DEVELOPMENT OF PRIORITY BASED STATEWIDE SCOUR MONITORING SYSTEMS IN NEW ENGLAND

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Prepared for
The New England Transportation Consortium

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16. Abstract

A project was funded by the New England Transportation Consortium to research the creation of a scour monitoring system that would assist in the allocation of resources during potentially destructive flood events in New England. Emphasis was placed upon the adoption and use of existing tools and infrastructure to accomplish these tasks. A web-based approach using a spatial decision support system (SDSS) would be adopted for development of the monitoring system. A SDSS is a platform independent software application that can be used as both a decision and research tool. The versatility of the model enables discretion to be used, which emphasizes the importance of engineering judgment with respect to the analytical method used to evaluate scour potential in this system.

Potential components of the system are identified and reviewed, such as existing scour analyses, instrumentation, and automated gages. Internet websites are discussed in detail to familiarize DOTs with sources of available real-time weather products pertinent to the assessment of scour conditions. A GIS is created for each New England state to geographically integrate bridge, dam, and gage infrastructure in order to recognize the relation between them. Various scour models are presented along with methods for determining hydraulic input parameters to be entered into the models. The framework of a conceptual scour monitoring system is outlined and a potential scenario is used to illustrate the operation of the monitoring system for real-time warning and assessment of scour conditions. The sum result of these tasks was the development of a prototype real-time scour monitoring and assessment tool that integrated web-based assessment tools, geographic information systems, and Internet resources.

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REAL-TIME BRIDGE SCOUR ASSESSMENT AND WARNING

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ABSTRACT

Scour is the removal of sediment from streambeds and streambanks and is caused by the erosive action of flowing water. It can occur at anytime, but is more significant during high flow events, when water is moving at a high velocity. Due to the complexity of stream dynamics, scour is often exacerbated at bridge piers and abutments, potentially undermining the structure and jeopardizing its stability.

The FHWA initially focused its efforts on identifying and coding all bridges regarding their scour susceptibility through qualitative and quantitative means. Now that the task of assessing the vulnerability of bridges to scour is largely complete, attention has shifted toward using available resources to monitor, prepare, and respond to scour-inducing weather events. A project was funded by the New England Transportation Consortium to research the creation of a scour monitoring system that would assist in the allocation of resources during potentially destructive flood events in New England. Emphasis was placed upon the adoption and use of existing tools and infrastructure to accomplish these tasks.

A web-based approach using a spatial decision support system (SDSS) would be adopted for development of the monitoring system. A SDSS is a software application that can be used as both a decision and research tool. The SDSS code could be written in Sun Microsystems Java 1.2. Java is platform independent and can be run on any operating system.

An effective scour monitoring system is one that is flexible enough to cope with the dynamic nature of scour and requires the management and organization of data, people, and resources transcending several disciplines. The strength of the proposed system is its versatility. This is particularly important in light of predictive scour methods that are often overly conservative. The versatility of the model enables discretion to be used, which emphasizes the importance of engineering judgement in this system.

Potential components of the system are identified and reviewed, such as existing scour analyses, instrumentation, and automated gages. Internet websites are discussed in detail to familiarize DOTs with sources of available real-time weather products pertinent to the assessment of scour conditions. A GIS is created for each New England state to geographically integrate bridge, dam, and gage infrastructure in order to recognize the relation between them. Various scour models are presented along with methods for determining hydraulic input parameters to be entered into the models. The framework of a conceptual scour monitoring system is outlined and a potential scenario is used to illustrate the operation of the monitoring system for real-time warning and assessment of scour conditions. The sum result of these tasks was the development of a prototype real-time scour monitoring and assessment tool that integrated web-based assessment tools, geographic information systems, and Internet resources.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF SYMBOLS

ENGLISH

A	=	drainage area, in square miles
A_e	=	the flow area of the approach cross section obstructed by the embankment
c	=	region-specific coefficient
CSM	=	cubic feet per second per square mile
d	=	region-specific coefficient
DA	=	drainage area into gage, in square miles
Fr	=	Froude number = $V_e/(g\ y_a)^{0.5}$
Δh	=	difference in water surface elevation
K_1	=	coefficient for abutment shape (See Table 6, Section 4.3.6 in HEC-18, Third Ed., dated Nov. 95)
K_2	=	coefficient for angle of embankment to flow (Refer to Section 4.3.6, Figure 16 in HEC-18, Third Ed., dated Nov. 95)
L_1	=	the length of abutment projected normal to flow
q_2	=	unit discharge per foot-width of main channel at the contracted section, in cubic feet per second per foot width
Q	=	discharge for x-year flow event, in cubic feet per second
Q_e	=	the flow obstructed by the abutment and approach embankments
Q_2	=	x-year discharge through bridge opening, in cubic feet per second
V_e	=	Q_e/A_e
V_2	=	average main channel velocity at the bridge contraction at the downstream bridge opening
W_2	=	estimated top width of x-year flow at the downstream face of the bridge opening, adjusted for any skewness to flow and for effective pier width, in feet
Y_a	=	average depth of flow in the floodplain = A_e/a'
Y_s	=	scour depth
y_1	=	flow depth in the approach section, in feet
y_2	=	flow depth at the downstream face of bridge, in feet

LIST OF ACRONYMS

ADDS	=	Aviation Digital Data Service
ADT	=	average daily traffic
AFOS	=	Automation of Field Operations and Services
AFWS	=	Automated Flood Warning System
ALERT	=	Automated Local/Statewide Evaluation in Real Time
AOMC	=	ASOS Operations and Monitoring Center
ASOS	=	Automated Surface Observing System
BSE	=	Bridge Scour Evaluator
CDOT	=	Connecticut Department of Transportation
COOP	=	Cooperative Observer Program
CRREL	=	Cold Regions Research and Engineering Laboratory
DCP	=	Data Collection Platform
DCS	=	Data Collection System
DEP	=	Department of Environmental Protection
DOD	=	Department of Defense
DOT	=	Department of Transportation
EMWIN	=	Emergency Managers Weather Information Network
FAA	=	Federal Aviation Administration
FEMA	=	Federal Emergency Management Agency
FFG	=	flash flood guidance
FHWA	=	Federal Highway Administration
FI	=	fixed instrumentation
FM-CW	=	frequency modulated – continuous wave
FSP	=	Fundamental Scour Parameter
FT	=	field team
GIS	=	Geographic Information System
GM	=	geophysical methods
GOES	=	Geostationary Operational Environmental Satellites
GPR	=	ground-penetrating radar
GUI	=	Graphical User Interface
HADS	=	Hydrometeorological Automated Data System
HARN	=	High Accuracy Reference Network
HEC	=	Hydraulic Engineering Circular
HECRAS	=	HEC River Analysis System
HG	=	height, river stage (ft, m)
HIC	=	Hydrologic Information Center
HTB	=	heated tipping bucket
H&D	=	Hydraulic & Drainage Unit
IFLOWS	=	Integrated Flood Observing and Warning System
IWIN	=	Interactive Weather Information Network
LEFP	=	liquid-equivalent of frozen precipitation
METAR	=	Aviation Routine Weather Report
MS	=	Microsoft
MSHA	=	Maryland State Highway Administration

