.0161
	320	17.91	0	0	16.29	10.45	13.29	
Farnsworth Dr at Richland Creek	100	3.35	0	0	0	3.98	4.03	0.0138
	320	3.8	0	0	0	3.95	4	
Newsome Stn Rd at Harpeth River	100	14.67	0	0	14.87	13.11	8.71	0.0276
	320	16.26	0	0	15.29	10.06	8.85	
Pettus Rd at Mill Creek	100	7.82	0	0	0	2.37	2.27	0.0223
	320	8.71	0	0	0	2.27	2.69	

Table 2: Predicted Scour and Scour Factor

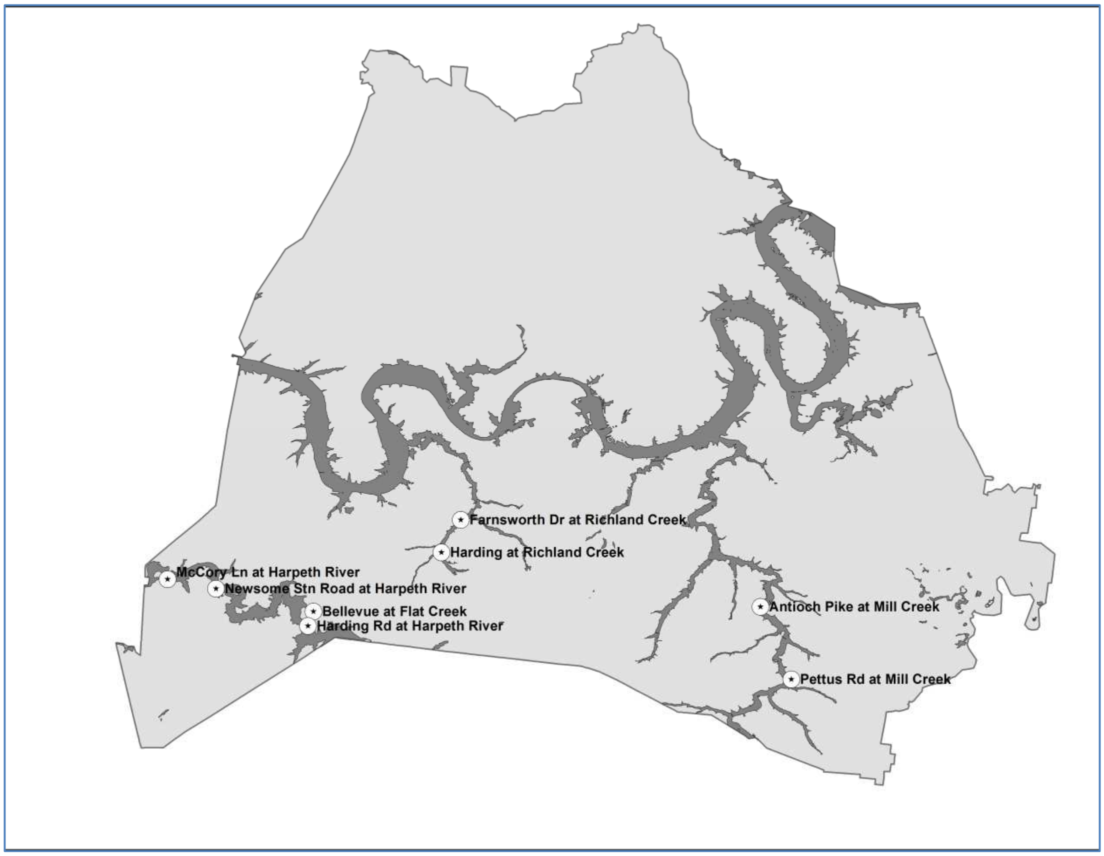

Figure 1: Bridges Studied in Davidson County

As discussed previously, bridge damage was monetized by determining the bridge area from NBI data and multiplying it by the 2012 USDOT estimate of $1,803 per square meter for new construction cost. The resulting values were then adjusted to 2010 dollars using Equation 14, employing an interest rate of 2.5%. This interest rate represented the average inflation rate for the period of 2000 to 2013 (McMahon 2014). Results of the calculations indicated predicted damage ranging from a low of $2,400 to a high of $78,000. Table 3 provides a summary of predicted damage and observed damage for each bridge.

Bridge	Scour Factor	Area (m2)	2010 Unit Cost/m2	Estimated Bridge Cost in 2012 Dollars	Estimated Cost Adjusted to 2010 Dollars	Estimated Damage	2010 Damage
Bellevue Rd @ Flat Creek	0.0254	55.3	$1,803	$99,700	$94,900	$2,400	$3,000
Harding Pl @ Richland Creek	0.0153	636.12	$1,803	$1,100,000	$1,090,000	$16,700	$13,000
Old Harding Pk @ Harpeth River	0.019	959.12	$1,803	$1,700,000	$1,600,000	$30,400	$19,000
McCrory Lane @ Harpeth River	0.03	1533.81	$1,803	$2,700,000	$2,600,000	$78,000	$30,000
Antioch Pike at Mill Creek	0.0161	843.48	$1,803	$1,500,000	$1,400,000	$22,500	$17,000
Farnsworth Dr @ Richland Creek	0.0138	112.24	$1,803	$202,000	$192,000	$2,600	$3,000
Newsome Stn @ Harpeth	0.0276	568.32	$1,803	$1,020,000	$975,000	$26,900	$11,000
Pettus Rd @ Mill Creek	0.0223	533.6	$1,803	$962,000	$915,000	$20,400	$11,000

Table 3: Estimated Damage and Observed Damage

4.3.3 Analysis of Predicted and Observed Damage

An assessment of data agreement between the predicted and observed damage values was conducted using the Pearson Product Moment Coefficient (Pearson's *r).* This test indicates if correlation exists between data sets and if the correlation is positive or negative. Values of the test range between -1 and 1, with -1 indicating a strong negative correlation, 1 indicating a strong positive correlation and 0 indicating no correlation (Mendenhall, Beaver et al. 2013). Results of the Pearson's r indicated a value of $r = 0.94$, $p<0.05$, suggesting a statistically significant, strong positive correlation between the monetary damage predicted for the subject bridges and that observed arising from the 2010 flood.

Before applying additional statistical tools, analysis of normality was conducted on both the predicted and observed data. Results of the Shapiro-Wilk's Normality Test indicated both the predicted data and observed data were normally distributed. Normal probability plots were also constructed for each data set. An ideal normal probability plot will be linear when the data is ranked from lowest to highest and plotted against the expected Z score for each data value. If the data is not normally distributed, the result of the plot shows random scattering of the data points. As shown in Figures 2 and 2, the probability plots approximate linearity consistent with normality (NIST 2013).

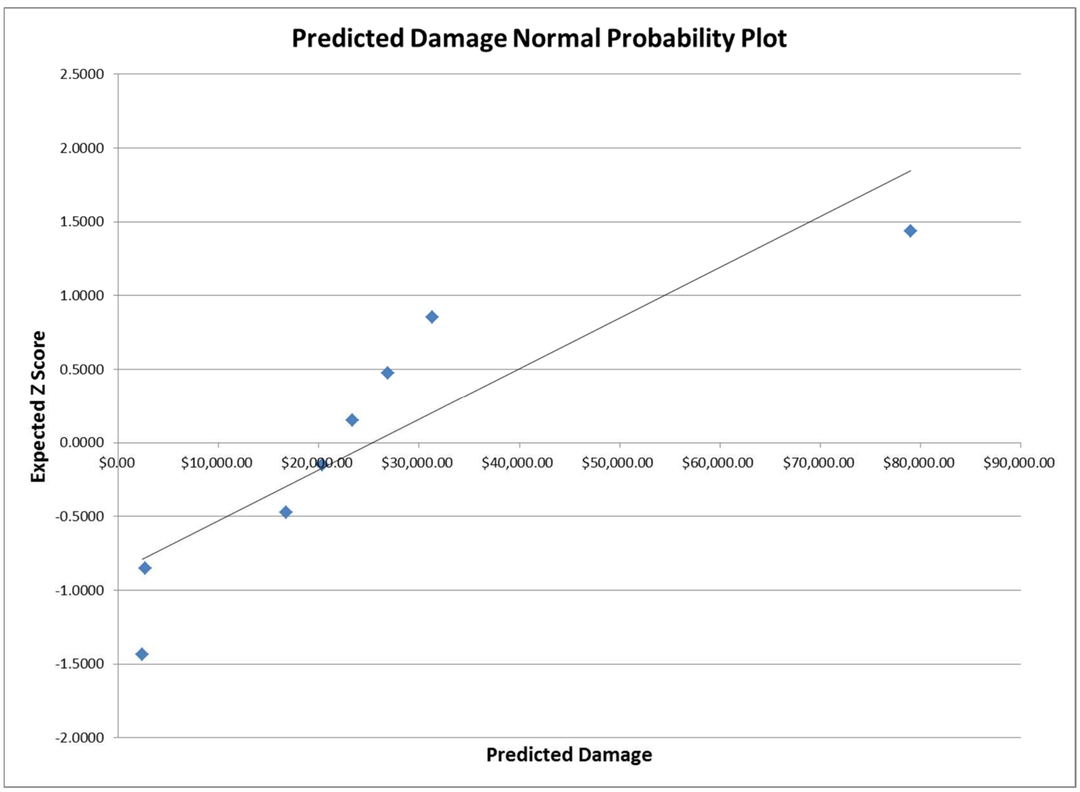

Figure 2: Predicted Damage Normal Probability Plot

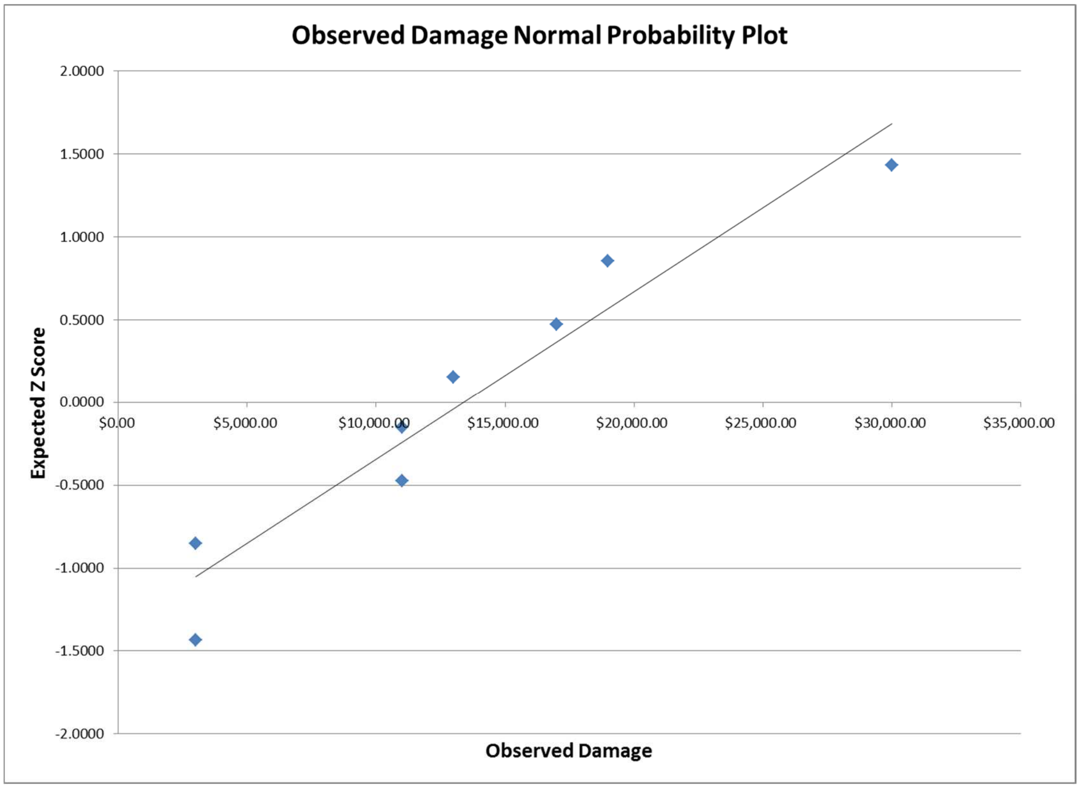

Figure 3: Observed Damage Normal Probability Plot

A comparison of the means of the two data sets was subsequently performed using the Student's t-Test assuming unequal variance, also known as Welch's t-Test. This method was chosen for two reasons: 1) since only two data sets are being compared, more complex methods such as analysis of variance is not applicable, and 2) this modification allows a t-statistic to be calculated when the variance of the data sets is unknown or unequal. A unique feature of this method is it does not utilize the traditional formula of n-1 for degrees of freedom, instead employing a method in which the variances are weighted to calculate degree of freedom (NIST 2013). Results of the t-test exhibited a p value of 0.22, indicating no statistically significant difference between the means of the predicted and observed data sets (Table 4).

	Estimated Damage	*2010 Damage*
Mean	24987.5	13375
Variance	564369821.4	78267857.14
Observations	8	8
Hypothesized Mean Difference	0	
df	9	
t Stat	1.295649787	
P(T<=t) one-tail	0.113669089	
t Critical one-tail	1.833112933	
P(T<=t) two-tail	0.227338177	
t Critical two-tail	2.262157163	

Table 4: Results of Student's t-Test

4.4 ANALYSIS OF SENSITIVITY

Although analysis indicated the predicted values for bridge damage were not statistically different from observed damage, the data did indicate estimated replacement cost correlates closely with estimated damage (Pearson's r = 0.998). This finding suggests ranking bridges by their estimated replacement costs alone may be an alternative to using scour factor analysis. To determine the significance of this observation, sensitivity analysis was performed on the scour factor methodology to determine if varying conditions would result in the methodology providing rankings different from estimated replacement cost alone. Sensitivity analysis is performed by changing individual key variables in an equation while holding all other variables constant. In doing this, the overall impact of the individual variable on the equation's outcome may be observed. This process is done in an iterative process with each variable until all have been assessed.

The equations for pier, contraction and abutment scour, previously discussed, each use variables associated with the bridge as well as the stream they span to estimate scour for the given component. The pier scour equation (Equation 4) utilizes pier width, angle of pier to the stream, and nose geometry of the pier as significant factors in pier scour calculation. The pier width is significant since it is the denominator in the equation's main ratio while pier nose geometry determines the value of k_1 (Table 1) and pier angle is used in the calculation of k_2 (Equation 6). Contraction scour may occur as either clear water or live bed scour as shown in Equations 3 and 4, respectively. Analysis of these equations indicates that width at the contraction is a contributing factor as an inverse square function for clear water scour and as an inverse function in live bed scour. Additionally, bed composition, represented by D in the clear water equation, is an inverse function and may vary from stream to stream. Finally, the abutment scour equation (Equation 7) employs abutment length as the denominator in the main equation ratio while abutment type and abutment angle to stream are used to calculate the K_1 and K_2 coefficients, respectively.

Five of the eight bridges used for the original scour factor calculations were chosen for analysis representing the extreme high and low costs for bridge replacement as well as three mid-range replacement cost bridges. The estimated replacement values of the bridges range from \$2,600,000 to \$193,000 with three bridges clustered with values near \$1 million. Scour calculations were performed for each bridge component using two additional values for the identified variables (Table 5).

<table>
<tr><th></th><th></th><th>McCrory Lane</th><th>Old Harding Pike</th><th>Farnsworth Dr.</th><th>Antioch Pike</th><th>Harding Place</th></tr>
<tr><td rowspan="3">Pier</td><td>Pier Width</td><td>6 and 9 feet</td><td>8 and 12 feet</td><td>2 and 6 feet</td><td>8 and 12 feet</td><td rowspan="3">No Piers</td></tr>
<tr><td>Pier Nose</td><td>Square, Sharp</td><td>Round, Sharp</td><td>Square, Sharp</td><td>Square, Sharp</td></tr>
<tr><td>Angle</td><td colspan="4">10 and 20 degrees</td></tr>
<tr><td rowspan="3">Abutment</td><td>Abutment</td><td>8 and 14 feet</td><td>7 and 11 feet</td><td>20 and 25 feet</td><td>80 and 90 feet</td><td>8 and 14 feet</td></tr>
<tr><td>Angle</td><td colspan="5">10 and 20 degrees</td></tr>
<tr><td>Abutment Type</td><td colspan="5">Wing Wall, Spill Through</td></tr>
<tr><td rowspan="2">Contraction</td><td>Contraction</td><td>90 and 98 feet</td><td>32 and 36 feet</td><td>77 and 83 feet</td><td>32 and 96 feet</td><td>50 and 55 feet</td></tr>
<tr><td>Bed Particle</td><td colspan="5">Individually gravel, clay and sand</td></tr>
</table>

Table 5: Variable Values

From these calculations minimum, median and maximum component scour factor values were identified, new bridge scour factors calculated, and new monetary damage estimated. Results of the analysis indicated maximum and median values provided scour factors whose damage estimates were consistent with replacement cost alone; however, scour factors calculated with the minimum component values provided a change in rank order (Table 6).

	MAXIMUM						
	Estimated Replacement Cost	**Maximum Pier Scour**	**Contraction Scour**	**Abutment Scour**	**Scour Factor**	**Estimated Damage**	**Rank**
McCrory Lane	$2,600,000	0.05225	0.01352	0.09960	0.05512	$143,000	1
Old Harding	$1,600,000	0.03474	0.01575	0.00847	0.01965	$31,000	2
Farnsworth	$193,000	0.03956	0.00000	0.00288	0.01415	$2,700	5
Harding Place	$1,090,000	0	0.03090	0.02034	0.01708	$19,000	4
Antioch Pike	$1,400,000	0.03183	0.00067	0.01613	0.01621	$23,000	3
	MEDIAN						
	Estimated Replacement Cost	**Pier Scour**	**Contraction Scour**	**Abutment Scour**	**Scour Factor**	**Estimated Damage**	**Rank**
McCrory Lane	$2,600,000	0.05225	0.01347	0.02432	0.03001	$78,000	1
Old Harding	$1,600,000	0.03329	0.01574	0.00809	0.01904	$30,000	2
Farnsworth	$193,000	0.03908	0	0.00249	0.01386	$2,600	5
Harding Place	$1,090,000	0	0.03086	0.01515	0.01534	$17,000	4
Antioch Pike	$1,400,000	0.03169	0.00067	0.01602	0.01613	$22,000	3
	MINIMUM						
	Estimated Replacement Cost	**Pier Scour**	**Contraction Scour**	**Abutment Scour**	**Scour Factor**	**Estimated Damage**	**Rank**
McCrory Lane	$2,600,000	0.02442	0	0.01968	0.01470	$38,000	1
Old Harding	$1,600,000	0.03143	0	0.0066	0.01268	$20,000	3
Farnsworth	$193,000	0.03327	0	0.00230	0.01186	$2,300	5
Harding Place	$1,090,000	0	0	0.01177	0.00392	$4,300	4
Antioch Pike	$1,400,000	0.03166	0	0.01376	0.01514	$21,000	2

Table 6: Sensitivity Analysis

Results of this analysis suggest that estimated replacement value may be of use in performing a gross ranking of bridges for adaptation planning priority with the scour factor method useful for refining estimates when bridges have closely clustered replacement values.

4.5 FURTHER DISCUSSION

Results of the statistical and sensitivity analysis suggest that using estimated replacement cost and scour factor analysis may be useful in prioritizing bridges for adaptation measures for future flood events. However, further discussion is warranted to ensure the advantages and limitations of the methodology are fully understood.

4.5.1 Methodology Advantages

The developed methodology provides a straightforward way to estimate and refine bridge priority and scour damage prediction (at a screening level) for flood adaptation planning using Hazus, a free and not overly cumbersome tool that has flood modeling capabilities that are adequate and appropriately supported for local municipalities use within a GIS platform (Banks, Camp et al. 2014). As previously discussed, scour analysis for bridges typically involves potentially time consuming geotechnical engineering and physical assessment of structures above and below the water surface, and is based on conditions at time of survey. Given Hazus' capability of modeling floods with varying return periods and the proposed methodology, planners now have the ability to estimate damage from a variety of future flood events and to estimate scour damage on multiple bridges in a few hours. Although lacking the exhaustive and comprehensive nature of traditional scour surveys, the developed methodology may be employed to rapidly assess a suite of bridges for the purpose of identifying those most susceptible to scour. This information may then be used as a screening tool for adaptation resource prioritization or to identify structures warranting more extensive scour surveys.

4.5.2 Methodology Limitations

The natural process of scour and the equations that have been developed to describe this phenomenon are complex. The goal of this research was to develop a screening methodology that can be made accessible to a wide variety of users which produces an estimation of future flood impact for use in adaptation planning with little investment in software and training costs. While being readily accessible by users with a variety of technical expertise, the Hazus flood model is not as complex as other available flood modeling tools (Banks, Camp et al. 2014). As a result, although the Hazus flood model provides estimates of flood depth and extent, it does not perform more complex operations such as tube flow experienced at obstructions such as abutments. Such limitations could be overcome by using the US Army Corps of Engineers HEC-RAS tool and importing the flood data generated by HEC-RAS into Hazus (FEMA 2009). Although not impacting this methodology, a limitation of which users should be cautious is the inventory data included with Hazus, such as building cost, structure inventory and population data, is over a decade old (FEMA 2009). Caution should be exercised in basing any estimates of loss on the traditional Hazus application unless the underlying data has been updated.

The scour equations presented in HEC-18 provide mathematical estimates of complex natural phenomena. These mathematical estimates may not accurately describe the actual actions taking place at a bridge during floods due to simplifying assumptions. As previously noted, scour for contractions, piers and abutments were considered, while complex scour conditions related to stream bed aggradation and degradation were not. In addition, the HEC-18 equations provide only estimates of scour and do not factor in naturally occurring scour limiting factors such as bed armoring (US DOT 2012). Consequently, the HEC-18 equations may produce results for a specified flood condition that overestimate scour (See Table 2 contraction scour for "Old Harding Road at Harpeth River").

4.5.3 Methodology Application Scenario - Pulaski County (Little Rock), Arkansas

Regional downscaling of climate models indicates a significant likelihood that Pulaski County (Little Rock), Arkansas will experience climate change-induced extreme flooding events (Camp and Abkowitz August 2014). Given the city is a regional nexus of several major components of the National Transportation System, prioritizing and adapting the transportation infrastructure for resilience to these events is prudent (US DOT 2012). The NBI indicates that Pulaski County contains approximately 712 bridges of which 504 pass over water (US DOT 2012). Of the overwater bridges, three were selected to demonstrate application of the scour factor methodology for adaptation prioritization relative to a 1000-year flood event. This example was done without regard to pre-screening by estimated replacement value to provide a demonstration of how the scour factor methodology alone would is employed. For actual implementation, bridges would first be triaged by estimated replacement value with scour factor used to refine data for bridges with similar replacement value. For the purposes of this example, a 100-year flood event is stipulated as the return period for which the three bridges were designed. The locations of the bridges selected for analysis and prioritization are presented in Figure 4.

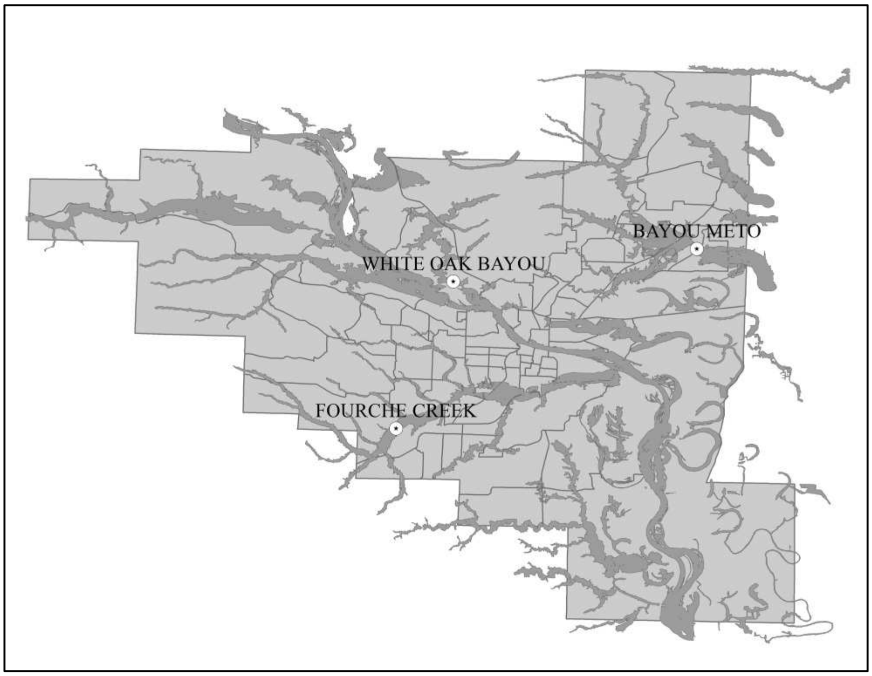

Figure 4: Pulaski County, Arkansas (Little Rock) Bridges

To perform the analysis, data is required that describes the bridges as well as the floods. Estimates of bridge and component dimensions were obtained from Google Earth™ and the NBI while elevations were estimated using Google Earth™ and ArcGIS. USGS stream gauge data was consulted for non-flood water levels. Values for flood depth at abutments, centerline flow depth, stream volumetric flow, and width of the flood were obtained using Hazus. Depths were obtained using pixel values for the stream centerline and abutment. Width was determined immediately upstream from the bridge contraction and was measured parallel to the bridge across the entire flood width. In accordance with guidance in HEC-18, if flood width exceeded bridge span, the bridge span was used as flood width (US DOT 2012). Where flood width exceeded bridge span, the ratio of span to the total flood width was multiplied by total volumetric flow to represent volumetric flow impacting bridges. Table 5 summarizes data obtained for the bridges and streams from sources outside of Hazus while Table 6 summarizes data obtained from Hazus.

Required Data (Dimensions are in feet)	Data Source	SH161 at Bayou Meto	I-430 NB at White Oak Bayou	I-430 NB at Fourche Creek
Deck Elevation	Google Earth™	247	266	290
Contraction Width	Google Earth™	158	253	337
Distance from Bottom of Deck to Stream Bed	Google Earth™	9.5	21.71	15.59
Right Abutment Length	Google Earth™	75	261	217
Right Abutment Height	Google Earth™	75	29	15.59
Left Abutment Length	Google Earth™	0	261	217
Left Abutment Height	Google Earth™	0	29	15.59
Number of Piers	Google Earth™	0	3	4
Pier Width	Google Earth™	0	4	4
Pier Length	Google Earth™	0	31	42
Average Non-Flood Stream Depth	Google Earth™	3	3	5
Channel Width	Google Earth™	35	20.38	183
Bridge Length	NBI	165	289	337
Bridge Width	NBI	31	63	42

Table 7: Data Required for Scour Analysis and Source

Required Data (Unless otherwise noted, dimensions are in feet)	Data Source	SH161 at Bayou Meto		I-430 NB at White Oak Bayou		I-430 NB at Fourche Creek	
		100 RP	1000 RP	100 RP	1000 RP	100 RP	1000 RP
Flood Depth	Hazus/ArcGIS	21	22.9	20.38	28.43	21.23	22.77
Flood Width	Hazus/ArcGIS	165	165	172	172	337	337
Volumetric Flow (cfs)	Hazus/ArcGIS	32,535	49,905	10,761	15,875	15,699	24,208
Left Abutment Flood Depth	Hazus/ArcGIS	11.89	13.04	16.7	23.26	7.98	10.5
Right Abutment Flood Depth	Hazus/ArcGIS	15.18	14.76	16.68	16.34	7.98	10.7
Distance of Bridge from Upstream Elevation Point	Hazus/ArcGIS	1257		1160		917	
Upstream Elevation	Hazus/ArcGIS	238		241		271	
Downstream Elevation	Hazus/ArcGIS	225		238		268	
Distance between Elevations	Hazus/ArcGIS	3660		2031		3102	

Table 8: Data from Hazus

The HEC-18 equations for contraction, abutment and pier scour appear in Table 7, using the data from Tables 5 and 6 for both a 100-year (base year) and 1000-year (future) flood. Once scour values were determined, the ratios of the 100-year and 1000-year flood scour were calculated for the pier, contraction and abutment scour using Equation 10. To demonstrate calculations, data for the I-430 Bridge at Fourche Creek is used. An example of the scour ratio calculation is presented in Equation 16 for pier scour.

			Contraction Scour (ft)			Abutment Scour (ft)	
	Return Period	Pier Scour (ft)	Gravel	Sand	Clay	Left	Right
SH161 at Meto Bayou	100	0	22.06	22.06	21.61	45.83	42.21
	1000	0	22.57	22.57	22.1	57.37	55.01
I-430 NB at White Oak Bayou	100	17.21	0	2.41	2.13	17.66	17.67
	1000	25.06	0	3.23	2.86	19.84	22.28
I-430 NB at Fourche Creek	100	20.54	0	9.15	8.9	34.65	34.65
	1000	25.78	0	9.69	9.42	40.91	40.65

Table 9: Scour Predictions for Little Rock Bridges

$$\text{Pier Scour Ratio: } \left|\left(1-\frac{20.54}{25.78}\right)\right| = 0.2032 \qquad [16]$$

Once individual component scour ratios were determined, Equations 11a and 11b were used to determine the composite contraction scour and composite abutment scour ratios, respectively (Equations 17 and 18).

$$Contraction\ Scour\ Ratio = 0.33(0)_g + 0.33(0.0557)_s + 0.33(0.0552)_c = 0.0365 \qquad [17]$$

$$Abutment\ Scour\ Ratio = 0.5(0.1530) + 0.5(0.1476) = 0.0366 \qquad [18]$$

After completing scour calculations for bridge components, Equation 12 was employed to arrive at the scour factor for the I-430 Fourche Creek bridge under 1000-year flood conditions:

$$\frac{0.33\ (0.2032) + 0.33(0.0366) + 0.33(0.1503)}{3} = 0.0429 \qquad [19]$$

Once the scour factor is determined, it is multiplied by the estimated bridge construction cost to estimate the damage of the future flood event. As was previously discussed, to estimate the construction cost, the area of the bridge is calculated utilizing bridge length and width data from NBI (fields 49 and 52). The estimated construction cost per square meter of bridge is adjusted from its value in 2012 dollars ($1803/m^2) to present value in 2014 dollars ($1894/m^2) using Equation 14 and an interest rate of 2.5%. Table 8 summarizes the monetization of damage estimates for the three bridges.

Bridge	Structure Length (NBI Field 49, in meters)	Structure Width (NBI Field 52, in meters)	Area (m2)	2014 $/m2 for Construction	Estimated Replacement Cost	Scour Factor	Estimated Damage
I-430 NB at White Oak Bayou	88.1	19.3	1700	$1,894	$3,200,000	0.0704	$225,000
I-430 NB at Fourche Creek	103	12.9	1329	$1,894	$2,500,000	0.0429	$107,000
SH161 at Meto Bayou	50.3	9.7	488	$1,894	$924,000	0.0263	$24,300

Table 10: Summary of Monetized Damage

An alternative method to calculate damage is to use the depreciated present value of the bridge. There are several methods of depreciation calculation available but in keeping with the goal of developing a tool that is available to a large user base, the straight-line depreciation method was chosen due to its simplicity of application. Straight-line depreciation is calculated by first dividing the full cost of the bridge by the structure's designed useful life. This provides the amount of depreciation per year. The annual depreciation amount is multiplied by the difference between the year the bridge was constructed and the year in which analysis is conducted. The resulting value is subtracted from the total estimated construction cost to provide the present residual value of the bridge (FASAB 2013).

Once damage is monetized, the bridges are prioritized for adaptation planning using rank order of damage from greatest to least value. Table 9 provides an example of straight-line depreciation applied to the Little Rock bridges. Note that the White Oak Bayou bridge is ranked as the highest priority.

Bridge	Estimated Replacement Cost	Year Built	Years of Depreciation (Construction to 2014)	Depreciation per Year ($/Yr 100 year service life)	Total Depreciation (2014 $)	Residual Value	Estimated Damage	Percent Depreciated Value
I-430 NB at White Oak Bayou	$3,200,000	1971	43	$32,000	$1,300,000	$1,800,000	$226,000	12.5%
I-430 NB at Fourche Creek	$2,500,000	1973	41	$25,000	$1,030,000	$1,400,000	$108,000	7.8%
SH161 at Meto Bayou	$924,000	1954	60	$9,000	$554,000	$369,000	$24,000	6.5%

Table 11: Depreciated Monetization

In addition to adaptation prioritization, this methodology may also assist in classifying a bridge as "failed". A municipality or planning entity could establish a percent monetary damage relative to the full or depreciated cost beyond which replacement of the entire bridge would be warranted. In such an event, if multiple bridges exceed a municipality's failure threshold, the NCHRP Report 107 methodology could be used to differentiate priority. Utilizing the NCHRP method on the two I-430 bridges, the method estimates the failure of the White Oak bridge will produce almost $400,000 more in indirect loss than the Fourche Creek bridge. Including an analysis of indirect costs such as this is prudent to comprehend the total risk from a failure event in determining prioritization. Major factors present in the NCHRP method that will impact differences in indirect cost are average daily traffic, detour length, and percentage of commercial traffic carried by the structure (Stein and Sedmara 2006). Table 10 provides a comparison of indirect costs for the White Oak and Fourche Creek bridges.

Bridge	Estimated Indirect Cost
I-430 NB at White Oak Bayou	$5,200,000
I-430 NB at Fourche Creek	$4,800,000

Table 12: Indirect Costs of Bridge Failure

4.6 CONCLUDING REMARKS

Case study results utilizing the developed methodology suggest that Hazus and HEC-18 may be used to establish semi-quantitative estimates of scour damage from future flood events. Predicted and observed damage values for bridges demonstrated strong positive correlation and no statistically significant difference. However, the study was limited to only eight bridges in the same region with similar stream characteristics. Application of the method to additional structures in other geographic locations is recommended, as presented in a small case study here, to evaluate whether the methodology yields consistent results at other sites. Care should also be exercised due to the comparatively simple manner in which Hazus models flood events. Utilizing more complex flood models, such as HEC-RAS, and importing the data into Hazus could improve predictive ability, yet would also increase the skills required by the user for implementation.

The developed methodology in conjunction with initial ranking by estimated replacement cost could also be employed by municipalities to provide a relatively quick and inexpensive screening tool to identify bridges for traditional scour assessment. The mode of implementation by the municipality would require integration into the larger process of resource allocation, but having this method available would allow decision-makers to communicate potential impacts to the community. In the context of anticipated increases in precipitation frequency and duration brought about by climate change, utilizing a methodology for assisting municipalities in cost-effective allocation of finite resources to critical infrastructure, such as bridges, is a prudent strategy.

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CHAPTER 5

Research Contribution and Additional Research Topics

5.1 INTRODUCTION

The purpose of research is to expand the body of knowledge regarding what is known about a given topic. Even though knowledge will be gained through research, the process will uncover even more areas for study. The following chapter is a synopsis of the contributions made by this research as well as opportunities identified for further study.

5.2 RESEARCH CONTRIBUTIONS

This research focused on developing a decision support tool useful to a wide variety of organizations with varying technical skills for rapidly assessing and prioritizing bridges for adaptation to climate-induced flood events. A state-of-the-art review produced a candidate list of programs used for flood modeling and damage assessment. Analysis of these tools indicated that the majority were focused on flood modeling with damage assessment to structures being a secondary activity. Four of the tools identified did both flood modeling and damage assessment, with only two, HEC-FIA and HAZUS-MH (also referred to as Hazus), offering a possible cost-effective solution. In all products, bridge damage assessment was absent or only rudimentarily assessed.

In addition to functionality, the tools were assessed relative to technical expertise required for use. Hazus was identified as the most promising, commonly available, low cost, and easily used program for further study. Analysis was conducted on Hazus to determine its capability for performing more sensitive bridge damage analysis. A significant finding during this phase of research was the limitation of Hazus relative to modeling floods at sub-county levels. This was important for understanding the limitations in use of the program.

The final research contribution was the development of a rapid, minimally complex methodology for bridge damage assessment. The methodology was developed using Hazus and other resources such as the National Bridge Inventory to obtain the variables necessary to solve scour equations developed by the US Department of Transportation. These equations were solved for the bridges' designed return period as well as a future return period of interest. A relationship was then developed between the future scour and the base year scour that resulted in the formulation of a scour factor. This scour factor was multiplied by the estimated replacement cost of the bridge to provide a monetary damage estimate. The method was applied to eight bridges in Davidson County (Nashville), Tennessee, and the results validated against actual flood damage values from floods that impacted the bridges in May 2010. Results of applying the calibrated methodology indicated predicted and observed damage values did not exhibit a statistically significant difference ($p=0.22$, $t_{\alpha=0.05}$). Additionally, a Pearson's correlation coefficient of approximately 0.94 was observed. The methodology was then applied to selected bridges in Pulaski County (Little Rock), Arkansas, to demonstrate use in decision making. Pulaski County was chosen since it has been identified as an area susceptible to climate-change induced flooding. Overall, comparison of the methodology to known flood damage data suggests it may be used in conjunction with estimated bridge damage as a tool to screen bridges for adaptation planning or to prioritize bridges for more traditional scour assessment approaches.