NAD27	=	North American Datum of 1927
NAD83	=	North American Datum of 1983
NAE	=	United States Army Corps of Engineers, New England District
NBI	=	National Bridge Inventory
NBIS	=	National Bridge Inspection Standards
NERFC	=	Northeast River Forecast Center
NESDIS	=	National Environmental Satellite, Data Information Service
NETC	=	New England Transportation Consortium
NEXRAD	=	Weather Surveillance Radar 1988 Doppler (WSR-88D)
NID	=	National Inventory of Dams
NOAA	=	National Oceanic and Atmospheric Administration
NTSB	=	National Transportation Safety Board
NWS	=	National Weather Service
PC	=	precipitation, accumulator (in, mm)
QPF	=	quantitative precipitation forecast
RRT	=	Reservoir Regulation Team
SDSS	=	spatial decision support system
SHEF	=	Standard Hydrometeorological Exchange Format
SPECI	=	Aviation Selected Special Weather Report
TA	=	technical advisory
TDR	=	time domain reflectometry
U	=	unknown foundation (Item 113 code)
UMTC	=	University of Massachusetts Transportation Center
USACE	=	United States Army Corps of Engineers
USGS	=	United States Geological Survey
UTC	=	Coordinated Universal Time
UTM	=	Universal Transverse Mercator
WRI	=	Water-Resources Investigations
WSPRO	=	Water-Surface Profile Model

1.0 INTRODUCTION

Scour is the removal of sediment from streambeds and streambanks and is caused by the erosive action of flowing water. It can occur at anytime but is more significant during high flow events, when water is moving at a high velocity. Due to the complexity of stream dynamics, scour is often exacerbated at bridge piers and abutments, potentially undermining the structure and jeopardizing its stability. The extent of this potential problem is magnified by the fact that approximately 84% of the nation's 575,000 bridges in the National Bridge Inventory (NBI) span waterways (Richardson and Davis 1995). Factors that affect bridge scour include channel and bridge geometry, floodplain characteristics, flow hydraulics, bed material, channel protection, channel stability, riprap placement, ice formations, and debris (Richardson and Davis 1995).

Bridge scour is the most common cause of bridge failures. Shirhole and Holt reported that in a survey of 823 bridge failures since 1950, sixty percent of the failures were attributed to the effects of flow hydraulics, including both channel bed scour around bridge foundations and channel instability ("Strategic Plan", p.2, 2000). A 1973 national study prepared for the Federal Highway Administration (FHWA) reported that of 383 bridge failures caused by catastrophic floods, one quarter of them suffered pier damage and nearly three quarters experienced abutment damage (Richardson and Davis 1995). Annual costs for scour related bridge failures and repairs for flood damage to bridges receiving federal aid are approximately $30 million and $50 million, respectively (Holnbeck and Parrett, p.3, 1997), although total scour-related costs for catastrophic events can run much higher. In 1994, flooding from storm Alberto in Georgia was responsible for scour damage to over 500 state and locally owned bridges and total highway damage costs of approximately $130 million (Richardson and Davis 1995).

Bridge scour may be observed, but the extent or severity of it may be unknown as the scour process can be cyclic in nature. Scour holes may be formed during high flows and subsequently refilled as sediment is deposited by receding floodwaters. Post-flood bridge inspections, therefore, may not reveal the actual magnitude of bridge scour at its peak (Richardson and Davis 1995).

Bridge scour first garnered national attention with the 1987 collapse of the I-90 bridge over Schoharie Creek in New York. Without warning, five vehicles plunged into the creek as two spans of the bridge fell into the floodwaters on April 5, 1987, killing 10 people. Investigations into the collapse by the National Transportation Safety Board (NTSB) determined the cause of failure to be bridge scour stemming from inadequate riprap around the base of the piers and the shallow depth of the foundation ("Ten Years"). Since then, the Federal Highway Administration (FHWA) has focused its efforts on identifying and coding all bridges regarding their scour susceptibility through qualitative and quantitative means.

The FHWA issued technical advisories TA5140.20 "Scour at Bridges" (U.S. Department of Transportation 1988) and TA5140.23 "Evaluating Scour at Bridges" (U.S. Department of Transportation 1991) in 1988 and 1991, respectively, to provide guidance for states as they developed and implemented scour evaluation programs for existing bridges and new bridge designs. In 1991, Hydraulic Engineering Circular No. 20 (HEC-20) "Stream Stability at Highway Structures" was published by the FHWA to help provide guidelines for identifying stream instability at highway stream crossings (Lagasse et al. 1991). In 1995, Hydraulic Engineering Circular No. 18 (HEC-18) "Evaluating Scour at Bridges Third Edition" was released by the FHWA, which presented a revised methodology for a full scour analysis, including the design, evaluation, and inspection of bridges for scour (Richardson and Davis

1995). Of particular concern in these documents were scour critical bridges, bridges that could experience catastrophic failure or become structurally unstable as a result of excessive scour caused by a destructive flood event. A single digit rating system within the National Bridge Inspection Standards (NBIS) was developed by the FHWA to help classify the vulnerability of bridges to scour (U.S. Department of Transportation 1995).

Today, it is realized that scour is a problem involving several disciplines that must be addressed through collaborations between researchers, engineers, forecasters, and emergency personnel. All states must deal with the problem of scour, yet when it comes to available resources such as money and personnel, no two states are alike. New technologies have emerged with the potential to assist personnel and agencies to monitor, prepare, and respond to critical storm events. The implementation of a SDSS would help level the field for all states, permitting all parties to evaluate and monitor scour using the same models. It is important to make use of these tools and resources in order to reduce the threat of scour-induced bridge failures.

1.1 Purpose/ Objectives

The first scour initiatives focused on inventory and evaluation of bridges susceptible to scour-induced failure. The next step is the development of a systematic classification and prioritization scheme for bridge remediation. As part of this goal, in September 1999, the New England Transportation Consortium (NETC) funded a project to research the development of priority based statewide scour monitoring systems in New England through the University of Massachusetts Transportation Center (UMTC). The objective of this research is to develop a strategy for the creation of a statewide scour monitoring network to assist in the allocation of resources during potentially destructive flood events, including real-time assessment of bridge scour.

There are three main research tasks for this project. The first task is to document sources of information pertaining to stream monitoring, precipitation, storm prediction, and evacuation routing. The second task is to identify locations of existing state monitoring systems and scour critical bridges, and catalog attributes for all of them using Geographic Information Systems (GIS). The final task is to develop a conceptual model of a monitoring system that incorporates hazard and risk assessment in order to prioritize bridges jeopardized by scour. Since predictive scour methods are often overly conservative, it is necessary to adopt and incorporate several analytical tools to assess the full level of scour hazard at bridges. The proposed system will be web-based and platform independent for universal accessibility, allowing each state to monitor scour at scour critical bridges during a storm event independent of existing monitoring schemes. These requirements will be met through the use of a spatial decision support system (SDSS), which consists of a platform independent code written in Microsystems Java 1.2 that can be run on any operating system. The SDSS serves as both a decision and research tool.

1.2 Scope of Research

The scope of this project is to conduct a comprehensive investigation of scour that reviews all topics relevant to this problem. Current scour analyses and methodologies are examined along with the various monitoring techniques and/or instrumentation that are used. A review and documentation of Internet sources of hydrological and meteorological data is conducted to identify websites that provided information relevant to scour. A GIS is established to catalog and display existing monitoring systems and bridges as well as for use as an analytical tool. A web-based, conceptual model is also developed that includes possible approaches to real-time bridge scour assessment and incorporates multiple analyses.