5.3 FUTURE RESEARCH OPPORTUNITIES

In performing the research to develop this methodology, a number of areas were identified that merit further exploration. The following items are suggested as potential research topics, either building on or stemming from this original research:

- Develop an extension or additional tool for Hazus to automate the determination of the scour factor and resulting damage estimate.
- Expand method validation to other geographic regions where known flood damage values are available and use it in actual municipalities of varying size to determine its effectiveness and ability in broad application.
- Perform an in-depth analysis of the United States Army Corps of Engineers HEC-FIA tool and Hazus to determine if the tools are complementary and if they could be combined into a single predictive tool.
- Re-evaluate the equations used by Hazus to estimate flood return frequency and peak discharge flow in light of climate-change conditions.
- To facilitate no or low-cost evaluation of potential adaptation measures, develop within Hazus the capability of performing "what if" analysis of the impact of selected adaptation measures.
- Investigate limitations in Hazus' hydrology and hydraulics function with an emphasis on identifying how high-resolution DEMs may be used to improve flood prediction at both a county and sub-county level.

APPENDIX A
Davidson County (Nashville), Tennessee Bridge Data

Bellevue Rd @ Flat Creek	Pier	Gravel	Sand	Clay	Left	Right
100	0	0	1.92	1.94	3.77	3.25
320	0	0	2.58	2.60	4.03	3.46
Ratio	0	0	0.2558	0.2538	0.0645	0.0607
		0	0.0844	0.0838	0.0323	0.0303
Composite Scour	Pier	0				
	Contraction	0.05550				
	Abutment	0.02066				
Scour Factor	0.02539					

Harding Pl @ Richland Creek	Pier	Gravel	Sand	Clay	Left	Right
100	0	0	0	3.54	2.23	2.53
320	0	0	0	4.94	2.33	2.66
	0	0	0	0.28340	0.04292	0.04887
		0	0	0.09352	0.02146	0.02444
Composite Scour	Pier	0				
	Contraction	0.03086				
	Abutment	0.01515				
Scour Factor	0.01534					

Old Harding @ Harpeth	Pier	Gravel	Sand	Clay	Left	Right
100	20.41	0	72.81	83.12	6.98	0
320	22.7	0	78.48	89.6	7.34	0
	0.10088	0	0.07225	0.07232	0.04905	0
		0	0.02384	0.02387	0.02452	0
Composite Scour	Pier	0.03329				
	Contraction	0.01574				
	Abutment	0.00809				
Scour Factor	0.01904					

McCory Ln @ Harpeth	Pier	Gravel	Sand	Clay	Left	Right
100	13.45	0	0	25.29	3.24	4.51
320	15.98	0	0	28.86	3.07	4.13
	0.15832	0	0	0.12370	0.05537	0.09201
		0	0	0.04082	0.02769	0.04600
Composite Scour	Pier	0.05225				
	Contraction	0.01347				
	Abutment	0.02432				
Scour Factor	0.03001					

Antioch Pike	Pier	Gravel	Sand	Clay	Left	Right
100	16.19	0	0	16.39	9.97	12.61
320	17.91	0	0	16.29	10.45	13.29
	0.09604	0	0	0.00614	0.04593	0.05117
		0	0	0.00203	0.02297	0.02558
Composite Scour	Pier	0.03169				
	Contraction	0.00067				
	Abutment	0.01602				
Scour Factor	0.01613					
Newsome Stn Rd	**Pier**	**Gravel**	**Sand**	**Clay**	**Left**	**Right**
100	14.16	0	0	0	9.71	6.81
320	16.26	0	0	0	10.06	8.85
	0.12915	0	0	0	0.03479	0.23051
		0	0	0	0.01740	0.11525
Composite Scour	Pier	0.04262				
	Contraction	0				
	Abutment	0.04377				
Scour Factor	0.02880					
Pettus Rd	**Pier**	**Gravel**	**Sand**	**Clay**	**Left**	**Right**
100	7.82	0	0	0	2.37	2.27
320	8.55	0	0	0	2.07	2.25
	0.08538	0	0	0	0.14493	0.00889
		0	0	0	0.07246	0.00444
Composite Scour	Pier	0.02818				
	Contraction	0				
	Abutment	0.02538				
Scour Factor	0.01785					
Farnsworth	**Pier**	**Gravel**	**Sand**	**Clay**	**Left**	**Right**
100	3.35	0	0	0	3.98	4.03
320	3.8	0	0	0	3.95	4
	0.11842	0	0	0	0.00759	0.0075
		0	0	0	0.00380	0.0038
Composite Scour	Pier	0.03908				
	Contraction	0				
	Abutment	0.00249				
Scour Factor	0.01386					

APPENDIX B
Pulaski County (Little Rock), Arkansas Bridge Data

SH161 at Meto Bayou	Pier	Gravel	Sand	Clay	Left	Right
100	0	22.06	22.06	21.61	45.83	42.21
1000	0	22.57	22.57	22.1	57.37	55.01
	0	0.02260	0.02260	0.02217	0.20115	0.23268
		0.00746	0.00746	0.00732	0.10058	0.11634
Composite Scour	Pier	0				
	Contraction	0.0073				
	Abutment	0.0716				
Scour Factor	0.02631					
Area	5115	$ 9,687,810				
		$ 254,850				

I-430 NB at White Oak Bayou	Pier	Gravel	Sand	Clay	Left	Right
100	17.21	0	2.41	2.13	17.66	17.67
1000	25.06	0	3.23	2.86	19.84	22.28
	0.31325	0	0.25387	0.25524	0.10988	0.20691
		0	0.08378	0.08423	0.05494	0.10346
Composite Scour	Pier	0.10337				
	Contraction	0.05544				
	Abutment	0.05227				
Scour Factor	0.07036					
Area	18207	$ 34,484,058				
		$ 2,426,356				

I-430 NB at Fourche Creek	Pier	Gravel	Sand	Clay	Left	Right
100	20.54	0	9.15	8.9	34.65	34.65
1000	25.78	0	9.69	9.42	40.91	40.65
	0.20326	0	0.05573	0.05520	0.15302	0.14760
		0	0.01839	0.01822	0.07651	0.07380
Composite Scour	Pier	0.06708				
	Contraction	0.01208				
	Abutment	0.04960				
Scour Factor	0.04292					
Area	14154	$ 26,807,676				
		$ 1,150,566				

APPENDIX C
Visual Basic for Applications Code for Scour Calculations

Used with Microsoft Access 2010 to calculate contraction, pier and abutment scour.
Script was executed by the “On Got Focus” event of the output form.

```
Dim lngYellow As Long
Dim lngWhite As Long
Dim Vg, VTRatioG, VTRatioS, VTRatioC, Kg, Ks, Kc, PierLen As Variant
Dim CSTotalScourG, CSTotalScourS, CSTotalScourC, NewDepthG, NewDepthS, NewDepthC
As Variant
Dim A, B, C As Variant
Dim g, sg As Variant
Dim hb, ht As Variant
Dim PSVar1, PSVar2, FinalPSVar As Double
Dim Dg, Ds, Dc As Variant
Dim Rep1G, Rep1S, Rep1C As Variant
Dim Rep2G, Rep2S, Rep2C As Variant
Dim RepG, RepS, RepC As Variant
Dim RepGS, RepSS, RepCS As Variant
Dim RfG, RfS, RfC As Variant
Dim Xg, Yg, Xs, Ys, Xc, Yc As Variant
Dim CSQ1, CSQ2, Que, LBCSVar1, FloodHt As Variant
Dim Noflowadjustment, RegularFlow As Label
Dim Overtop, NoOvertop, NoPS, EOF As Label
Dim ARk1, ARk2, ALk1, ALk2 As Variant
Dim RtFlow, LtFlow, RtArea, LtArea As Variant
Dim Rpercent, LPercent As Variant
Dim Ver, Vel As Variant
Dim FrAL, FrRL As Variant
Dim yal, yar As Variant
Dim LeftLength, RightLength As Variant
Dim LAScour, RAScour As Variant
Dim hml, hmr As Variant
Dim BridgeFlow, ContractionFlow As Variant
Dim AbutmentScour As Label
Dim RightAbutment As Label
Dim Done As Label



'This code flags the fields yellow for areas susceptible to live bed scour

lngWhite = rgb(255, 255, 255)
lngYellow = rgb(255, 244, 0)

If [VcGravel] < [Velocity] Then [VcGravel].BackColor = lngYellow Else [VcGravel].BackColor
= lngWhite
```

```
If [VcSand] < [Velocity] Then [VcSand].BackColor = lngYellow Else [VcSand].BackColor =
lngWhite
If [VcClay] < [Velocity] Then [VcClay].BackColor = lngYellow Else [VcClay].BackColor =
lngWhite

If [Velocity] > [VcGravel] Then [LiveBedLabel].Visible = True Else [LiveBedLabel].Visible =
False
If [Velocity] > [VcSand] Then [LiveBedLabel].Visible = True Else [LiveBedLabel].Visible =
False
If [Velocity] > [VcClay] Then [LiveBedLabel].Visible = True Else [LiveBedLabel].Visible =
False

If [VcGravel] < [Velocity] Then [VcGravel].BackColor = lngYellow Else [VcGravel].BackColor
= lngWhite
If [VcSand] < [Velocity] Then [VcSand].BackColor = lngYellow Else [VcSand].BackColor =
lngWhite
If [VcClay] < [Velocity] Then [VcClay].BackColor = lngYellow Else [VcClay].BackColor =
lngWhite


'Begin calculation of live bed scour.  All particle widths have both live bed and clear water
calculated
'These portions are elements common to all particle equations

   'Calculate total pier width to reduce contraction

      PierLen = [NumberPiers] * [PierWidth]

   'Calculate V* for the equation

      Vg = (32.2 * [hm] * [StreamSlope]) ^ 0.5


'If flow is such that not all the flow goes through the bridge opening
'this section estimtates the amount using a  proportionality relationship between the flood area
'and the bridge area to estimate flow through bridge
'The first If Then statement steps over this step if the flag is not set

    If [FlowAdjust] = -1 Then GoTo Noflowadjustment



    LBCSVar1 = 1
    CSQ1 = [Flow]
    CSQ2 = [FracFlow]
    LBCSVar1 = (CSQ1 / CSQ2) ^ (6 / 7)
```

```
Noflowadjustment:

'Resume execution of contraction scour
'The following determines if pressur flow is present as well as what type of pressure flow, with
'or without overtopping

'This step determines if overtopping is present and adjusts flow (Q2) for overtopping.

    LBCSVar1 = 1
    CSQ1 = [Flow]
    If [hm] <= [BridgeOpenHt] Then GoTo NoPS Else Que = ([FracFlow]) * ([hue] / [hm]) ^ (8 /
7)
    LBCSVar1 = (CSQ1 / Que) ^ (6 / 7)


'The following are calculations for pressure flow conditions
'This determines if pressure flow is occuring and whether it is with or without overtopping of
bridge

    hb = [BridgeOpenHt]
    ht = [hm] - hb
    hw = [hm] - hb - [DeckWidth]

    If [hm] > (hb + [DeckWidth]) Then GoTo Overtop Else GoTo NoOvertop

Overtop:

    'This secton calculates pressure flow scour with bridge overtopping

    [OTCondition] = "Pressure flow scour with overtopping"

    PSVar1 = (([BridgeOpenHt] * ht) / [hm] ^ 2) ^ 0.2
    PSVar2 = (1 - (hw / ht)) ^ -0.1
    FinalPSVar = (0.5 * PSVar1 * PSVar2 * hb)
    [PST] = FinalPSVar

    GoTo EOF

NoOvertop:

    'This section calculates pressure flow scour only

    [OTCondition] = "Pressure flow scour only"
    PSVar1 = (((([BridgeOpenHt] * ht) / [hm] ^ 2) ^ 0.2) * 0.5) * hb
```

```
    FinalPSVar = 0.5 * PSVar1 * hb
    [PST] = PSVar1

GoTo EOF

NoPS:
    'No pressure flow scour present
    [OTCondition] = "No pressure flow scour present"
    [PST] = "N/A"

EOF:


RegularFlow:

'The following section computes both live bed and clearwater contraction scour

    'Calculate settling velocity for each particle size

    'Particle settling velocity calcualation (Dietrich, 1982)used to determine the variable V*/T
    'Program asks for D in feet, divide by 0.00328 to convert to mm for the equation

        g = 9.81
        sg = 2.65
        Dg = ([GravelD50] / 0.00328)
        Ds = ([SandD50] / 0.00328)
        Dc = ([SiltD50] / 0.00328)

   'Explicit particle Reynolds number - Gravel

    Rep1G = (g * sg * Dg / 1000) ^ 0.5
    Rep2G = (Dg / 1000) / 0.000001
    RepG = Rep1G * Rep2G
    RepGS = RepG * RepG
    Xg = Math.Log(RepGS) / 2.303
    Yg = -3.76715 + 1.92944 * Xg - 0.09815 * Xg * Xg - 0.00575 * Xg * Xg * Xg + 0.00056 * Xg
* Xg * Xg * Xg
    [RnG] = RepG

    'Dimensionless fall velociy - Gravel

    RfG = (10 ^ Yg / RepG) ^ 0.33
    [DFG] = RfG

    'Fall velocity converted from cm/s to ft/s by dividing by 30.48 - Gravel
```

```
A = (RfG * ((sg * g * (Dg / 1000)) ^ 0.5) * 100) / 30.48

[FVG] = A


'Explicit particle Reynolds number - Sand

Rep1S = (g * sg * Ds / 1000) ^ 0.5
Rep2S = (Ds / 1000) / 0.000001
RepS = Rep1S * Rep2S
RepSS = RepS * RepS
Xs = Math.Log(RepSS) / 2.303
Ys = -3.76715 + 1.92944 * Xs - 0.09815 * Xs * Xs - 0.00575 * Xs * Xs * Xs + 0.00056 * Xs *
Xs * Xs * Xs

[RnS] = RepS

'Dimensionless fall velociy - Sand

RfS = (10 ^ Ys / RepS) ^ (1 / 3)

[DFS] = RfS

'Fall velocity converted from cm/s to ft/s by dividing by 30.48 - Sand

B = (RfS * ((sg * g * (Ds / 1000)) ^ 0.5) * 100) / 30.48

[FVS] = B


'Explicit particle Reynolds number - Clay

Rep1C = (g * sg * Dc / 1000) ^ 0.5
Rep2C = (Dc / 1000) / 0.000001
RepC = Rep1C * Rep2C
RepCS = RepC * RepC
Xc = Math.Log(RepCS) / 2.303
Yc = -3.76715 + 1.92944 * Xc - 0.09815 * Xc * Xc - 0.00575 * Xc * Xc * Xc + 0.00056 * Xc
* Xc * Xc * Xc

[RnC] = RepC

'Dimensionless fall velociy - Clay

RfC = (10 ^ Yc / RepC) ^ (1 / 3)
```

```
    [DFC] = RfC

    'Fall velocity converted from cm/s to ft/s by dividing by 30.48 - Clay

    C = (RfC * ((sg * g * (Dc / 1000)) ^ 0.5) * 100) / 30.48

    [FVC] = C

'Calculation of k1 for particles

    'Gravel k1

        VTRatioG = Vg / A

        If VTRatioG < 0.5 Then Kg = 0.59
        If VTRatioG > 2 Then Kg = 0.69 Else Kg = 0.64

    'Sand k1

        VTRatioS = Vg / B

        If VTRatioS < 0.5 Then Ks = 0.59
        If VTRatioS > 2 Then Ks = 0.69 Else Ks = 0.64

    'Clay k1

        VTRatioC = Vg / C

        If VTRatioC < 0.5 Then Kc = 0.59
        If VTRatioC > 2 Then Kc = 0.69 Else Kc = 0.64

'Calculate new depths after scour

    'Gravel
    NewDepthG = [hm] * LBCSVar1 * (([ChannelWidth] / ([ContractionWidth] - PierLen)) ^ Kg)
    CSTotalScourG = NewDepthG + FinalPSVar

    'CSTotalScourG = (NewDepthG - [AvgWaterHt])

    'Sand
    NewDepthS = [hm] * LBCSVar1 * ([ChannelWidth] / ([ContractionWidth] - PierLen)) ^ Ks
    CSTotalScourS = NewDepthS + FinalPSVar

    'Clay
    NewDepthC = [hm] * LBCSVar1 * (([ChannelWidth] / ([ContractionWidth] - PierLen)) ^ Kc)
    CSTotalScourC = NewDepthC + FinalPSVar
```

```
'k1 values used in live bed equations

    [k1g] = Kg
    [k1s] = Ks
    [k1c] = Kc

'Populate depth after scour

    [NewDepthCSG] = NewDepthG
    [NewDepthCSS] = NewDepthS
    [NewDepthCSC] = NewDepthC
    If CSTotalScourG < 0 Then [CLBScourG] = "N/A" Else [CLBScourG] = CSTotalScourG
    If CSTotalScourS < 0 Then [CLBScourS] = "N/A" Else [CLBScourS] = CSTotalScourS
    If CSTotalScourC < 0 Then [CLBScourC] = "N/A" Else [CLBScourC] = CSTotalScourC


Clearwatercs:


Dim Q, Dmg, Dms, Dmc, W As Variant
Dim CWg, CWs, CWc As Variant
Dim CSCWG, CSCWS, CSCWC As Variant



If [FlowAdjust] = -1 Then Q = [Flow] Else Q = [FracFlow]
Dmg = 1.25 * [GravelD50]
Dms = 1.25 * [SandD50]
Dmc = 1.25 * [SiltD50]
W = ([BridgeLength] - PierLen)



    'Clear water scour gravel

    CWg = ((0.0077 * Q ^ 2) / (Dmg ^ 0.66 * W ^ 2)) ^ (3 / 7)

    'Clear water scour sand

    CWs = ((0.0077 * Q ^ 2) / (Dms ^ 0.66 * W ^ 2)) ^ (3 / 7)

    'Clear water scour clay

    CWc = ((0.0077 * Q ^ 2) / (Dmc ^ 0.66 * W ^ 2)) ^ (3 / 7)
```

```
'Total Scour

    CSCWG = CWg + FinalPSVar - [BridgeOpenHt]
    CSCWS = CWs + FinalPSVar - [BridgeOpenHt]
    CSCWC = CWc + FinalPSVar - [BridgeOpenHt]


'Display results of clear water scour on form

[CWCg] = CWg
[CWCs] = CWs
[CWCc] = CWc

If CSCWG < 0 Then [NCWg] = "N/A" Else [NCWg] = CSCWG
If CSCWS < 0 Then [NCWs] = "N/A" Else [NCWs] = CSCWS
If CSCWC < 0 Then [NCWc] = "N/A" Else [NCWc] = CSCWC


'Contraction scour analysis

Dim CSLiveBed, CSClear As String

CSLiveBed = "Live Bed"
CSClear = "Clear Water"

If [Velocity] > (11.17 * [hm] ^ (1 / 6) * [GravelD50] ^ (1 / 3)) Then [CSLimitg] = CSLiveBed
Else [CSLimitg] = CSClear
If [Velocity] > (11.17 * [hm] ^ (1 / 6) * [SandD50] ^ (1 / 3)) Then [CSLimits] = CSLiveBed Else
[CSLimits] = CSClear
If [Velocity] > (11.17 * [hm] ^ (1 / 6) * [SiltD50] ^ (1 / 3)) Then [CSLimitc] = CSLiveBed Else
[CSLimitc] = CSClear


'***************************************
'This section computes basic pier scour
'***************************************

Dim PK1, PK2, PK3, Fr, LAc, PierScour As Variant

'Defines or determines the values to use in pier scour equation
'PK1, PK2, PK3 are variables while Fr is the Froude number
'Equation is 7.1 in the HEC-18 book

PK3 = 1.1

'Max value of L/A is 12 this evaluates and sets value
```

```
If [LA] = 0 Then GoTo AbutmentScour

If [LA] > 12 Then LAc = 12 Else LAc = [LA]

PK2 = (Math.Cos([PierAngle] * (3.14 / 180)) + (LAc * Math.Sin([PierAngle] * (3.14 / 180)))) ^
0.65

'Max value for pk2 is 5

If PK2 > 5 Then PK2 = 5

If [PierNose] = "Square" Then PK1 = 1.1 Else If [PierNose] = "Sharp" Then PK1 = 0.9 Else PK1
= 1

Fr = [Velocity] / (32.2 * [hm]) ^ 0.5

'Calculate scour at the pier

PierScour = [hm] * (2 * PK1 * PK2 * PK3 * (([hm] / [PierWidth]) ^ 0.35) * Fr ^ 0.43)

[PierK1] = PK1
[PierK2] = PK2
[PierK3] = PK3
[FrPier] = Fr
[TotalPierScour] = PierScour


'***********************************
'Abutment scour calculations
'***********************************
AbutmentScour:

If [LeftAbutmentLength] = 0 Then GoTo RightAbutment

'Left abutment calcuations
'Assign values of k

If [AbutmentType] = "Vertical" Then ALk1 = 1 Else If [AbutmentType] = "Vert w/Wing" Then
ALk1 = 0.82 Else ALk1 = 0.55
If [LeftAbutAngle] = 0 Then ALk2 = 1 Else ALk2 = ([LeftAbutAngle] / 90) ^ 0.13


If [LeftAbutAngle] > 0 Then LeftLength = Math.Abs(([LeftAbutmentLength] * Math.Cos((90 *
(3.14 / 180)))) - [LeftAbutAngle]) Else LeftLength = [LeftAbutmentLength]
```

```
'Estimation of obstruction of flow

LPercent = [LeftAbutmentLength] / [BridgeLength]


'Ae-the flow area is the depth at the abutment multiplied by the lenght of the abutment (a square channel)

LtArea = [LeftAbutmentLength] * [LeftAbutDepth]

'ya - this is proportionally adjusted by dividing depth at abutment by total flood depth and multiplying by hm

yal = ([LeftAbutDepth] / [TotalFloodDepth]) * [hm]


'Qe

LtFlow = LPercent * ([FracFlow])

'Ve
Vel = LtFlow / LtArea

'Fr number
FrAL = Vel / (32.2 * yal) ^ 0.5

'Calculate the scour

LAScour = yal * 2.27 * ALk1 * ALk2 * ((LeftLength / yal) ^ 0.43) * (FrAL ^ 0.61) + 1

[LeftScour] = LAScour
[LeftK1] = ALk1
[LeftK2] = ALk2
[Lhm] = yal
[LAe] = LtArea
[LQe] = LtFlow
[LVe] = Vel
[LFr] = FrAL
[LFlowPercent] = LeftLength
[LFlowPerc] = LPercent

RightAbutment:

If [RightAbutmentLength] = 0 Then GoTo Done
If [RightAbutDepth] = 0 Then GoTo Done
```

```
'Right abutment calcuations
'Assign values of k

If [AbutmentType] = "Vertical" Then ARk1 = 1 Else If [AbutmentType] = "Vert w/Wing" Then ARk1 = 0.82 Else ARk1 = 0.55
If [RightAbutAngle] = 0 Then ARk2 = 1 Else ARk2 = ([RightAbutAngle] / 90) ^ 0.13

If [RightAbutAngle] > 0 Then RightLength = Math.Abs(([RightAbutmentLength] * Math.Cos((90 * (3.14 / 180))) - [RightAbutAngle])) Else RightLength = [RightAbutmentLength]


'Estimation of obstruction of flow

Rpercent = [RightAbutmentLength] / [BridgeLength]


'Ae-the flow area is the depth at the abutment multiplied by the lenght of the abutment (a square channel)
RtArea = [RightAbutmentLength] * [RightAbutDepth]

'ya - this is proportionally adjusted by dividing depth at abutment by total flood depth and multiplying by hm

yar = ([RightAbutDepth] / [TotalFloodDepth]) * [hm]

'Qe
RtFlow = Rpercent * ([FracFlow])

'Ve
Ver = RtFlow / RtArea

'Fr number
FrRL = Ver / (32.2 * yar) ^ 0.5

'Calculate the scour

RAScour = yar * 2.27 * ARk1 * ARk2 * ((RightLength / yar) ^ 0.43) * (FrRL ^ 0.61) + 1

[RightScour] = RAScour
[RightK1] = ARk1
[RightK2] = ARk2
[Rhm] = yar
[RAe] = RtArea
[RQe] = RtFlow
```

```
[RVe] = Ver
[RFr] = FrAL
[Rflowpercent] = RightLength
[Rflowperc] = Rpercent

Done:

End Sub
```

APPENDIX D
Data Used for Davidson County (Nashville) Scour Calculations

Bridge **Antioch Pike**

StreamName	Mill Creek		
Deck Height(ft)	3	Width of Channel (ft)	55
Deck Elevation (ft)	502	Width of Contraction (ft)	64
Bridge Opening (ft)	18	Channel Area (sq ft)	2080
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	3
Bridge Width (ft)	70	Stream Slope (ft/ft)	0.00038300
Bridge Length (ft)	130	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	29	19	9	1238

Volumetric Flow (cfs)	Stream Velocity (f/s)
23888	1.2060

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
320	29.99	22.69	10.59	1238

Volumetric Flow (cfs)	Stream Velocity (f/s)
28757	1.4082

Bridge **Bellevue Rd over Flat Creek**

StreamName	Flat Creek		
Deck Height(ft)	3	Width of Channel (ft)	26.25
Deck Elevation (ft)	582	Width of Contraction (ft)	22
Bridge Opening (ft)	8	Channel Area (sq ft)	44.59
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	0
Bridge Width (ft)	22	Stream Slope (ft/ft)	0.00579710
Bridge Length (ft)	26	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	3.43	1.87	3.43	247

Volumetric Flow (cfs)	Stream Velocity (f/s)
2295	5.4178

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
320	4.6	1.87	3.43	247

Volumetric Flow (cfs)	Stream Velocity (f/s)
2662	4.6858

Bridge **Farnsworth Drive at Richland Creek**

StreamName	Richland Creek

Deck Height(ft)	3	Width of Channel (ft)	88
Deck Elevation (ft)	469	Width of Contraction (ft)	71
Bridge Opening (ft)	9	Channel Area (sq ft)	367.2
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	2
Bridge Width (ft)	15	Stream Slope (ft/ft)	0.00333492
Bridge Length (ft)	80	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	7.18	3.9	3.7	1138

Volumetric Flow (cfs)	Stream Velocity (f/s)
4358	0.8343

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
320	9.02	3.98	3.77	1182

Volumetric Flow (cfs)	Stream Velocity (f/s)
4497	0.6905

Bridge **Harding Pl at Richland Creek**

StreamName	Richland Cr

Deck Height(ft)	3	Width of Channel (ft)	46.25
Deck Elevation (ft)	504	Width of Contraction (ft)	45
Bridge Opening (ft)	8	Channel Area (sq ft)	423.95
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	0
Bridge Width (ft)	56	Stream Slope (ft/ft)	0.00484392
Bridge Length (ft)	122	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	6.95	4.45	2.34	968

Volumetric Flow (cfs)	Stream Velocity (f/s)
3865	1.1490

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
320	9.7	4.45	2.34	968

Volumetric Flow (cfs)	Stream Velocity (f/s)
4421	0.9417

Bridge **McCory Ln at Harpeth**

StreamName	Harpeth River

Deck Height(ft)	3	Width of Channel (ft)	98.88
Deck Elevation (ft)	545	Width of Contraction (ft)	82
Bridge Opening (ft)	37	Channel Area (sq ft)	6825
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	3
Bridge Width (ft)	42	Stream Slope (ft/ft)	0.00091158
Bridge Length (ft)	390	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	32	22	6	759

Volumetric Flow (cfs)	Stream Velocity (f/s)
20083	1.5120

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
320	36.95	26	7.78	899

Volumetric Flow (cfs)	Stream Velocity (f/s)
22909	1.2757

Bridge **Newsome Stn Rd**

StreamName	Harpeth River

Deck Height(ft)	3	Width of Channel (ft)	88
Deck Elevation (ft)	545	Width of Contraction (ft)	95
Bridge Opening (ft)	32	Channel Area (sq ft)	3551.94
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	3
Bridge Width (ft)	24	Stream Slope (ft/ft)	0.00058624
Bridge Length (ft)	252	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	25.19	2.02	7.47	1010

Volumetric Flow (cfs)	Stream Velocity (f/s)
19088	1.3408

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
320	27.34	5.76	8.74	1010

Volumetric Flow (cfs)	Stream Velocity (f/s)
21476	1.4017

Bridge **Old Harding Pike**

StreamName	Harpeth River
Deck Height(ft)	3
Deck Elevation (ft)	562
Bridge Opening (ft)	28
Height of Parapet (ft)	3
Bridge Width (ft)	56
Bridge Length (ft)	122
Width of Channel (ft)	56.61
Width of Contraction (ft)	28
Channel Area (sq ft)	1629.31
Average Non-Flood Stream Depth (ft)	4
Stream Slope (ft/ft)	0.00057471
Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)	Volumetric Flow (cfs)	Stream Velocity (f/s)
100	22.71	17.41	0	207	18035	6.5238
320	24.79	18.38	0	207	20430	6.8562

Bridge **Pettus Rd at Mill Creek**

StreamName	Mill Creek
Deck Height(ft)	3
Deck Elevation (ft)	525
Bridge Opening (ft)	17
Height of Parapet (ft)	3
Bridge Width (ft)	31
Bridge Length (ft)	193
Width of Channel (ft)	40
Width of Contraction (ft)	191
Channel Area (sq ft)	2262.925
Average Non-Flood Stream Depth (ft)	3
Stream Slope (ft/ft)	0.00094563
Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)	Volumetric Flow (cfs)	Stream Velocity (f/s)
100	20.45	9	11.27	2233	15851	0.6054
320	22.216	14	6.2	2233	18093	0.6427

APPENDIX E
Data Used for Pulaski County (Little Rock) Scour Calculations

Bridge **I-430 NB at Fourche Creek**

StreamName			
Deck Height(ft)	5	Width of Channel (ft)	183
Deck Elevation (ft)	290	Width of Contraction (ft)	337
Bridge Opening (ft)	15.5912314635719	Channel Area (sq ft)	4419.755
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	5
Bridge Width (ft)	42	Stream Slope (ft/ft)	0.00064475
Bridge Length (ft)	337	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	21.23	7.98	7.98	337

Volumetric Flow (cfs)	Stream Velocity (f/s)
15669	3.5452

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
1000	22.77	10.5	10.7	337

Volumetric Flow (cfs)	Stream Velocity (f/s)
24208	5.1735

Bridge **I-430 North Bound**

StreamName			
Deck Height(ft)	5	Width of Channel (ft)	20.38
Deck Elevation (ft)	266	Width of Contraction (ft)	253
Bridge Opening (ft)	21.7134416543575	Channel Area (sq ft)	3378.41
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	3
Bridge Width (ft)	63	Stream Slope (ft/ft)	0.00147710
Bridge Length (ft)	289	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	20.38	16.7	16.68	172

Volumetric Flow (cfs)	Stream Velocity (f/s)
10761	3.1852

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
1000	28.43	23.26	16.34	289

Volumetric Flow (cfs)	Stream Velocity (f/s)
15875	3.4954

Bridge **SH 161 at Bayou Meto**

StreamName	Bayou Meto		
Deck Height(ft)	4	Width of Channel (ft)	35
Deck Elevation (ft)	247	Width of Contraction (ft)	158
Bridge Opening (ft)	9.46475409836066	Channel Area (sq ft)	2037.75
Height of Parapet (ft)	3	Average Non-Flood Stream Depth (ft)	3
Bridge Width (ft)	31	Stream Slope (ft/ft)	0.00355191
Bridge Length (ft)	165	Channel Geometry	Triangle

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
100	21.7	11.89	15.18	165

Volumetric Flow (cfs)	Stream Velocity (f/s)
32535	15.9661

Return Period	Center Line Depth (ft)	Left Abutment Flood Depth (ft)	Right Abutment Flood Depth (ft)	Flood Width Upstream (ft)
1000	22.9	13.04	14.76	165

Volumetric Flow (cfs)	Stream Velocity (f/s)
49905	23.3556

APPENDIX F
Sensitivity Analysis Data

		Old Harding at Harpeth River 2010 Estimated Replacement Value = $1,600,000				
		Pier	Contraction	Abutment	Scour Factor	Estimated Damage
	Base Value	0.03329	0.01574	0.00809	0.01904	$30,000
Pier	8 ft Pier	0.03336	0.01574	0.00809	0.01906	$31,000
	12 ft Pier	0.03330	0.01574	0.00809	0.01905	$30,000
	Round	0.03143	0.01574	0.00809	0.01842	$29,000
	Sharp	0.03474	0.01574	0.00809	0.01952	$31,000
	10 Angle	0.03332	0.01574	0.00809	0.01905	$30,000
	20 Angle	0.03327	0.01574	0.00809	0.01904	$30,000
Abutment	7 ft Abutment	0.03329	0.01574	0.00832	0.01912	$31,000
	11 ft Abutment	0.03329	0.01574	0.00847	0.01917	$31,000
	10 Angle	0.03329	0.01574	0.0066	0.01854	$30,000
	20 Angle	0.03329	0.01574	0.00731	0.01878	$30,000
	Wing Wall	0.03329	0.01574	0.00772	0.01892	$30,000
	Spill Through	0.03329	0.01574	0.00735	0.01879	$30,000
Contraction	32 ft Contraction	0.03329	0.01575	0.00809	0.01905	$30,000
	36 ft Contraction	0.03329	0.01574	0.00809	0.01904	$30,000
	Gravel Only	0.03329	0	0.00809	0.01379	$22,000
	Sand Only	0.03329	0.00787	0.00809	0.01642	$26,000
	Clay Only	0.03329	0.00788	0.00809	0.01642	$26,000

		Farnsworth Drive 2010 Estimated Replacement Value = $192,000				
		Pier	Contraction	Abutment	Scour Factor	Estimated Damage
	Base Value	0.0391	0	0.0025	0.0139	$2,700
Pier	2 ft Pier	0.0389	0	0.0025	0.0138	$2,700
	6 ft Pier	0.0390	0	0.0025	0.0138	$2,700
	Square	0.0395	0	0.0025	0.0140	$2,700
	Sharp	0.0396	0	0.0025	0.0140	$2,700
	10 Angle	0.0333	0	0.0025	0.0119	$2,300
	20 Angle	0.0333	0	0.0025	0.0119	$2,300
Abutment	20 ft Abutment	0.0391	0	0.0026	0.0017	$330
	25 ft Abutment	0.0391	0	0.0028	0.0018	$340
	10 Angle	0.0391	0	0.0023	0.0016	$307
	20 Angle	0.0391	0	0.0026	0.0017	$329
	Wing Wall	0.0391	0	0.0029	0.0018	$345
	Spill Through	0.0391	0	0.0025	0.0017	$321
Contraction	77 ft Contraction	0.0391	0	0.0025	0.0139	$2,700
	83 ft Contraction	0.0391	0	0.0025	0.0139	$2,700
	Gravel Only	0.0391	0	0.0025	0.0139	$2,700
	Sand Only	0.0391	0	0.0025	0.0139	$2,700
	Clay Only	0.0391	0	0.0025	0.0139	$2,700

		McCrory Lane 2010 Estimated Replacement Value = $2,600,000				
		Pier	Contraction	Abutment	Scour Factor	Estimated Damage
	Base Value	0.05225	0.01347	0.02432	0.03001	$78,000
Pier	6 ft Pier	0.02442	0.01347	0.02432	0.01625	$42,000
	9 ft Pier	0.02445	0.01347	0.02432	0.01626	$42,000
	Square	0.02457	0.01347	0.02432	0.01630	$42,000
	Sharp	0.02449	0.01347	0.02432	0.01627	$42,000
	10 Angle	0.02452	0.01347	0.02432	0.01628	$42,000
	20 Angle	0.02455	0.01347	0.02432	0.01629	$42,000
Abutment	8 ft Abutment	0.05225	0.01347	0.02789	0.02671	$69,000
	14 ft Abutment	0.05225	0.01347	0.09960	0.05062	$132,000
	10 Angle	0.05225	0.01347	0.02665	0.02630	$68,000
	20 Angle	0.05225	0.01347	0.02848	0.02691	$70,000
	Wing Wall	0.05225	0.01347	0.02288	0.02504	$65,000
	Spill Through	0.05225	0.01347	0.01968	0.02398	$62,000
Contraction	90 ft Contraction	0.05225	0.01349	0.02432	0.03002	$78,000
	98 ft Contraction	0.05225	0.01352	0.02432	0.03003	$78,000
	Gravel Only	0.05225	0.00000	0.02432	0.02552	$66,000
	Sand Only	0.05225	0	0.02432	0.02552	$66,000
	Clay Only	0.05225	0	0.02432	0.02552	$66,000