1.3 Organization

Chapter 2 provides background on scour processes, scour analyses and methodologies, and scour monitoring techniques. Contemporary approaches to scour evaluation and assessment by agencies such as the United States Geological Survey (USGS) and Departments of Transportation (DOTs) are discussed along with state of the art scour applications like ScourWatch™. Unique scour processes, such as those under ice, are also examined. Finally, scour monitoring techniques/instrumentation are reviewed in this chapter.

Chapter 3 documents an Internet search for websites containing sources of hydrological and meteorological data, including automated stream and rain gage networks, weather forecast information, and radar imagery. Real-time automated gage networks are identified as well as the various websites where gage information is found. All of the documented websites are discussed in detail to inform the reader of the type of information available on these sites.

Chapter 4 outlines the development of a GIS for the project. The pros and cons of both ArcView 3.1 and ARC/INFO v7.2.1 are discussed. Sources of existing GIS coverages are presented and explanations are provided as to why these coverages were included. Coverages created exclusively for this project are also explained, including how attributes were selected.

Chapter 5 contains the layout and implementation of the conceptual model, and the framework for a real-time scour monitoring system is suggested. An outline is shown of the system architecture. Some algorithms and bridge scour analyses used by various states are researched as possible components of the model. Methods of estimating discharges at bridge sites are presented, including those found in the literature and one proposed by UMass Amherst. An example is given to illustrate the use of the proposed scour monitoring system.

The summary and conclusions of the project are provided in Chapter 6. This chapter includes a review of the information presented and recommendations for current and future work. Suggestions are made for improvements in calculating, detecting, and monitoring scour in real-time through adoption and modification of existing scour analyses and utilization of Internet resources. A summary of the best Internet sources of hydrological and meteorological data, in the author's opinion, is provided.

2.0 BACKGROUND

Scour evaluation and assessment requires the collaboration of personnel from several disciplines, including hydraulics, structural, and geotechnical engineering, and bridge safety. A scour monitoring system likewise must draw upon resources made available by a variety of disciplines. Scour methodologies, GIS applications, web-based weather products, and instrumentation are all potential components of a scour monitoring system. The following sections elaborate on literature and Internet resources that are currently in use for either scour or non-scour related purposes.

2.1 State of the Art Applications

2.1.1 ScourWatch™

ScourWatch™ (patent applied for), developed by US Engineering Solutions of West Hartford, CT, is a web-based bridge scour monitoring product designed to facilitate preparation and coordination of transportation personnel during storm events as well as provide them with a better understanding of bridge scour. Beta testing of ScourWatch commenced in late October for use by the NY State DOT's Region 1 Bridge Maintenance Office, located in Albany, NY ("US Engineering Solutions Homepage"). The flexibility of the system offers the user secure, remote access via the Internet. The product has numerous capabilities as an emergency management tool, ranging from direct communication links between emergency officials to prioritization of scour critical bridges to generation of historical scour archives ("ScourWatch Description").

The product identifies a flood event and collects pertinent scour-related data, including real-time hydrologic data, bridge information, and data from instrumentation. Based on these data, a list of scour critical bridges is generated along with the bridges' respective critical event. The prediction of bridge scour hazard is based on the exceedance of precalculated threshold values. Information is then automatically disseminated to the appropriate personnel to prepare and mobilize for the event ("ScourWatch Description"). This integration of communication links within the design of the product is a very powerful feature of ScourWatch. Bridge reports, which are issued for the scour critical bridges based upon an event, provide information regarding the bridges and their scour conditions, and provide places for information, comments, and recommendations to be filled out online. These reports can then be dispersed to DOT websites, email addresses, and fax numbers with the click of a button. All of this results in a more organized and efficient method of linking agencies and personnel together to prepare, identify, and respond to an event ("ScourWatch Demo").

Another nice feature of ScourWatch is that it allows the user to simulate storm events to examine the effects on the state's transportation infrastructure and identify weaknesses in the bridge inventory. For example, the ScourWatch Demo examines the combined effects of a 10-year event and 50-year event simultaneously occurring in Rhode Island in 1998 ("ScourWatch Demo"). In this case, the product predicts scour depths for bridges during these events without accessing web-based data, but rather from user input and information stored in the bridge database within ScourWatch, and generates lists of scour critical bridges along with their critical event. Simulation fulfills many purposes; (a) bridges can be prioritized for replacement or scour countermeasures, (b) bridges that require more frequent inspections can be identified, and (c) the development and implementation of action plans based upon these scenarios will enable emergency officials to respond more quickly and efficiently, particularly in the case of evacuations or bridge closures.

2.1.2 Other Web-based Applications

Although DOTs do not currently provide scour information on their websites, it is apparent that these agencies have realized the potential of web-based applications and have begun moving in a direction similar to the project's goals. For instance, the Vermont Agency of Transportation recently posted an interactive map on their website that identifies current road conditions. A link from their page to the Interactive Weather Information Network (IWIN) website for Vermont, which offers forecast information for the state and is described further in Chapter 3, is also provided ("VTrans Road Conditions"). The Maine Emergency Management Agency (MEMA) also offers a website with an interactive map linked to weather products. This site can also be accessed from the Maine DOT site ("Maine Zone Forecasts").

GIS web-based applications also exist. Examples of websites with these applications include the Hydrometeorological Automated Data Systems (HADS) and the National Inventory of Dams (NID). These sites allow the user to access and graphically display database information. This information, however, is limited to the scope of the website. Thus, the HADS and NID websites only depict automated gage information and dam information, respectively. No one site incorporates all of the relevant components of scour monitoring and analysis.

Java applications are demonstrated on websites such as the one for the Aviation Digital Data Service (ADDS). Java is a computer language used on the Internet that can run on many different platforms and operating systems, allowing for web access by all users and algorithmic flexibility of analysis. The ADDS website clearly illustrates the capabilities of Java tools; interactive maps are shown that textually and graphically display real-time weather conditions at airports and layers such as counties and rivers can be overlain.

2.2 Contemporary Scour Applications

Through the NBIS, scour critical bridges are addressed in the Item 113 code in the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (Report No. FHWA-PD-96-001). A bridge is classified as scour critical according to one of the following: (1) observed scour at the bridge site or (2) scour potential as determined by a scour evaluation study. A single digit code is used to describe the stability of the bridge and its vulnerability to scour. Descriptions for all Item 113 codes are presented in Appendix A. Scour critical bridges are identified by a code of 0, 1, 2, or 3, with 0 indicating that the bridge has failed (U.S. Department of Transportation 1995).

Over the past ten years, state DOTs in New England have devoted a large amount of time to assigning Item 113 codes for each bridge. While states have coded the majority of their bridges, no state has completely finished the task as many bridges either still need to be evaluated or were assigned a temporary code until more thorough analyses could be performed. Codes were assigned to many structures after an initial screening was conducted, without the need for a full scour analysis. For other bridges, the initial screening was not sufficient, requiring instead a more comprehensive scour analysis to assign a code. Many of the older structures could not be thoroughly evaluated since no plans were available and the foundations were thus unknown. In other cases, hydraulic or Federal Emergency Management Agency (FEMA) studies were not available or complex hydraulic conditions at a bridge site necessitated an even more intensive analysis.

There are two approaches for assigning Item 113 codes to bridges with unknown foundations. One is to code the bridge as a 3 (scour critical). This is done to save time and money and is based upon results of other similar bridges that have received full scour evaluations. Another approach is to code the bridge as U (unknown foundation) until subsurface investigations can be performed based upon prioritization. The investigations can be accomplished through borings or geophysical testing methods such as ground penetrating radar. While this approach is more costly, it permits a full scour evaluation to be conducted, potentially removing some bridges from the scour critical list.

2.2.1 General Scour Analyses

To some extent, all of the states in New England have developed a flowchart that outlines the general procedure to be followed for a typical bridge scour analysis. Each state's scour program is a result of a collective effort between geotechnical, hydraulic, and structural engineers. Several state DOTs cooperate on scour projects with their respective state USGS office to collect preliminary scour data at existing bridges. In many cases, the services of outside consultants are also needed, particularly for more detailed analyses. In general, all bridges initially undergo a qualitative review of existing information, which includes, but is not limited to, bridge plans, hydrologic files, FEMA flood studies, and USGS stream gage data. Bridges that are clearly stable or unstable are given an Item 113 code after this process. Those bridges determined as scour susceptible after the initial screening (i.e. their vulnerability to scour was not as apparent) are put through either a full scour analysis or some abbreviated scour analysis before they receive a code (Glenn 2000).

Engineering judgement is brought into the analysis by considering flood and bridge history along with existing data, records, and reports. For example, considerations are made in the instance where a bridge is determined to be scour critical for a 10-year event, but has withstood two separate 50-year events. Some states address this issue by adding a second character to the single-digit Item 113 code, based upon a modified version of the Maryland State Highway Administration (MSHA) 113 rating system, to supplement the code in order to more realistically describe the scour susceptibility of a bridge. An example of this is described below:

> "…a single-span bridge which has been standing for 50 years may be scour critical, solely due to the calculated abutment scour. For such a bridge, we might select a MSHA rating of '3A' which denotes scour critical, but with a mild scour risk." (Whitman & Howard, Inc., 1996)

This additional character in the code can also be useful in the prioritization of bridges for remediation.

Most bridge scour data have been maintained and organized by DOTs using spreadsheet programs or databases such as Microsoft Excel or Microsoft Access. Pontis and HYRISK are Windows-based bridge management tools that have been used by states to assist in the prioritization and remediation of bridges. Pontis relies upon collected cost data and condition data of bridge components to predict maintenance needs, improve planning, and schedule improvements ("FHWA Bridge Management"). HYRISK calculates the relative risk of scour failure for bridges using NBI data without detailed field investigations ("Bridge Risk Analysis Software").

2.2.1.1 Hydraulic Engineering Circular No. 18 (HEC-18)

DOTs evaluate their bridge inventory for scour susceptibility using a number of different scour methodologies, the most common of which is HEC-18. HEC-18 covers all aspects of scour, including bridge design for scour, scour assessment, inspection procedures, and scour countermeasures. This circular presents a methodology for a detailed scour analysis, commonly referred to as Level 2 scour analysis, which is described in the following paragraphs (Richardson and Davis 1995).

Three types of scour are addressed in the HEC-18 manual: (1) long-term aggradation and degradation, (2) contraction scour, and (3) local scour. Long-term aggradation and degradation, affected by either natural or man-made causes, refers to changes in streambed elevation over time. Contraction scour is primarily the result of channel constriction at a bridge crossing, where increased velocities scour the channel bed, but can also be caused by a change in local base-level elevation or flow around a bend. Typically, bridge approach abutments that block flow in the floodplain or extend out into the main channel are responsible for this scour type. Local scour is concentrated around piers, abutments, spurs, and embankments. Obstructions in the waterway impede and redirect flow, inducing the formation of vortices that accelerate the removal of bed material around the bases of obstructions. The cumulative sum of these scour types is the total scour (Richardson and Davis 1995).

Additionally, there are two components of both contraction scour and local scour: live-bed scour and clear-water scour. Live-bed scour occurs when bed material is transported from the upstream reach into the bridge crossing. Clear-water scour occurs when either no significant bed material is carried from the upstream reach into the downstream bridge reach or the material transported from the upstream reach is carried mostly in suspension through the bridge crossing to the downstream reach. HEC-18 provides the tools to evaluate both scenarios (Richardson and Davis 1995).

Although HEC-18 is widely used as the model to perform full scour analyses, there are two main problems with the methodology. First, in order to determine flow variables at a bridge, HEC-18 recommends the use of hydraulic modeling programs such as Water-Surface Profile Model (WSPRO) and HEC River Analysis System (HECRAS) (Richardson and Davis 1995). While these programs provide the some of the best estimates of flow variables, they are very costly and time consuming to perform. With large bridge inventories, states are reluctant to employ such time-intensive programs as part of their analyses for many of their bridges. Second, it is well documented that the HEC-18 equations can regularly give overly conservative scour depths. This may be due, among other things, to the inability of researchers to conduct tests on large-scale laboratory models. While it is better to have predictive methods that are conservative, excessive overestimation on a regular basis can increase costs to monitor, remediate, and even design and build bridges. These problems do not preclude the use of HEC-18 equations for scour evaluation, but rather should encourage DOTs to investigate other scour methodologies, in particular those that can generate similar results in a much shorter time period. This is discussed further in Chapter 5.

2.2.1.2 Comparative Scour Analysis

The Connecticut Department of Transportation (CDOT) initially conducted its scour evaluation studies in general accordance with the aforementioned procedures. After performing Level 2 scour analyses on a few hundred bridges and faced with prohibitive costs and a large number of bridges remaining to be analyzed, CDOT looked to an alternative scour methodology to evaluate its bridges. The CDOT Hydraulic & Drainage Unit (H&D), along with the FHWA and consultants, developed a new, qualitative method that would provide NBIS Item 61, 71, and 113 codes for unanalyzed bridges without requiring full Level 2 scour analyses. This new method, called the comparative scour analysis, utilized the results of previous Level 2 scour analyses while generating time and cost savings (CHA 1998).

The comparative scour analysis is considered an intermediary step in the Comparison Methodology, the revised approach to scour assessment at bridges by CDOT. Its primary purpose is as a screening tool to provide NBIS code recommendations to as many previously unanalyzed bridges as possible during the early phases of the Comparison Methodology, thus eliminating them from further consideration and reducing the number of structures that ultimately receive more time-intensive scour analyses. It should be noted that the comparative scour analysis specifically does not calculate scour depths (CHA 1998).

To aid in the screening process, methodologies were established for collection of information during field visits and office reviews. Field reviews were performed by documenting field observations of site attributes related to the susceptibility of bridges to scour. These observations were quantified using fundamental scour parameters (FSPs) as a means of evaluating bridges according to the same criteria. Rating guidelines for the FSPs were provided to ensure consistent application of the documentation process. The existing 287 Level 2 bridges (i.e. those bridges that already received a full scour analysis) were evaluated and scored for the project according to the FSPs in order to verify that high ratings corresponded to low risk Item 113 ratings and low ratings reflected scour critical Item 113 ratings. Based upon the results, the ratings derived from the scour parameters were in good correlation with the Item 113 ratings for the Level 2 bridges, and the procedure was affirmed for field use (CHA 1998).