		Harding Place at Richland Creek 2010 Estimated Replacement Value = $1,090,000				
		Pier	Contraction	Abutment	Scour Factor	Estimated Damage
	Base Value	0	0.03086	0.01515	0.01534	$16,700
No Piers						
Abutment	8 ft Abutment	0	0.03086	0.01902	0.01663	$18,000
	14 ft Abutment	0	0.03086	0.02034	0.01707	$19,000
	10 Angle	0	0.03086	0.01823	0.01636	$18,000
	20 Angle	0	0.03086	0.01983	0.01690	$18,000
	Wing Wall	0	0.03086	0.01331	0.01472	$16,000
	Spill Through	0	0.03086	0.01177	0.01421	$15,000
Contraction	50 ft Contraction	0	0.02509	0.01515	0.01341	$15,000
	55 ft Contraction	0	0.03090	0.01515	0.01535	$17,000
	Gravel Only	0	0	0.01515	0.00505	$5,500
	Sand Only	0	0	0.01515	0.00505	$5,500
	Clay Only	0	0.03090	0.01515	0.00505	$5,500

		Antioch Pike at Mill Creek				
		2010 Estimated Replacement Value = $1,400,000				
		Pier	**Contraction**	**Abutment**	**Scour Factor**	**Estimated Damage**
	Base Value	0.03169	0.00067	0.01602	0.01613	$23,000
Pier	8 ft Pier	0.03171	0.00067	0.01602	0.01613	$23,000
	12 ft Pier	0.03167	0.00067	0.01602	0.01612	$23,000
	Square	0.03166	0.00067	0.01602	0.01612	$23,000
	Sharp	0.03173	0.00067	0.01602	0.01614	$23,000
	10 Angle	0.03183	0.00067	0.01602	0.01617	$23,000
	20 Angle	0.03180	0.00067	0.01602	0.01616	$23,000
Abutment	80 ft Abutment	0.03169	0.00067	0.01598	0.01611	$23,000
	90 ft Abutment	0.03169	0.00067	0.01613	0.01616	$23,000
	10 Angle	0.03169	0.00067	0.01376	0.01537	$22,000
	20 Angle	0.03169	0.00067	0.01477	0.01571	$22,000
	Wing Wall	0.03169	0.00067	0.01588	0.01588	$23,000
	Spill Through	0.03169	0.00067	0.01527	0.01527	$22,000
Contraction	32 ft Contraction	0.03169	0.00067	0.01602	0.01613	$23,000
	96 ft Contraction	0.03169	0.00064	0.01602	0.01612	$23,000
	Gravel Only	0.03169	0	0.01602	0.01590	$22,000
	Sand Only	0.03169	0	0.01602	0.01590	$22,000
	Clay Only	0.03169	0.00067	0.01602	0.01613	$23,000

Old Harding at Harpeth River			
2010 Estimated Replacement Value = $1,600,000			
	Pier Width		
	4 ft	8 ft	12 ft
100 Year		29.97	23.52
320 Year		33.34	26.16
	0.03329	0.03336	0.03330
	Pier Nose		
	Square	Round	Sharp
100 Year		19	17
320 Year		21	19
	0.03329	0.03143	0.03474
	Pier Angle		
	0	10	20
100 Year		28.58	35.14
320 Year		31.79	39.08
	0.03329	0.03332	0.03327
	Abutment Length		
	3 ft	7 ft	11 ft
100 Year		9.61	11.46
320 Year		10.12	12.08
	0.00809	0.00832	0.00847
	Abutmnent Angle		
	0	10	20
100 Year		3.12	4.1
320 Year		3.25	4.29
	0.00809	0.00660	0.00731
	Abutment Type		
	Vertical	With Wing	Spill Through
100 Year		5.91	4.29
320 Year		6.2	4.49
	0.00809	0.00772	0.00735
	Contraction Width 32 Feet		
	Gravel	Sand	Clay
100 Year	0	46.72	51.52
320 Year	0	50.36	55.54
	0	0.02385	0.02389
	Contraction Width 36 Feet		
	Gravel	Sand	Clay
100 Year	0	36.04	38.95
320 Year	0	38.85	41.98
	0	0.02387	0.02382
	Bed Composition		
	Gravel Only	Sand Only	Clay Only
100 Year	0	72.81	83.12
320 Year	0	78.48	89.6
	0	0.0079	0.0079

Farnsworth Drive at Richland Creek				
2010 Estimated Value = $193,000				
	Pier Width			
	2 ft	4 ft	6 ft	
100 Year	4.27		2.91	
320 Year	4.84		3.3	
	0.03886	0.03908	0.03900	
	Pier Nose			
	Square	Round	Sharp	
100 Year	3.68		3.01	
320 Year	4.18		3.42	
	0.03947	0.03908	0.03956	
	Pier Angle			
	0	10	20	
100 Year		28.58	35.14	
320 Year		31.79	39.08	
	0.03908	0.03332	0.03327	
	Abutment Length			
	20 ft		25 ft	
100 Year	Left	Right	Left	Right
320 Year	4.37	4.43	4.71	4.78
	4.33	4.4	4.67	4.74
	0.00924	0.00682	0.00857	0.00844
	0.00265		0.00281	
	Abutment Angle			
	10		20	
	Left	Right	Left	Right
100 Year	2.88	2.91	3.77	3.82
320 Year	2.86	2.89	3.74	3.79
	0.00699	0.00692	0.00802	0.00792
	0.00230		0.00263	
	Abutment Type			
	With Wing		Spill Through	
	Left	Right	Left	Right
100 Year	3.44	3.49	2.64	2.67
320 Year	3.41	3.46	2.62	2.65
	0.00880	0.00867	0.00763	0.00755
	0.00288		0.00250	
	Contraction Width 77 Feet			
	Gravel	Sand	Clay	
100 Year	0	0	0	
320 Year	0	0	0	
	0	0	0	
	Contraction Width 83 Feet			
	Gravel	Sand	Clay	
100 Year	0	0	0	
320 Year	0	0	0	
	0	0	0	
	Bed Composition			
	Gravel Only	Sand Only	Clay Only	
100 Year	0	0	0	
320 Year	0	0	0	
	0	0	0	

McCrory Lane at Harpeth River				
2010 Estimated Value = $2,600,000				
	Pier Width			
	6 ft	**9 ft**	**12 ft**	
100 Year	17.14	14.87		
320 Year	18.51	16.06		
	0.02442	0.02445	0.05225	
	Pier Nose			
	Square	**Round**	**Sharp**	
100 Year	14.79		12.1	
320 Year	15.98		13.07	
	0.02457	0.05225	0.02449	
	Pier Angle			
	0	**10**	**20**	
100 Year		18.19	22.02	
320 Year		19.65	23.79	
	0.05225	0.02452	0.02455	
	Abutment Length			
	8 ft		**14 ft**	
	Left	Right	Left	Right
100 Year	5.07	7.37	4.71	4.78
320 Year	4.75	6.69	5.77	8.24
	0.06737	0.10164	0.18371	0.41990
	0.02789		0.09960	
	Abutment Angle			
	10		**20**	
	Left	Right	Left	Right
100 Year	4.36	6.27	5.96	8.77
320 Year	4.1	5.71	5.58	7.94
	0.06341	0.09807	0.06810	0.10453
	0.02665		0.02848	
	Abutment Type			
	With Wing		**Spill Through**	
	Left	Right	Left	Right
100 Year	2.84	3.88	2.23	2.93
320 Year	2.7	3.57	2.14	2.72
	0.05185	0.08683	0.04206	0.07721
	0.02288		0.01968	
	Contraction Width 90 Feet			
	Gravel	**Sand**	**Clay**	
100 Year	0	0	23.13	
320 Year	0	0	26.4	
	0	0	0.01349	
	Contraction Width 98 Feet			
	Gravel	**Sand**	**Clay**	
100 Year	0	0	21.37	
320 Year	0	0	24.4	
	0	0	0.01352	
	Bed Composition			
	Gravel Only	**Sand Only**	**Clay Only**	
100 Year	0	0	0	
320 Year	0	0	0	
	0	0	0	

Antioch Pike at Mill Creek				
2010 Estimated Value = $1,400,000				
	Pier Width			
	4 ft	**8 ft**	**12 ft**	
100 Year		12.7	11.02	
320 Year		14.05	12.19	
	0.03169	0.03171	0.03167	
	Pier Nose			
	Round	**Square**	**Sharp**	
100 Year		17.81	14.57	
320 Year		19.7	16.12	
	0.03169	0.03166	0.03173	
	Pier Angle			
	0	**10**	**20**	
100 Year		33.54	46.33	
320 Year		37.12	51.27	
	0.03169	0.03183	0.03180	
	Abutment Length			
	80 ft		**90 ft**	
100 Year	Left	Right	Left	Right
320 Year	10.5	13.29	10.99	13.93
	11	14.01	11.52	14.69
	0.04545	0.05139	0.04601	0.05174
	0.01598		0.01613	
	Abutment Angle			
	10		**20**	
	Left	Right	Left	Right
100 Year	3.91	4.77	5.3	6.56
320 Year	4.07	4.99	5.53	6.89
	0.03931	0.04409	0.04159	0.04790
	0.01376		0.01477	
	Abutment Type			
	With Wing		**Spill Through**	
	Left	Right	Left	Right
100 Year	8.35	10.52	5.93	7.38
320 Year	8.75	11.08	6.2	7.76
	0.04571	0.05054	0.04355	0.04897
	0.01588		0.01527	
	Contraction Width 32 Feet			
	Gravel	**Sand**	**Clay**	
100 Year	0	0	29.41	
320 Year	0	0	29.23	
	0	0	0.00067	
	Contraction Width 96 Feet			
	Gravel	**Sand**	**Clay**	
100 Year	0	0	12	
320 Year	0	0	11.93	
	0	0	0.00064	
	Bed Composition			
	Gravel Only	**Sand Only**	**Clay Only**	
100 Year	0	0	16.39	
320 Year	0	0	16.29	
	0	0	0.00067	

Harding Place at Richland Creek				
2010 Estimated Value = $1,090,000				
No Piers Present on Bridge				
	Abutment Length			
	8 ft		**14 ft**	
	Left	Right	Left	Right
100 Year	3.23	3.78	3.83	4.54
320 Year	3.42	4.02	4.08	4.84
	0.05556	0.05970	0.06127	0.06198
	0.01902		0.02034	
	Abutment Angle			
	10		**20**	
	Left	Right	Left	Right
100 Year	2.84	3.3	3.72	4.39
320 Year	3	3.5	3.95	4.68
	0.05333	0.05714	0.05823	0.06197
	0.01823		0.01983	
	Abutment Type			
	With Wing		**Spill Through**	
	Left	Right	Left	Right
100 Year	2.01	2.26	1.67	1.84
320 Year	2.09	2.36	1.73	1.91
	0.03828	0.04237	0.03468	0.03665
	0.01331		0.01177	
	Contraction Width 50 Feet			
	Gravel	**Sand**	**Clay**	
100 Year	0	0	3.54	
320 Year	0	0	4.6	
	0	0	0.02509	
	Contraction Width 55 Feet			
	Gravel	**Sand**	**Clay**	
100 Year	0	0	3.08	
320 Year	0	0	4.3	
	0	0	0.03090	
	Bed Composition			
	Gravel Only	**Sand Only**	**Clay Only**	
100 Year	0	0	3.08	
320 Year	0	0	4.3	
	0	0	0.03090	

APPENDIX G
Scour Factor Method Users Guide

INTRODUCTION

Bridges are important conduits for the transportation of goods, services and people. When bridges are damaged both direct costs to the structure and indirect costs from increased commute time, increased gas expenses, or delays in moving goods to and from market are incurred. A significant risk to the structural life of a bridge is scour. Scour occurs from water moving in and around the bridge components, like piers and abutments, resulting in the removal of bed material. Scour can undermine components and shorten a bridge's useful life or lead to catastrophic failure. In recent years, the United States has experienced heavier rainfall and severe flooding, factors that increases bridge scour. This methodology was developed to assist communities in assessing bridge scour risk from future floods and prioritizing which bridges may require protective measures. The method is provided only as a tool and should not be used for budgeting or forecasting activities.

REQUIREMENTS

This scour prediction methodology was developed using HAZUS-MH 2.1 (or Hazus) and ArcGIS, Version 10, Service Pack 2. Hazus is available for download from the United States Federal Emergency Management Agency. Other flood modeling tools may be used to provide the data for this methodology but the predictive ability has not been evaluated. The user assumes all liability for the application of this method and any decisions based on the results. No warranty, expressed or implied, is given.

OVERVIEW OF DAMAGE PREDICTION

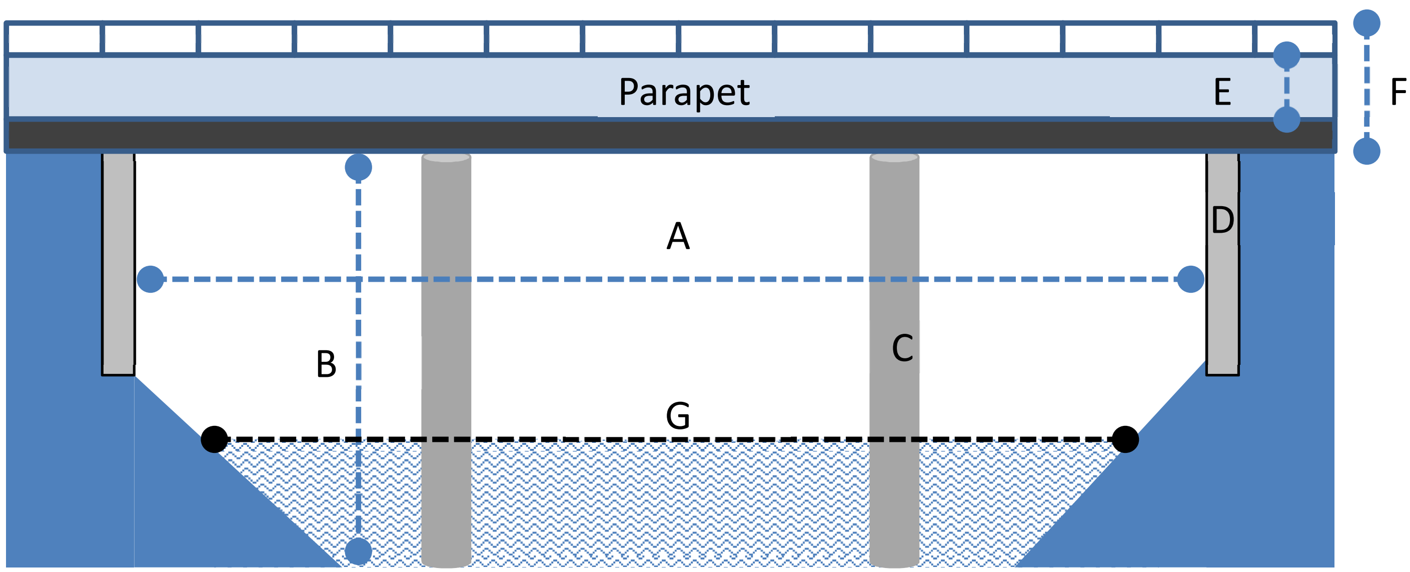
Once the bridges for adaptation have been identified, the first step is to calculate the estimated replacement value. This is done by using the National Bridge Inventory to find the bridges overall length and width, in meters (fields 49 and 52). These are multiplied together then by $1803 (in 2012 dollars) to estimate bridge replacement cost. Once this has been calculated, the bridges can be ranked in order for prioritization. For bridges that are within $300,000 to $400,000 of each other in replacement cost, the following scour factor method may be used to refine the ranking.

The instructions that follow utilize Hazus to create flood models. Once the models are complete, data is gathered from the models, and other sources, and entered into the Scour Calculator. Results from the Scour Calculator are used to calculate the scour factor and monetary damage. The following scenario illustrates how this methodology may be used.

A community has several bridges each designed to withstand a 100-year flood. Community members are concerned that 450-year floods may become more common. Each area with a bridge has formed a group to lobby for their bridge being protected first. The town treasury has limited money which prevents all of the bridges from being protected this year. How do the leaders of the town determine which bridge to protect first? Utilizing Hazus and the Scour Calculator, the community can develop semi-quantitative information to use in addressing the community's concerns.

BRIDGE DIAGRAM

The following provides a reference to assist in identifying measurement locations and bridge components. It is referenced as "bridge diagram" throughout this guide.



Label	Description
A	Contraction Width
B	Height of bridge bottom from stream bed
C	Pier
D	Abutment
E	Parapet Height
F	Deck Height
G	Channel Width

FLOOD MODEL

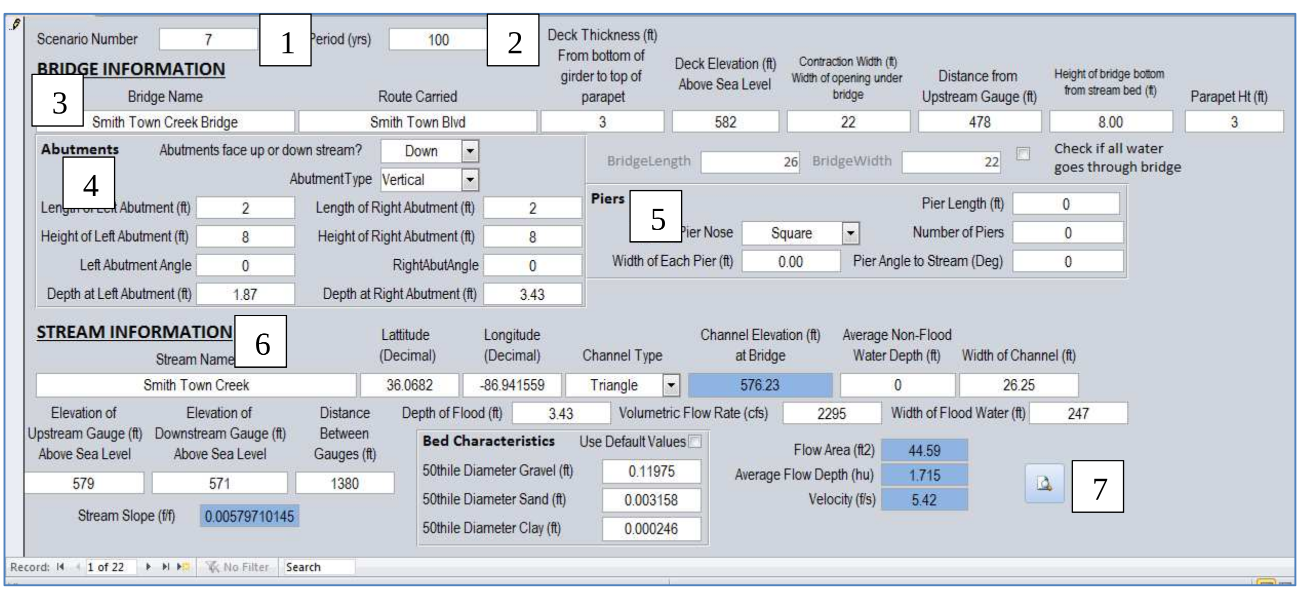
Two flood models will be required from Hazus. The first is the model for the bridges' design flood. Using our scenario from above, this would be a flood model with a 100-year return period.