In order to justify the comparison of two bridges, one rated and the other unrated, primary and secondary criteria had to be met. Bridges that were already rated using the Level 2 analysis served as the group of rated bridges with which the unrated bridges would be compared. Primary criteria were considered to be Single vs. Multiple Span and Stream Character Category. Secondary criteria were listed as Estimated Stream Velocity, Foundation Type (at Abutments and Piers), Ratio of the Upstream Channel Width to the Width of the Channel Beneath the Bridge, and Angle of Attack. A valid comparison mandated that, at the very least, all primary criteria were met. The greater the number of secondary criteria met, the closer the similarity of the two bridges (CHA 1998).

The comparative scour analysis was designed so that the field team could make the comparison while at the site of the unanalyzed bridge. Accordingly, the field team was given a laptop, database information, and all other relevant information to assist their efforts. The comparison included not only similarities in primary and secondary criteria between the two bridges, but also incorporated review of FSP scores and office information for the sites along with a detailed look at the structural, hydraulic, and geotechnical characteristics of the Level 2 bridge. Based upon review of all this information and engineering judgment, the field team either recommended NBIS codes for the unrated bridge or recommended additional, more detailed scour analyses (CHA 1998). A flowchart for the comparative scour analysis is presented in Figure 1.

2.2.1.3 Rapid-Estimation Method

Holnbeck and Parrett (1997) addressed the challenges of assessing bridge scour in a timely fashion in a report issued by the USGS and prepared in cooperation with the Montana DOT. As in other states, the large inventory of bridges in Montana, coupled with detailed scour analyses using hydraulic modeling programs, made it difficult to evaluate bridge scour at these sites in a short period of time. The rapid-estimation method was thus created for use as a quick screening tool to identify bridges susceptible to scour. It was also developed to provide results comparable to those from full scour analyses. Scour assessments at bridges using the rapid-estimation method were submitted for review to the Montana DOT, who then decided if a more thorough scour analysis was warranted for any bridge. Results from 122 detailed scour analyses

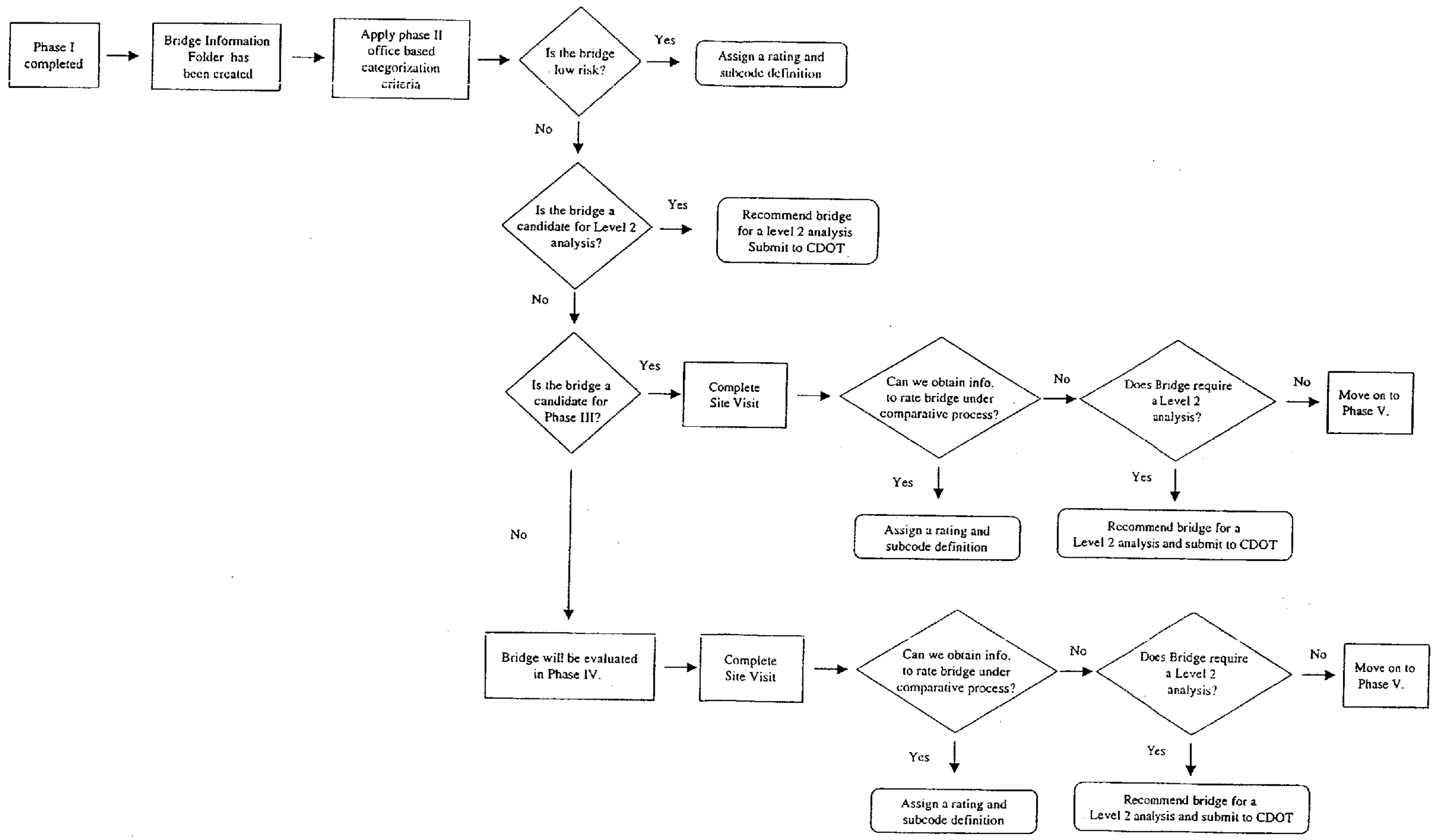

Figure 1. Comparative scour analysis process flowchart (from CHA 1998)

in 10 states were used to justify its application across all regions. Holnbeck and Parrett (1997) emphasize that although this method was developed for use in Montana, it could be applied to other geographic regions.

The rapid-estimation method limits input parameters to those that can easily and quickly be measured in the field, provides reasonable estimates of scour depths without underestimating, and generates results in a period of hours, not days. Scour depth estimations and hydraulic variables are related through simplification of standard Level 2 scour equations and graphical plots. Envelope curves are used in these relations as means to ensure the overestimation, rather than underestimation, of scour depths. The only requirement of this method is knowledge of the discharge at the site, regardless of the recurrence interval corresponding to that flow. Other hydraulic variables are calculated in the field using graphs relating velocity to unit discharge and flow depth to velocity. Bridge parameters are also determined in the field. Therefore, through the combination of limited site data and envelope curve relations, quick, yet reasonable estimates of scour depth at bridges are made in the field (Holnbeck and Parrett 1997). This method is discussed further in Chapter 5.

2.3 Scour Under Ice

Year-round scour in colder regions such as New England is subject not only to open water conditions, but ice and debris as well. Despite the extensive research on scour processes in general, research on scour under ice has been overshadowed by the more overt scour problems caused by open water flow. One main hindrance to this research is that ice cover on streams and rivers hampers efforts to detect and monitor scour.

Researchers at the USA Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH, have spent a great deal of time investigating scour conditions under ice. Zabilansky and Yankielun (2000) reported that the presence of ice can further complicate scour processes. They suggest that current scour and sediment models are hampered by their reliance exclusively on open water laboratory tests with limited field data for calibration. The models ignore other year-round scenarios, including ice and debris. They also state that if instrumentation was installed that was capable of continuously monitoring scour cycles under all real-time conditions, the rate of erosion and deposition of bed material could be correlated to hydrograph data, thus providing better calibration data for sediment models. Instrumentation was selected for their research that relied on time domain reflectometry (TDR) technology, which will be discussed extensively in Section 2.4.