To determine the design flood for a bridge, consult engineering documents from the bridge's construction or historical records for prevailing standards at the time of construction. The second model needed is for the future flood event. Again using the scenario above, the future flood would be a model with a 450-year return period. When modeling a flood with Hazus use the highest resolution DEM available. This will improve the program's ability to identify streams and determine flooding. Once the base and future flood models are complete data for the scour estimation entered in the Scour Calculator.

SCOUR CALCULATOR – OVERVIEW

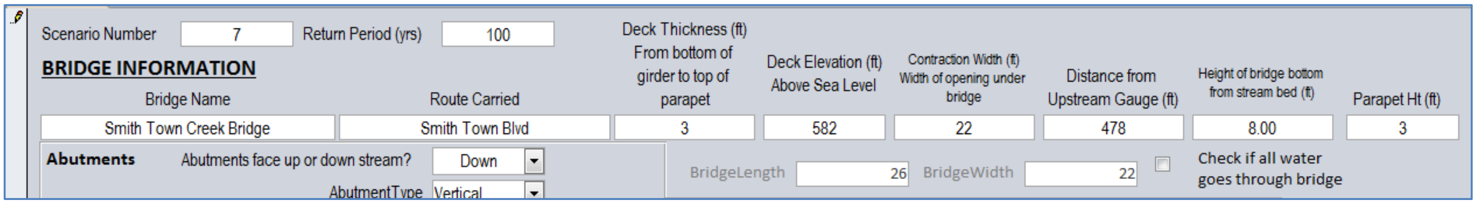
The Scour Calculator is written using Microsoft Access and Visual Basic for Applications (VBA). It is used to estimate the amount of scour at piers, abutments and bridge contractions. No programing or complex calculations are required for use. Using Hazus and other information sources, the user gathers data on the streams and bridges of interest and enters the data in the program. Once entered, the program performs all required calculations. The main screen provides the interface for data entry. The following illustration shows the main areas of the screen:

1) Scenario Number – The Scenario Number is assigned by the system and serves as a record number. The Scenario Number is used during the analysis phase to let the program know which scenario to analyze.
2) Return Period – This is the frequency of the flood that this scenario models. If it is for a 100-year flood enter "100". A separate screen is completed for each bridge/return period combination. There will be at least two screens completed for a given analysis, one for design return period scour and one for future return period scour.
3) Bridge Information – This area contains general information about the bridge
4) Abutments – This area is used to enter data on the bridge abutments
5) Piers – Data required for pier scour calculation.
6) Stream Information – This area is used to enter information that characterizes the stream
7) Analysis Button – This initiates the analysis for a given bridge and return period. When this is clicked the program will ask for the scenario number



BRIDGE INFORMATION

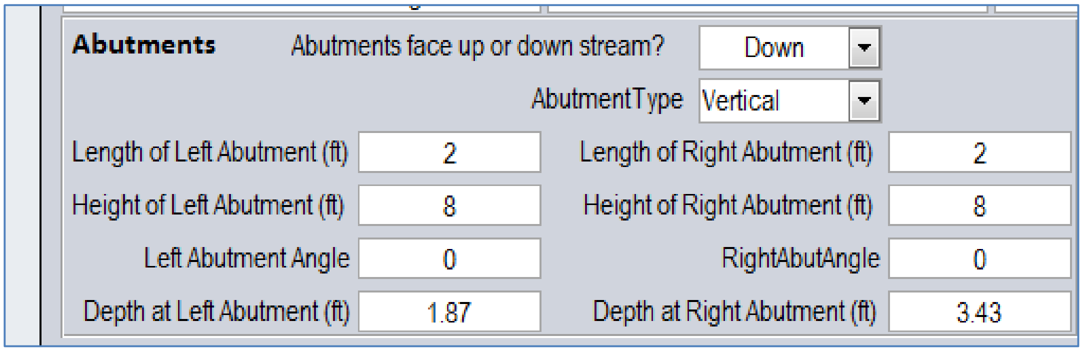
This section identifies important measurements about the bridge. The following table provides the field name, any special requirements for the information, a description of the field, and where it may be found.



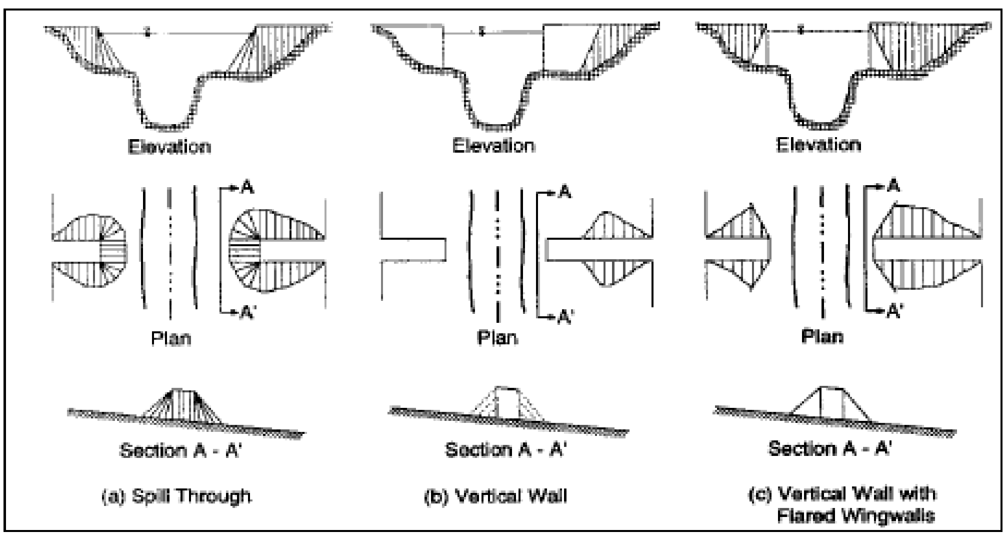
Field Name	Special Requirements	Description	Source
Bridge Name	No more than 255 characters	This may be the common name of the bridge or the name of the bridge from the National Bridge Inventory.	Community knowledge, National Bridge Inventory
Route Carried	No more than 255 characters	This is the road that the bridge carries across the stream.	Community knowledge, National Bridge Inventory
Deck Thickness	Number only	This is the thickness of the bottom of the bridge deck to the top of the parapet	Direct observation/estimation
Deck Elevation	Number only	This is the elevation above sea level of the road surface of the bridge	Google Earth estimate
Contraction Width	Number only	The width of the bridge between the abutments	Google Earth estimate
Distance from Upstream Gauge	Number only	Distance, in feet, of bridge from any upstream gauges	United States Geological Survey, distance estimate from ArcGIS or Google Earth
Parapet Height	Number only	Height of the parapet	Direct observation/estimation
Bridge Length	Number only	Total length of bridge	National Bridge Inventory, Field 49
Bridge Width	Number only	Total width of bridge	National Bridge Inventory, Field 52
Check if all water goes through bridge	N/A	This lets the program know if you want to calculate scour with all water going through the contraction. The default is unchecked	N/A

ABUTMENTS

This section identifies important measurements relative to the bridge abutments. The abutments are located at either end of the bridge where it joins the land. Label D in the bridge diagram above indicates the location of bridge abutments.

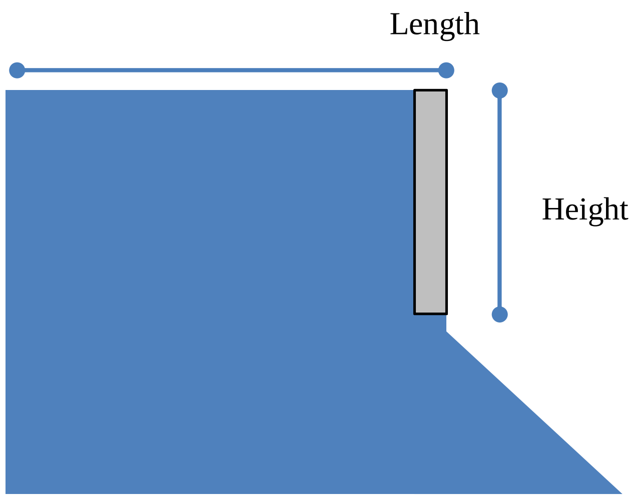


Once the type of abutment is selected, the user indicates whether the abutment faces up or down stream. If the abutment is perpendicular to the stream either value may be chosen. Selecting the type of abutment is next. The illustration below shows how each type of abutment appears when viewed from the channel or from above. Choose the one that most closely matches the bridge you are assessing.



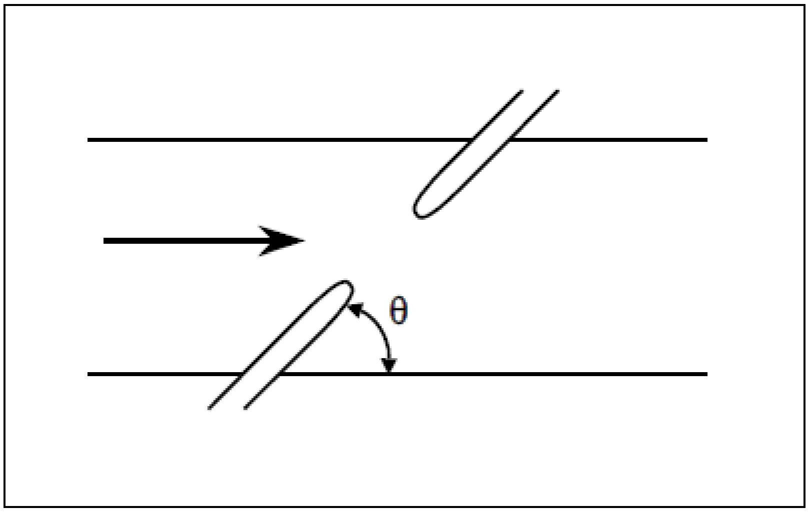
From US DOT, Hydraulic Engineering Circular 18, "Estimating Scour at Bridges"

The length and height of the abutment are required. The length of the abutment is measured from the bank to the abutment. Height is simply the distance between the top and bottom of the abutment. The following illustration shows the dimensions.



In some instances, there is very little embankment so the length is essentially the length of the abutment.

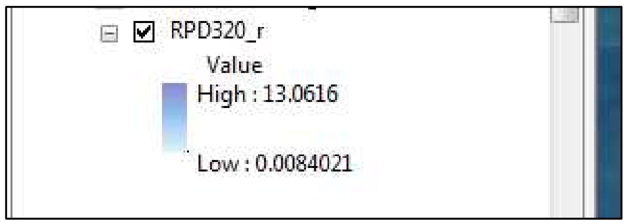
The angle of the abutment relative to the stream flow is required. The following illustration provides guidance on how to measure the angle. Note that it is the angle on the downstream side of the abutment.



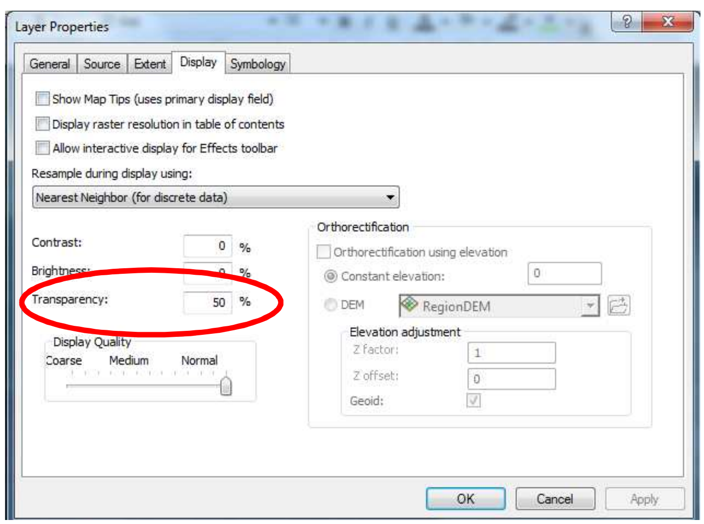
From US DOT, Hydraulic Engineering Circular 18, "Estimating Scour at Bridges"

The final value needed is the depth of the flood at the abutment. To determine this, Hazus and ArcGIS are used. To make sure your measurement is in the right area, use the “Add Data” tool to add a base map to the Hazus flood model. The tool is located in the tool bar: 

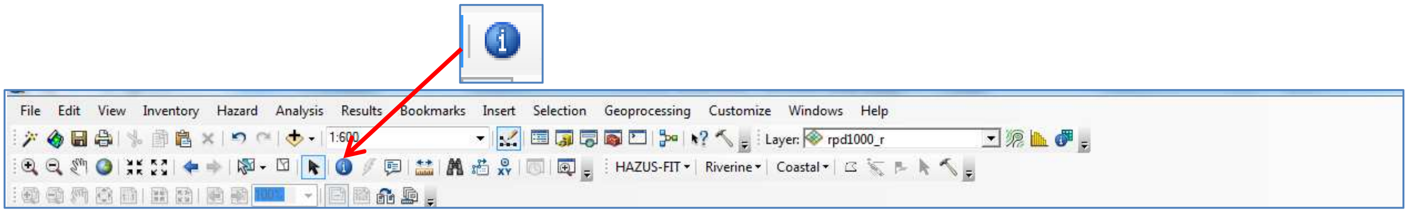
When prompted, select “Imagery” and select the satellite image for the area. Rearrange the Hazus layers so the flood layer is on top, followed by the streams and then the imagery layer. In the Hazus/ArcGIS “Table of Contents” window, double click the flood name to bring up the layer properties dialog box.



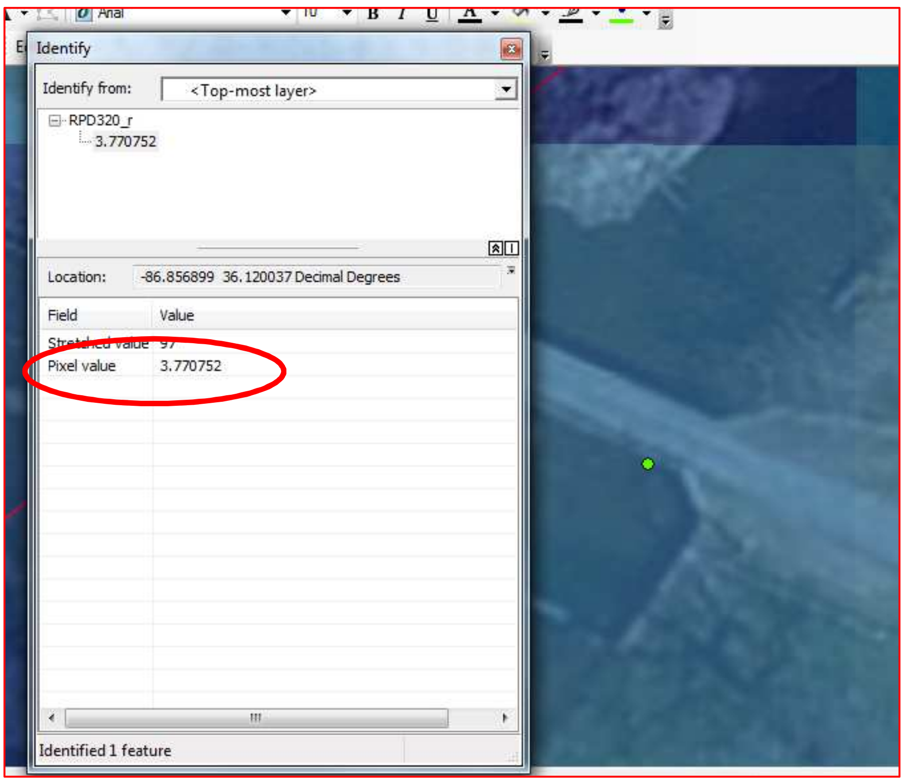
Once open, change transparency to 50% and click “OK”. This will allow the user to look “through” the flood to see the bridge below.



Click the “Identity” tool in Hazus/ArcGIS tool bar then click the flood over the abutment.

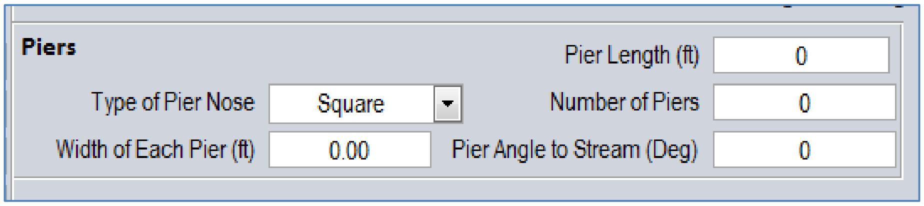


This will bring up a dialog box showing the pixel value for the clicked location. When Hazus calculates the flood it assigns each pixel of the flood layer raster the value of the flood depth, in feet. The pixel value is entered as “Depth at Abutment”. Ensure a value is obtained for each abutment, left and right.