Zabilansky and Yankielun (2000) observed two ice-related scenarios that upset equilibrium conditions, inducing bed scour. As the ice sheet first forms on a river, the sheet can be considered as a flexible boundary, which bows in response to an increase in stage. The rough underside of this sheet causes the stage to increase and forces the velocity profile towards the bed. As the ice sheet thickens, it acts more as a rigid boundary, and changes in discharge directly affect the velocity. As a result, the increasing velocity, due to a fixed water surface elevation along with a smoothing of the underside of the ice sheet, accelerates erosion of bed material until equilibrium conditions are reached. A rule of thumb is that the stage has to increase 2 to 4 times the ice thickness for the ice sheet to breakup (Zabilansky and Yankielun

2000). The increase in discharge necessary for breakup causes elevated bed stresses, thus triggering an increase in scour.

2.4 Scour Monitoring Techniques/Instrumentation

There are several problems associated with scour monitoring. One major problem is the nature of the scour cycle, during which both erosion and deposition can occur for the same event. Typically, high, turbulent flows make it difficult to monitor scour depths during the actual event. By the time post-flood measurements are made, scour holes may already be infilled, obscuring the maximum scour depth. Although this infill material is deposited in the scour hole, it has little structural value. Other problems with scour monitoring techniques/ instrumentation include cost, personnel safety, potential instrument damage due to debris or ice, fluctuating bed elevations, and availability of electrical power at the site (Boehmler and Olimpio 2000).

Several types of instrumentation have been experimented with for scour monitoring purposes. They include mechanical and electrical devices, sonar and radar systems, mobile and fixed instrumentation, and temporary and permanent devices. Zabilansky and Yankielun (2000) provide a concise and comprehensive explanation of the limitations of several of these devices and technologies. Three are discussed in detail below: ground-penetrating radar (GPR), time domain reflectometry (TDR), and frequency modulated-continuous wave (FM-CW).

Several authors have reported on the application of ground penetrating radar (GPR) for scour detection (Placzek and Haeni 1995, Jackson 1997, and Olimpio 2000). Olimpio (2000) used GPR to detect pre- and post-flood scour at several bridge sites in NH. GPR works by emitting radio-frequency electromagnetic pulses into the water and bed material and then receiving return signals from the pulses bouncing off some type of reflector, a boundary interface where physical and electrical properties change. Boundary interfaces include water-soil interfaces, changes in bed material stratigraphy, and the presence of manmade materials such as concrete or steel. Reflector depths are estimated from two-way travel times for various materials. Olimpio (2000) concluded that GPR is effective in detecting existing scour holes, infilled scour holes, and previous scour surfaces at bridge sites, although deep water (10 feet or greater) weakened the signal, limiting its penetration into the bed material to just a couple of feet. GPR has an advantage over fixed instrumentation because it is not limited to a specific location, instead allowing the collection of continuous streambed data.

Dowding and Pierce (1994) reported on the use of time domain reflectometry (TDR) to detect bridge scour and monitor pier movement. TDR, similar to radar, operates by generating a pulse and recording voltage reflections to identify the spatial location of reflectors. The TDR system proposed by the authors uses a vertically embedded cable, to which flanges are attached, in front of a bridge pier. As scour progresses, the flanges are torn off by high drag forces, shearing the cable. A signal reflection produced at the cable break identifies the scour depth. The main problem with this system is that it is sacrificial and can only be used for a single scour event (Zabilansky and Yankielun 2000).

Zabilansky and Yankielun (2000) conducted their own work on the development of a TDR-based system that would continuously locate bed elevation. Their TDR-based instrumentation, which consists of a probe connected to an on-shore instrumentation system through a weighted coaxial cable, has already been installed at several field locations. Field tests of this instrumentation reveal that TDR may be able to determine real-time scour and bed elevation data and thus be used within the framework of a monitoring system. TDR may also be capable of continuously monitoring dynamic sediment scour and deposition data during extreme flow events.

Another paper by the same authors addressed the feasibility of a frequency modulated – continuous wave (FM-CW) reflectometry system to detect and monitor bridge scour in real-time (Yankielun and Zabilansky 2000). This system, while less accurate than the TDR based system, is more versatile in that it can be used in wireless applications. This is particularly important because cables are difficult to install, subject to damage, and accuracy of the TDR signal is reduced with increasing cable length. A prototype of the FM-CW system has been laboratory tested, but the authors are looking for sponsors to fund installation and testing of the system in the field (Zabilansky 2000).

3.0 INTERNET REVIEW

Sources of hydrological and meteorological data are vital components of a real-time scour monitoring system. While bridge and stream attributes are used to identify bridges susceptible to scour, it is weather products that inform DOT officials of potential scour-inducing conditions at bridges. These products may include, but are not limited to, forecast information, real-time gage data, and radar imagery. Many agencies provide access to their hydrological and meteorological data in real-time via the Internet, which can help DOTs monitor, prepare, and respond to a storm event much more effectively.

The distinct advantages of the Internet may be obscured if users are not familiar with its offerings. Users may encounter problems such as redundant information, complex websites, non-comprehensive websites, and an overabundance of information. Redundancy is particularly prevalent for sites that present gage data. Often, the same gage is presented on two different websites, but may be identified differently, leading to confusion and misinterpretation. Of course, knowledge of sites that provide redundant information is particularly useful in situations when one of the sites is down at the time. Despite the wealth of information available on the Internet, it is important that DOT officials are familiar with sites that fit their needs. It is easy to be overwhelmed by the vast amounts of information on the Internet. The Internet is a valuable tool to obtain weather products, but only if the user knows how to use it effectively.

A review and documentation of web-based hydrological and meteorological data sources are summarized in Table 1. The purpose of this chapter is to facilitate understanding and use of these data sources. This information is intended to educate DOT and emergency officials as to what data are available and where they can be found. It is acknowledged that the websites presented in this chapter do not represent the gamut of weather-related websites; their sheer

Table 1. Summary of Internet sources of hydrological and meteorological data

Website	Agency	Features	Website Links	Comments
Automated Flood Warning Systems (AFWS) *http://www.afws.net/main.htm* (IFLOWS, ALERT)	NWS/ ALERT Groups	RT(SG, RG), RD	IWIN	Not a reliable source, Conn. DEP working to set up server with ALERT data
Aviation Digital Data Service (ADDS) *http://adds.awc-kc.noaa.gov/*	NWS	RT(RG), RD	NWS	Best source of real-time precipitation data, limited number of gages
Commercial Weather Vendors *http://www.nws.noaa.gov/im/dirintro.htm*	-	AWP	-	Various weather products offered by private providers
Hydrometeorological Automated Data System (HADS) *http://hsp.nws.noaa.gov/oh/hads/*	NWS	RT(SG, RG)	NWS	Reports nationwide DCP data, but only in graphical form
Interactive Weather Information Network (IWIN) *http://iwin.nws.noaa.gov/iwin/main.html*	NWS	AWP	Other NWS sites	Premiere Internet source of weather products
Massachusetts StreamStats *http://ma.water.usgs.gov/streamstats/*	USGS	SS	None	Streamflow statistics and basin characteristics (MA only)
Northeast River Forecast Center (NERFC) *http://www.nws.noaa.gov/er/nerfc/*	NWS	RT(SG), FF, RD, RF	WFOs, USGS, Commercial Weather Vendors	River forecasts, flood and flash flood forecasting