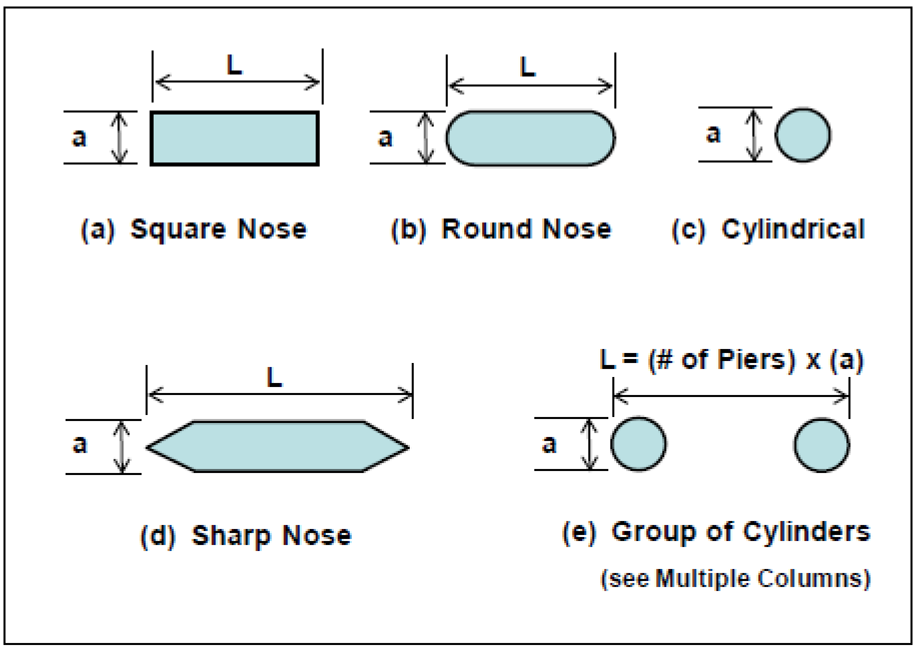


PIERS

Piers are labeled “C” in the bridge diagram. In some instances, small bridges will not have piers. In these cases leave the values as “0”. For bridges with piers, first select the nose type for the pier.



The following illustration assists in selecting the nose type:



From US DOT, Hydraulic Engineering Circular 18, “Estimating Scour at Bridges”

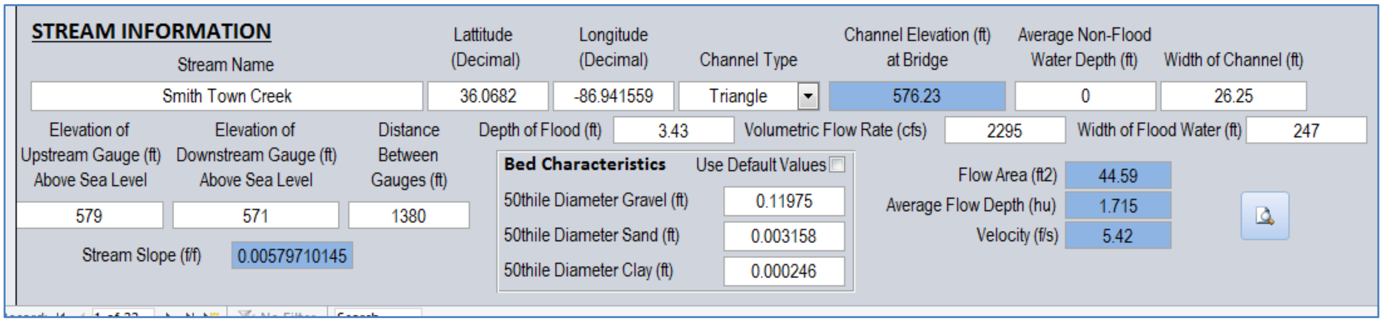
Once the nose type is determined, measure or estimate the width of each pier (dimension “a” in the illustration) and the length of each pier (dimension “L” in the illustration).

Count the piers and enter the value in “Number of Piers”. Grouped piers count as a single pier. Finally, enter the angle of the pier relative to the stream flow. If the pier nose faces directly into the flow, the angle is “0”.

STREAM INFORMATION

The remaining information pertains to the stream itself. The "Stream Name", "Latitude" and "Longitude" fields are optional but entering them will help document the stream assessed and its location.

The "Channel Type" is used to tell the program how to calculate the cross sectional area of the stream. "Triangle" and "Trapezoid" are the options, with "Triangle" as default. All blue shaded fields are calculated by the program. These fields are locked and not editable by users.



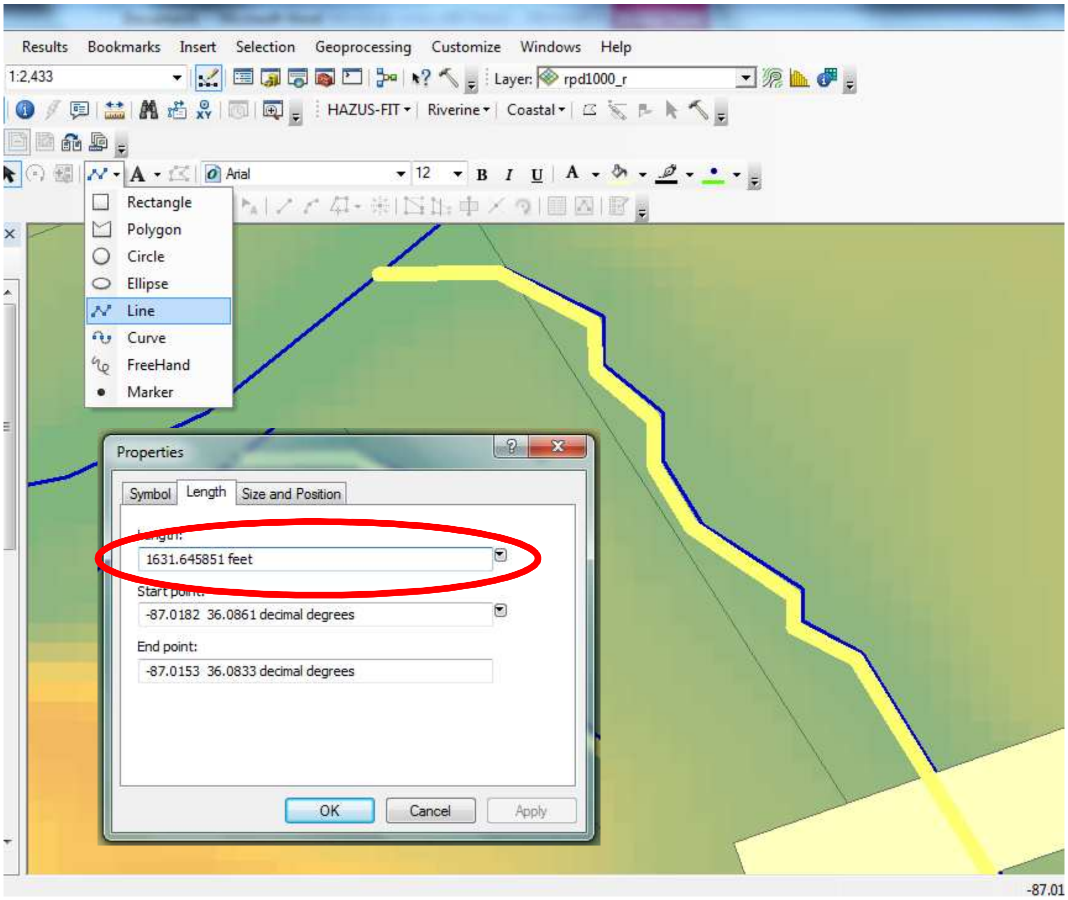
The "Average Non-Flood Water Depth" can be found from United States Geological Survey (USGS) stream gauge data, Army Corps of Engineers data or local data. This is the average yearly depth of water in the stream at the bridge when not flooded.

"Width of Channel" is the width of the stream channel. It may also be estimated by using Google Earth® and measuring the distance between the stream banks during normal flow.

ELEVATION, DISTANCES AND STREAM SLOPE

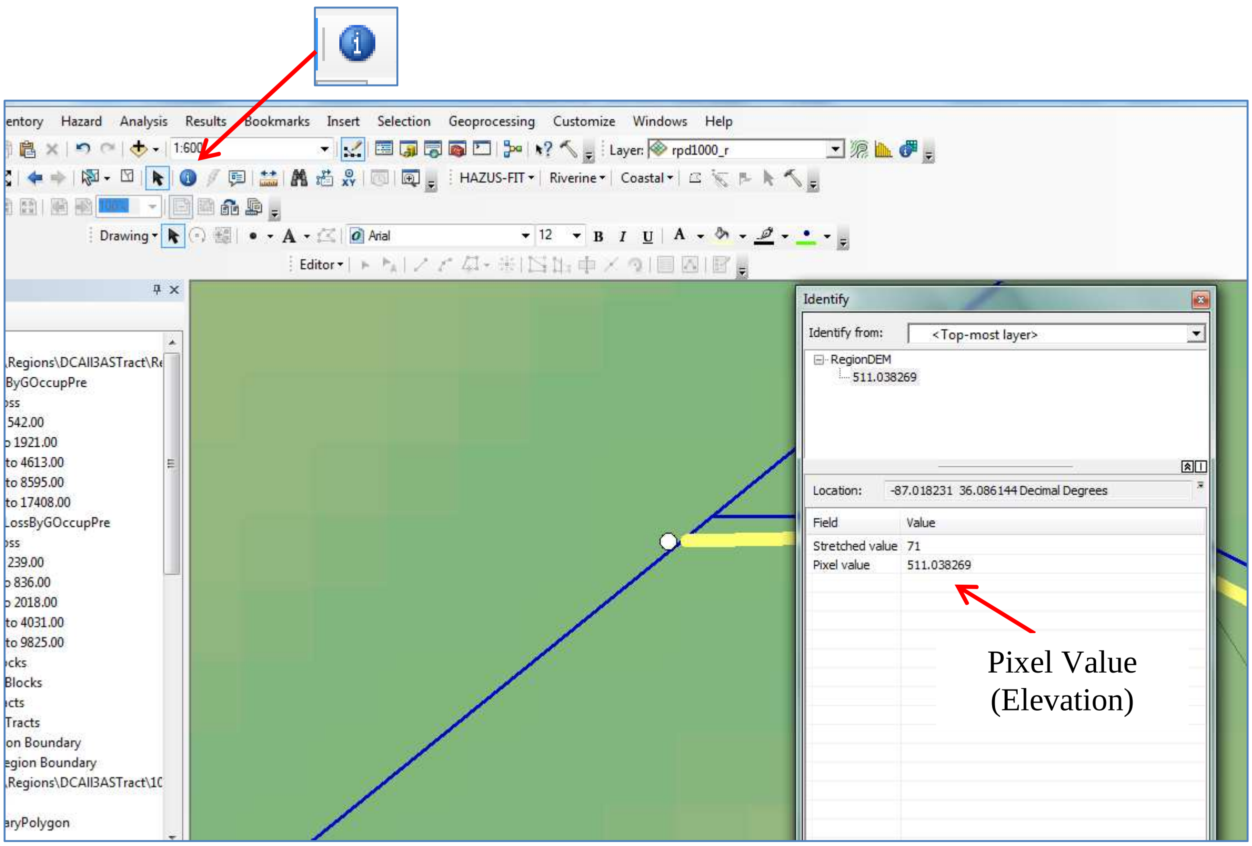
A key component of calculation is the stream slope. The stream slope is the amount a stream bed rises (or falls) over a given distance. Do not take measurements closure than 500 feet up and downriver from the bridge.

To obtain the data for entry, select two points, one above and one below the bridge. Using the ArcGIS "Line" tool, carefully trace the path of the stream between the points. The following shows the tracing in yellow and the stream in blue. Make sure the tracing follows the streambed as closely as possible. For the purposes of illustration, the tracing has been offset so the stream beneath can be seen.



Once the stream has been traced, select the line, right click to bring up the ArcGIS sub-menu and select "Properties". This will provide the length between the upstream and downstream points. Record this value as "Distance between Gauges".

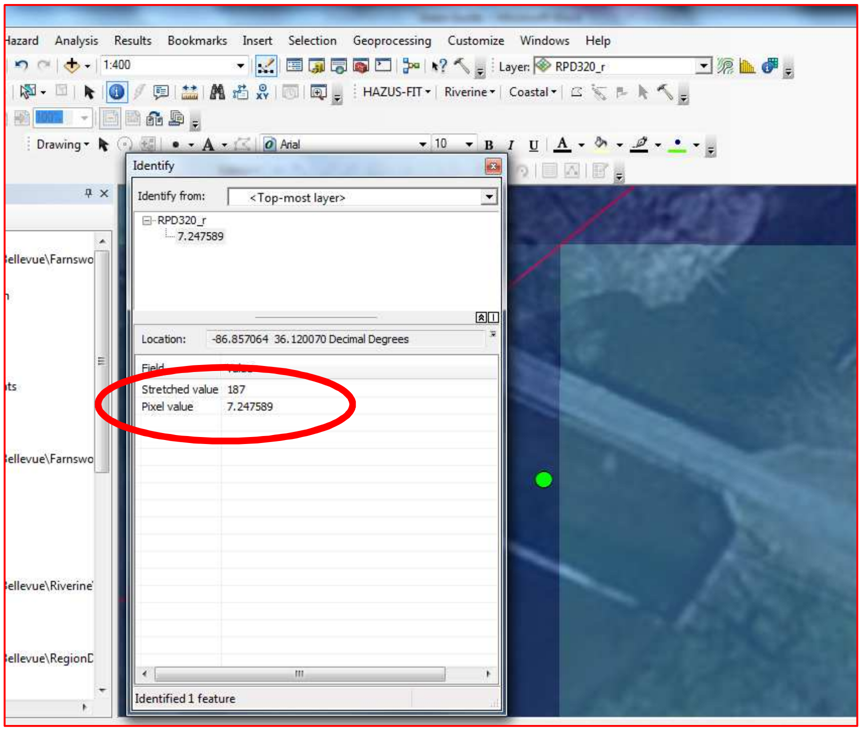
After the distance between the gauges is found, determine the elevations at both ends of the line. This is done using the "Identify" tool in ArcGIS to obtain the pixel value from the Digital Elevation Model (DEM). In Hazus, the pixel value from the DEM is the same as the elevation. Click the "Identify" tool (the "i") and then click the end of the line (the white dot in the figure below provides a reference). A dialog box will appear. The number shown next to "Pixel Value" is the elevation. In this case, it is 511 feet. Repeat this process for the other end of the line.



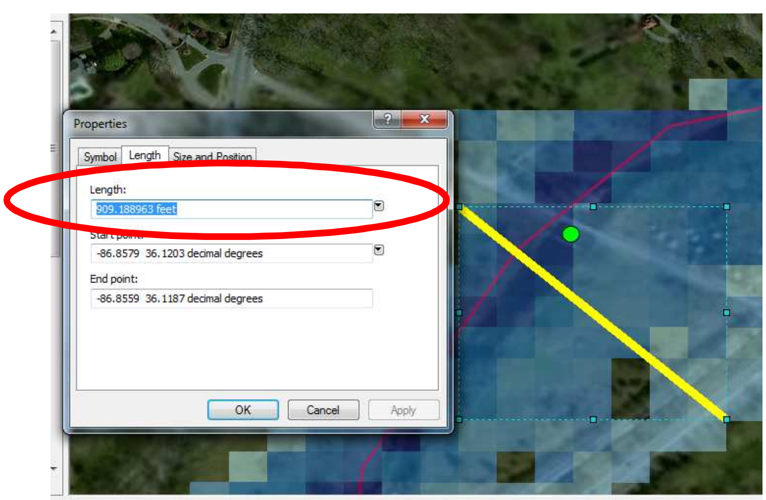
Record the higher number as the "Elevation of Upstream Gauge" and the lower number as "Elevation of Downstream Gauge".

DEPTH OF FLOOD AND WIDTH OF FLOOD WATER

The "Depth of Flood" and "Width of Flood Water" values are determined using Hazus. Again using the "Identify" tool, click directly in the center of the stream bed, immediately upstream from the bridge. As before, use the pixel value as the "Depth of Flood".



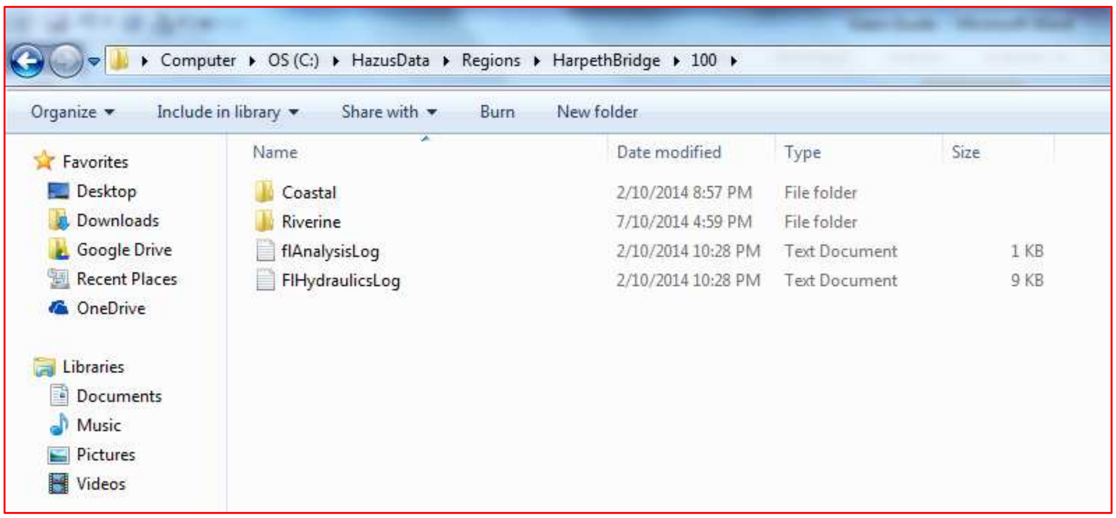
"Width of Flood Water" is determined by zooming out until the width of the flood in relation to the bridge may be seen. Using the "Line" tool, draw a line between the edges of the flood just upstream from the bridge. Once the line is drawn, select the line, right click to bring up the ArcGIS sub-menu and select "Properties". The length will be shown in the dialog box.



VOLUMETRIC FLOW RATE

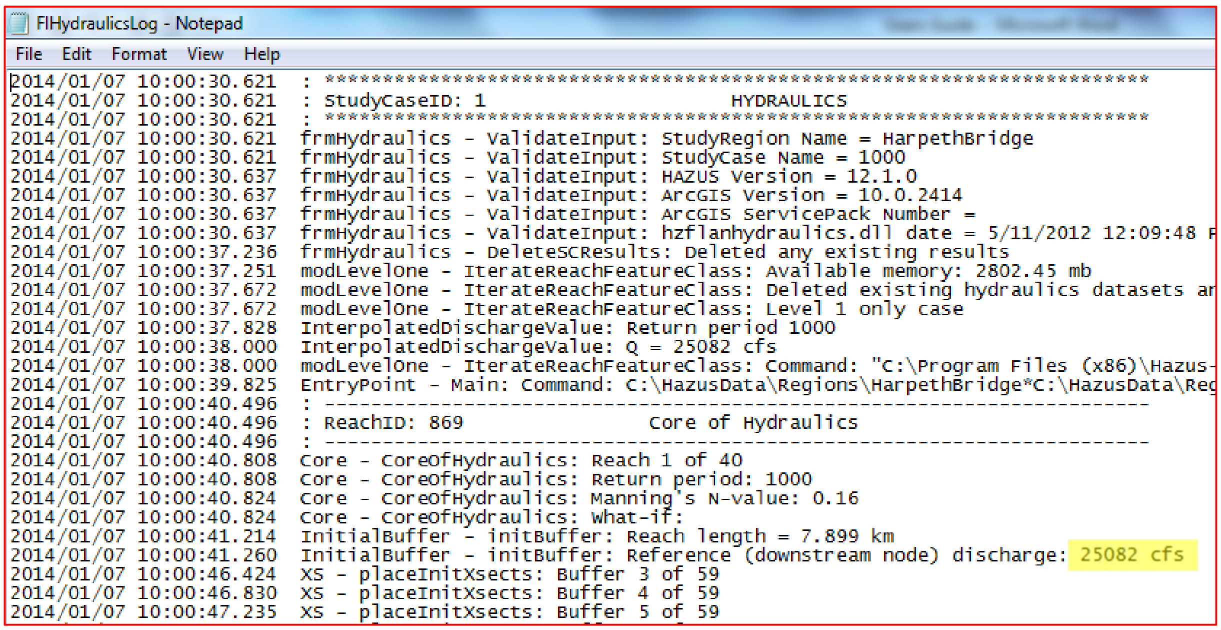
The volumetric flow rate is calculated by Hazus. The value is stored in the "FlHydraulicsLog.txt" file. Directions are required in finding the file.

When Hazus opens, the user must create a study region. This region is usually the general area in which flood studies are conducted, such as "Smith County" or "Harpeth River". Once created, multiple scenarios may be run for a single region. Each time a scenario is created Hazus creates a scenario directory under that region name. As an example, a study region named "Harpeth Bridge" was created and under this several scenarios were modeled one of which was named "100". To find the FlHydraulicsLog file for this scenario, the user opens Microsoft File Explorer and navigates to the directory where the Hazus regions are stored. Once there, the user would find and double click the directory called "100". Once there, double clicking the "FlHydraulicsLog.txt" file will open the file in Windows Note Pad or similar text editor.



The FlHydraulicsLog file contains information on all streams assessed in the scenario. To determine the stream needed for calculation, return to Hazus and identify the stream that runs beneath the bridge of interest. Using the “Identify” tool click the stream. The dialog box that pops up will have several items but the one of interst is “ArcID”. With the ArcID identified, open the FlHydraulicsLog.txt file. The ArcID is equal to the ReachID presented in the text file. Using the text editors search or find function, search for the ArcID. Once it is found, scroll down 4-8 lines to find the discharge value.

In the example below, if ArcID 869 was the stream of interest, the volumetric flow would be 25,082 cubic feet per second (highlighted). Enter this value in “Volumetric Flow Rate”.



FlHydraulicsLog - Notepad

File Edit Format View Help

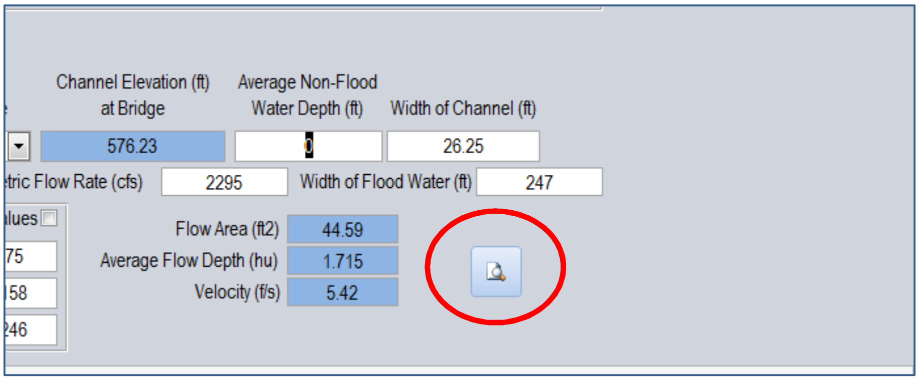
```
2014/01/07 10:00:30.621  : ***********************************************************************
2014/01/07 10:00:30.621  : StudyCaseID: 1                          HYDRAULICS
2014/01/07 10:00:30.621  : ***********************************************************************
2014/01/07 10:00:30.621  frmHydraulics - ValidateInput: StudyRegion Name = HarpethBridge
2014/01/07 10:00:30.621  frmHydraulics - ValidateInput: StudyCase Name = 1000
2014/01/07 10:00:30.637  frmHydraulics - ValidateInput: HAZUS Version = 12.1.0
2014/01/07 10:00:30.637  frmHydraulics - ValidateInput: ArcGIS Version = 10.0.2414
2014/01/07 10:00:30.637  frmHydraulics - ValidateInput: ArcGIS ServicePack Number =
2014/01/07 10:00:30.637  frmHydraulics - ValidateInput: hzflanhydraulics.dll date = 5/11/2012 12:09:48 P
2014/01/07 10:00:37.236  frmHydraulics - DeleteSCResults: Deleted any existing results
2014/01/07 10:00:37.251  modLevelOne - IterateReachFeatureClass: Available memory: 2802.45 mb
2014/01/07 10:00:37.672  modLevelOne - IterateReachFeatureClass: Deleted existing hydraulics datasets an
2014/01/07 10:00:37.672  modLevelOne - IterateReachFeatureClass: Level 1 only case
2014/01/07 10:00:37.828  InterpolatedDischargeValue: Return period 1000
2014/01/07 10:00:38.000  InterpolatedDischargeValue: Q = 25082 cfs
2014/01/07 10:00:38.000  modLevelOne - IterateReachFeatureClass: Command: "C:\Program Files (x86)\Hazus-
2014/01/07 10:00:39.825  EntryPoint - Main: Command: C:\HazusData\Regions\HarpethBridge*C:\HazusData\Reg
2014/01/07 10:00:40.496  : -----------------------------------------------------------------------
2014/01/07 10:00:40.496  : ReachID: 869                  Core of Hydraulics
2014/01/07 10:00:40.496  : -----------------------------------------------------------------------
2014/01/07 10:00:40.808  Core - CoreOfHydraulics: Reach 1 of 40
2014/01/07 10:00:40.808  Core - CoreOfHydraulics: Return period: 1000
2014/01/07 10:00:40.824  Core - CoreOfHydraulics: Manning's N-value: 0.16
2014/01/07 10:00:40.824  Core - CoreOfHydraulics: What-if:
2014/01/07 10:00:41.214  InitialBuffer - initBuffer: Reach length = 7.899 km
2014/01/07 10:00:41.260  InitialBuffer - initBuffer: Reference (downstream node) discharge: 25082 cfs
2014/01/07 10:00:46.424  XS - placeInitXsects: Buffer 3 of 59
2014/01/07 10:00:46.830  XS - placeInitXsects: Buffer 4 of 59
2014/01/07 10:00:47.235  XS - placeInitXsects: Buffer 5 of 59
```

Bed Particle Size

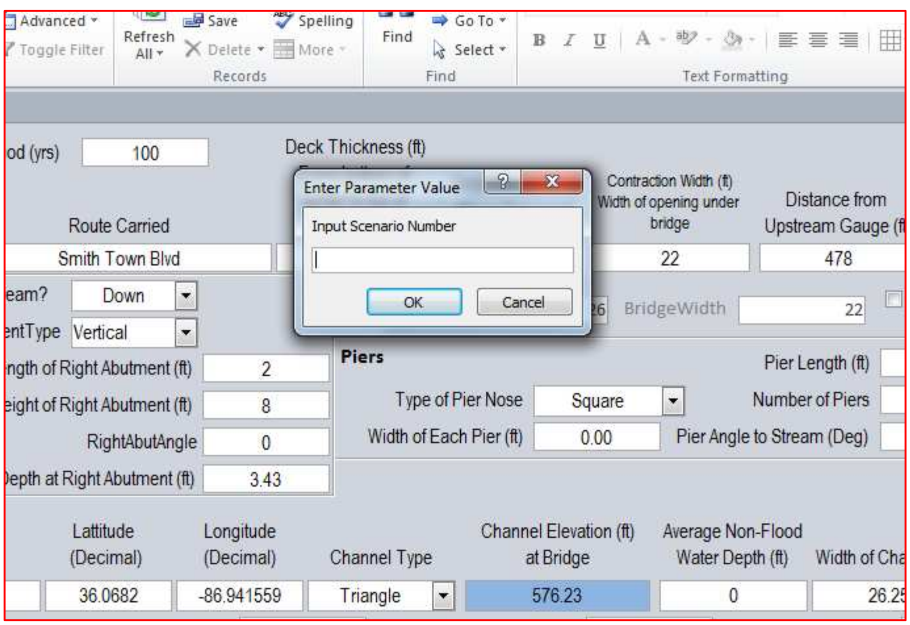
Calculating contraction scour depends on the distribution of particle types and average diameter of the particles making up the stream bed. Since bed characterization may not be possible, the program assesses scour for the median particle size for gravel, sand and clay. If “Use Default Values” is checked pre-loaded values representing the fiftieth percentile diameter for each size range (gravel, sand and clay) will be used. If the median particle size for each type is known for a stream, leave this box unchecked and manually enter the values, in feet.

CALCULATING SCOUR

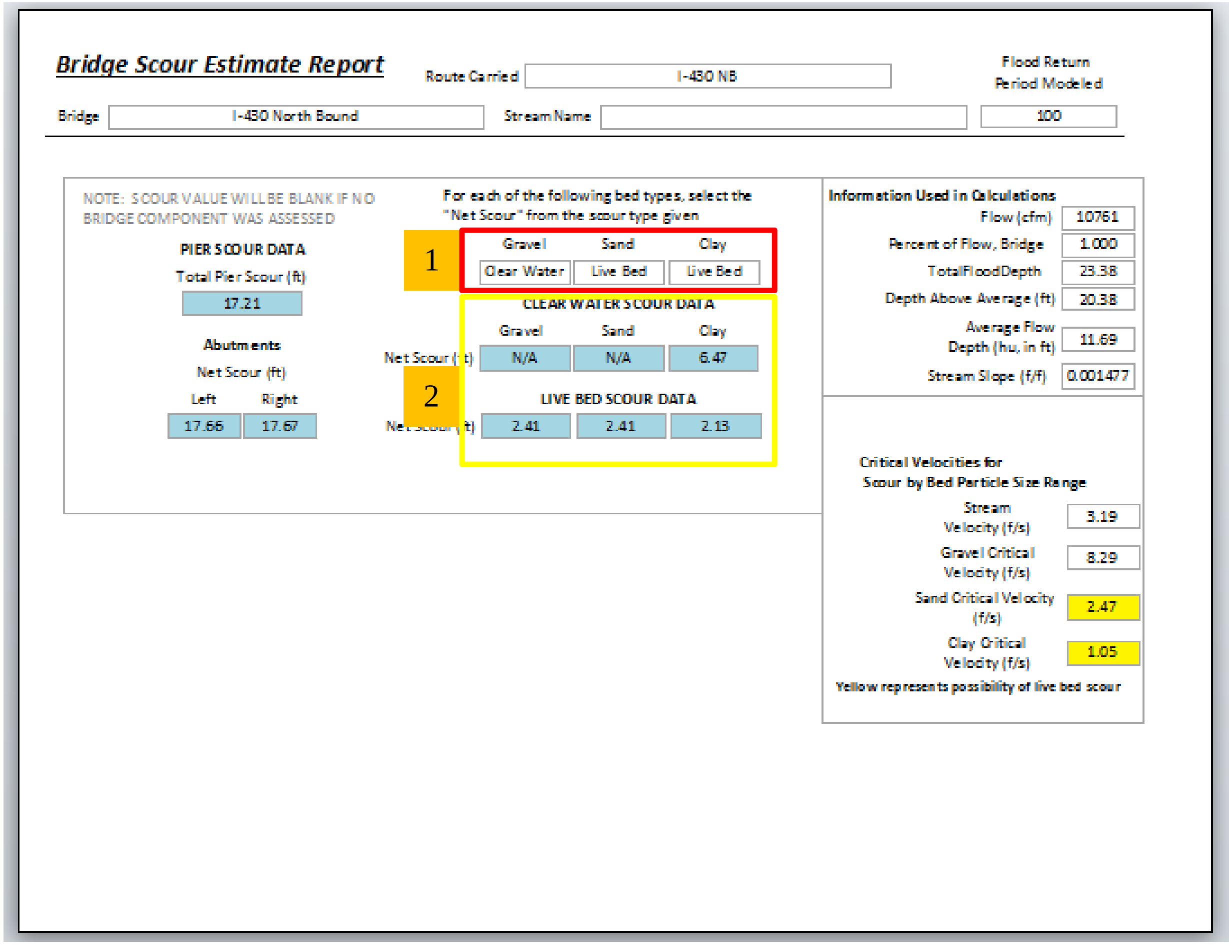
After entering all values flood scour is ready to be calculated. Note the scenario number. Click the analysis icon in the bottom right of the screen.



Once clicked, the program will open a dialog box. Input the Scenario Number and click "OK". The scour for that flood return period will be calculated.



When the analysis is complete a report will be displayed.



Pier and Abutment Scour are presented as single numbers. Contraction Scour requires interpretation. In area 1 note that each particle type is identified as “Clear Water” or “Live Bed”. Choose the values in area 2 based on “Clear Water” or “Live Bed” as indicated in area 1. As an example, in the above example, the value for clay in area 1 is “Live Bed”. Using this example, the value of 2.13 would be used instead of the 6.47 given for clear water.

Calculating the Scour Factor and Estimated Damage

When scour analysis is complete all that remains is estimating the monetary damage from the flood event. To perform this analysis, use the Scour Factor Workbook file for Microsoft Excel. Beginning with Base Year, enter the scour values for pier, abutment and contraction in the spaces provided. Repeat this process for the Future Year scour. The final step is to enter the bridge length and width. The workbook will automatically calculate the scour factor as well as the estimated monetary damage.

ADAPTATION PLANNING

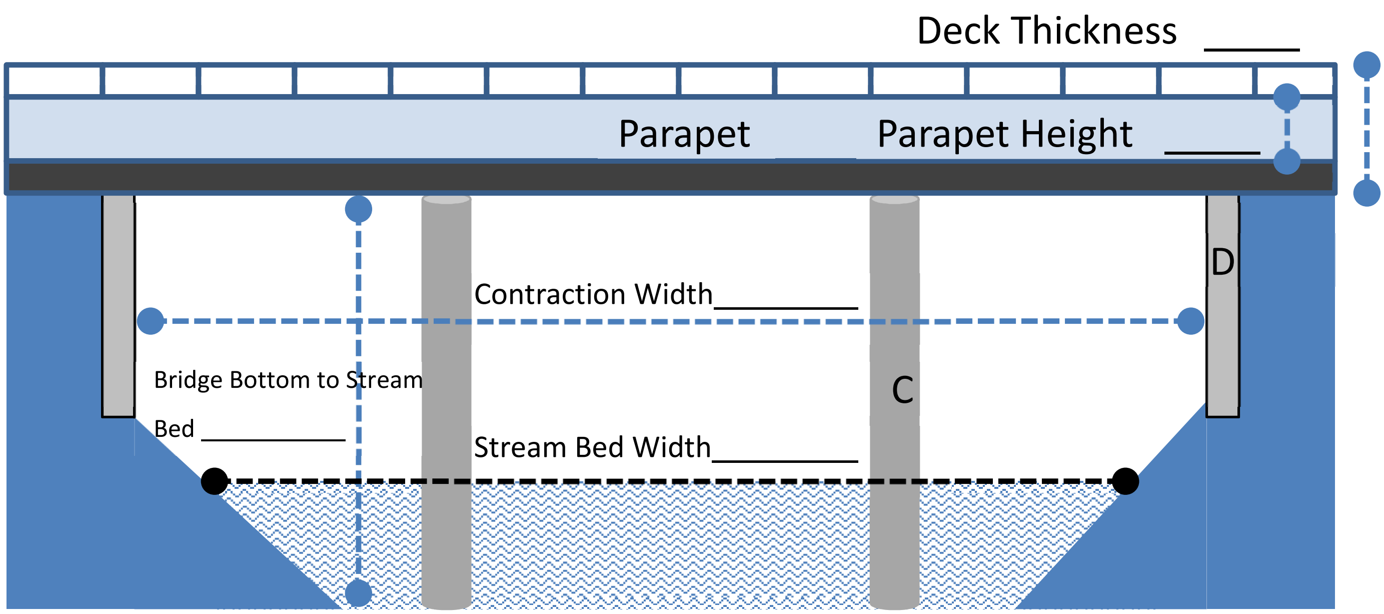
Bridge adaptation planning should proceed from highest monetary impact value to least. This will ensure those bridges with greatest economic impact value are protected first. It is recommended that the National Cooperative Highway Research Program (NCHRP) web-only document 107 "Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations" be used in conjunction with this methodology to ensure indirect costs for bridge failure are captured. The NCHRP document and spreadsheet for calculating indirect cost is available at http://www.trb.org/Main/Public/Blurbs/157792.aspx. Using this methodology will provide estimated indirect cost due to bridge failure resulting from increased commute time, increased fuel costs and diverted commercial traffic.

DATA COLLECTION SHEET

The following may be used to assist in collecting data for scour analysis.

Stream Name					
Road Carried					
Flood Return Period		Bridge Length		Bridge Width	

ALL UNITS ARE "FEET" UNLESS OTHERWISE NOTED



Left Abutment	
Length	
Height	
Angle (degrees)	
Depth	

Right Abutment	
Length	
Height	
Angle (degrees)	
Depth	

Pier	
Type	Square Round Circular Grouped Sharp
Width	
Length	
Number	
Angle (degrees)	

Stream Data	
Average Non-Flood Depth	
Depth of Flood (Center of Channel)	
Upstream Gauge Elevation	
Downstream Gauge Elevation	
Distance between Gauges	
Width of Flood	
Flow (cubic feet per second, cfs)	