RT, real-time gage data; SG, stream gages; RG, rain gages; HR, historical records; FF, flood forecasts; RF, river forecasts; RD, radar imagery; SS, streamflow statistics; AWP, all weather products

Table 1. Summary of Internet sources of hydrological and meteorological data (continued)

Website	Agency	Features	Website Links	Comments
Real-Time Water Data *http://water.usgs.gov/realtime.html*	USGS	RT(SG, RG), HR	NWS, IWIN, NERFC, WFOs	Good source of real-time streamflow data (stage and discharge)
Regional Weather Forecast Offices (WFOs) *http://web.nws.cestm.albany.edu/ (Albany, NY)* *http://www.nws.noaa.gov/er/box/ (Boston, MA)* *http://www.nws.noaa.gov/er/btv/ (Burlington, VT)* *http://www.nws.noaa.gov/er/okx/ (Brookhaven, NY)* *http://www.nws.noaa.gov/er/gyx/ (Gray, ME)* *http://www.nws.noaa.gov/er/car/ (Caribou, ME)*	NWS	AWP	NWS, IWIN, NERFC, WFOs, Commerical Weather Vendors	Good sources of local hydrological and meteorological data
Reservoir Regulation Team - NAE *http://www.nae.usace.army.mil/waterres/htdocs/index.html*	USACE	RT(SG, RG), RF	IWIN, NERFC, WFOs, Commercial Weather Vendors	Flow threshold values provided, CSM values, interactive maps
State Emergency Management Agencies (EMAs) *http://www.emergencymanagement.org/states/*	FEMA	-	None	Can access weather data through state EMA sites
Water Resources Data for USA *http://water.usgs.gov/nwis/nwis*	USGS	RT(SG, RG), HR	None	Easy to use, interactive, querying capabilities, real-time and hist. data

RT, real-time gage data; SG, stream gages; RG, rain gages; HR, historical records; FF, flood forecasts; RF, river forecasts; RD, radar imagery; SS, streamflow statistics; AWP, all weather products number makes that task nearly impossible. This chapter also presents background information on automated gage networks and radar sites.

3.1 Automated Gage Networks

3.1.1 Hydrometeorological Automated Data System (HADS)

Near real-time hydrological and meteorological data can be obtained from Geostationary Operational Environmental Satellites (GOES) Data Collection Platforms (DCPs) as part of the Hydrometeorological Automated Data System (HADS). The HADS network, which consists of a nationwide coverage of automated DCPs, was developed to provide near real-time hydrological and meteorological data for the National Weather Service, specifically in support of the Flood and Flash Flood Warning programs operated by weather service forecast centers and river forecast centers throughout the country. The Office of Hydrologic Development of the NWS presents real-time data from the HADS network on the Internet. Individual DCPs in the HADS network are owned by a variety of organizations. While the NWS is responsible for some of these gages, the vast majority of DCPs are owned by federal, state, and local agencies (i.e. private firms and city governments), who share the data with the NWS in return for hydrological and meteorological products and information provided by the NWS ("HADS Description"). In New England, the three main agencies that own and maintain DCPs are the USGS, United States Army Corps of Engineers (USACE), and New England Power Company (now Pacific Gas & Electric).

The National Environmental Satellite, Data Information Service (NESDIS), a division of the National Oceanic and Atmospheric Administration (NOAA), is responsible for the operation and maintenance of the GOES Data Collection System (DCS) for the NWS and cooperating agencies. Raw DCP data are downloaded to the GOES DCS, located at the Wallops Island Virginia Flight Facility, from the GOES East and GOES West satellites, which upload data from the DCPs. The reporting cycle varies between platforms, which operate in 1, 2, 3, or 4 hour cycles, although data can be collected every 15 minutes. Actual upload times are presented on the state site definition pages. The data are then converted into Standard Hydrometeorological Exchange Format (SHEF) products for distribution to weather service forecast centers and river forecast centers throughout the country via internal NWS communication systems and the Internet ("HADS Description").

SHEF is a documented set of rules for coding of data that facilitates the visual readability and understanding of DCP data as well as provides a format that is compatible with many different receiving databases. By adopting a universal coding format, data can be processed from various agencies using the same decoding software and agencies can easily share information. The format of the data consists of both DCP attributes and recorded data, including parameter descriptors, station identifiers, geographic locations (including latitude and longitude), physical element codes (e.g. river stage readings, precipitation counters, etc.), numerical values and their units, and times and time intervals of when the data were recorded and uploaded. DCPs can also be set up to collect data corresponding to multiple SHEF parameters. While hundreds of SHEF parameters exist, the two codes considered important for this project are HG and PC, which stand for *height, river stage* and *precipitation, accumulator,* respectively ("SHEF Users Manual"). DCPs assigned either of these physical element codes represent devices that collect real-time stage and/or precipitation data. Specific features of the HADS website are discussed in Section 3.3.4.

3.1.2 Automated Flood Warning Systems (AFWS)

The two main flood warning systems in operation in the US are the Automated Local/Statewide Evaluation in Real Time (ALERT) Systems and the Integrated Flood Observing and Warning System (IFLOWS). ALERT users have joined to form groups across various regions of the country, whereas the IFLOWS program is limited to several states in the eastern U.S. These networks were developed for a multitude of purposes, including real-time data acquisition, automated hydrologic/hydraulic modeling, and automated warnings. Both networks employ automated rain and stream gages, although the majority of gages are rain gages ("Flood Warning Homepage"). Initially, the ALERT and IFLOWS systems were developed separately, but now these systems have been linked under the auspices of AFWS to facilitate integration and sharing of information among states (Glowacki 2001). For example, Connecticut's ALERT system is an AFWS that comes under the umbrella of IFLOWS. Detailed descriptions of these automated flood warning systems are presented in the following sections.

3.1.2.1 Automated Local/Statewide Evaluation in Real Time (ALERT) System

ALERT was first developed in the 1970's as a method of using field sensors to relay data to a central computer in real-time. The standard was developed by the NWS and has been used by other local, state, and federal agencies as well as international organizations. ALERT hardware and software vary, but are largely compatible because they must meet communications criteria. As a result, competition has enabled agencies to reap the benefits of high performance, low cost ALERT systems ("Flood Warning Homepage").

An ALERT system was implemented in Connecticut in 1985 in response to severe June floods in 1982. Implementation of the system was a joint effort between the Natural Resources

Conservation Service (NRCS) and the Department of Environmental Protection (DEP). The system was designed as an early flood warning and response system that not only collected and distributed weather data to appropriate agencies within the state, but also established procedures to follow in case of weather emergencies (Connecticut DEP 2000).

Automated rainfall, river, tidal, and weather gages in the Connecticut ALERT network measure and relay data via VHF radio signals to computer base stations throughout the state. From base stations, rainfall and river data are uploaded to the Northeast River Forecast Center (NERFC) via a microwave link. The three regional NWS offices that provide weather forecasting for Connecticut receive these data through their Automation of Field Operations and Services (AFOS) computer network. During weather emergencies, forecasts, watches, and warnings issued by the NERFC are read off the AFOS network by personnel at the State Office of Emergency Management (OEM). These messages are then entered into the Connecticut Online Law Enforcement Teletype (COLLECT) system and quickly faxed to all towns across the state (Connecticut DEP, 2000).

Some individual communities in Connecticut that are prone to flooding have installed local ALERT systems. Each of these towns has its own computer base station that allows them to communicate with central base stations in Hartford. ALERT systems allow communities to monitor their own local conditions as well as access local weather information from other communities. As a result, the communities do not need to wait for other agencies to provide weather forecasts and warnings, thus enabling them to respond even more quickly to anticipated inclement weather conditions (Connecticut DEP, 2000).

3.1.2.2 Integrated Flood Observing and Warning System (IFLOWS)

The Integrated Flood Observing and Warning System (IFLOWS), sponsored by the federal government, is based upon flood warning technology similar to the ALERT system, but uses different communications and software ("Flood Warning Homepage"). IFLOWS was established as a result of the 1978 National Flash Flood Program Development Plan. The purpose of the IFLOWS program was to implement a flash flood warning system that would improve preparedness and response to flash floods inherent to the Appalachian Region of the United States, resulting in reduced human and economic costs. A prototype IFLOWS system was developed in 1979 for portions of Virginia, West Virginia, and Kentucky based upon their susceptibility to flooding and their available communications network. The system was completed in 1981 and later expanded throughout these states as well as into Pennsylvania and Tennessee. In 1985, Congress set aside additional funding specifically for IFLOWS to be established in regions devastated by the November 1985 floods. These regions included West Virginia, Virginia, and Pennsylvania. Expansion of the network later moved into areas of North Carolina and New York that also had histories of heavy floods ("IFLOWS").

Radio signals are used to transmit raw data to processing locations, either directly or through relays from mountain top receivers. The processed rain gage information is then distributed using UHF/VHF over the IFLOWS communication network to remote IFLOWS users. A receiver tuned to the correct IFLOWS frequency receives the data, which are taken and converted to a usable format by a modem. The data can then be displayed in various formats ("IFLOWS").

While limited funding has been available for continued growth of IFLOWS, a wide area communications network has been established using IFLOWS technology to link various flood warning systems together of local communities and state and federal agencies in order to share information. This indirect expansion of IFLOWS has encompassed other AFWSs from 13 states, such as the ALERT system in Connecticut. Connecticut ALERT data are thus available through the IFLOWS website. Real-time gage data are also posted for Massachusetts on the IFLOWS website, but the reporting gages are limited to just Hampden County in Massachusetts ("IFLOWS"). Specific features of AFWS websites, such as IFLOWS, will be presented in Section 3.3.1.

3.1.3 Automated Surface Observing Systems (ASOS)

Another source of precipitation data are found from the Automated Surface Observing Systems (ASOS), a collaborative effort between the NWS, the Federal Aviation Administration (FAA), and the Department of Defense (DOD) to create a surface weather observation network. The primary purpose of ASOS is to aid the aviation industry and forecasters in their prediction of weather conditions affecting airline travel. The first ASOS sites, which are part of the NWS modernization program, were commissioned in September 1992 ("AOMC Homepage"). ASOS sites are located near airport runway touchdown zones, thus restricting their placement within the entire coverage of a state. These sites currently comprise between 10% and 45% of all precipitation gages in New England states. Although the system is geared towards collecting weather parameters of significance to the airlines (i.e. sky condition, visibility, and wind), the data are also useful for meteorological, hydrological, and climatological purposes, particularly for developing and issuing forecasts and warnings ("ASOS Homepage").

Advantages of the ASOS include its rapidly expanding network, continuously updated information, and its ability to detect significant weather changes and transmit observations accordingly via the networks. ASOS can provide weather observations in the vicinity of the airport via a telephone dial-in port. Observations are made using automated systems, human observers, or a combination of the two. These systems are also capable of issuing special reports when preset thresholds have been exceeded (e.g. visibility decreases to less than 3 miles) ("ASOS Homepage"). ASOS sites perform maintenance on themselves by performing self tests. The sites alert the supervising agency, AOMC (ASOS Operations and Monitoring Center), to a potential problem. The agency can then dial into the site to diagnosis the source of the problem ("AOMC Homepage").

Rainfall is measured at these sites using a heated tipping bucket (HTB). The HTB is important for aviation purposes because it offers a method of quantifying freezing or frozen precipitation accumulations. Advancements in the design of HTBs have improved the performance of these gages in both liquid and freezing/frozen precipitation events, making the HTBs more reliable than before. Despite the design improvements, there are still some problems in accurately measuring the liquid-equivalent of frozen precipitation (LEFP). The main function of the HTB, therefore, remains the measurement of liquid accumulation. An additional limitation of the HTB precipitation gage occurs during heavy rainfall events, when the tipping bucket cannot operate fast enough to accurately measure rainfall. This results in reported accumulations that are lower than the actual accumulations. ASOS software was designed to correct for HTB bias for most heavy rainfall events (greater than 1.80 inch per hour), but rainfall events exceeding 10 inches per hour could still result in under-reported rainfall accumulations ("ASOS User's Guide").

Data provided by the ASOS sites are presented in METAR/SPECI code, a French acronym for *Aviation Routine Weather Report/Aviation Selected Special Weather Report*. This code is the international standard code for hourly and special surface weather observations, implemented on July 1, 1996. METAR messages are issued on a scheduled hourly basis, whereas SPECI messages, which are unscheduled reports in METAR format, are only issued during changing meteorological conditions ("ASOS User's Guide). The format of the data in these messages requires some basic decoding skills, which can be quickly learned.

As an example of the data format, four METAR/SPECI reports issued for the Miami International Airport in Miami, Florida are presented below. These reports were taken from the ADDS website, where they are available up until 24 hours after they were first issued. The ADDS website will be explained further in Section 3.3.7. Portions of the reports highlighted in bold font indicate codes of particular importance for the interpretation of precipitation data collected at ASOS sites and are explained in further detail. The first report is shown below:

> ***KMIA 191156Z*** *11011KT 10SM SCT027 BKN120 OVC250 24/21 A2992 RMK* ***AO2*** *SLP131* ***70159*** *T02390211 10239 20228 51012=*

Four codes are highlighted within this METAR report. **KMIA** is the station identifier for the ASOS site at Miami International Airport, while **191156Z** refers to the date and time of the report, which in this case was recorded on March 19, 2001 at 1156 UTC (Coordinated Universal Time) (UTC is 5 hours ahead of EST). The month and year of the report are not included because, as mentioned earlier, the reports are only available on the ADDS website up to 24 hours after they were issued. Scheduled METAR reports are typically issued right before the top of the hour; at this site, reports are always issued 56 minutes past the top of the hour. The **A02** code identifies the type of station with A02 being an automated station with precipitation descriminator. According to the report, 1.59 inches of rain or 159 hundredths of an inch of rain (**70159**) fell between 1200 UTC on March 18, 2001 and 1200 UTC on March 19, 2001. The 24-hour precipitation accumulation is reported in the daily 1200 UTC METAR message by a

“7RRRR” remark (with RRRR being precipitation totals in hundredths of an inch) if at least 0.01 inch of precipitation fell in the previous 24 hours.

The second METAR report is presented below:

KMIA 190256Z 04004KT 10SM FEW015 SCT060 SCT120 22/21 A2998 RMK AO2 RAE27 SLP151 ***P0050 60134*** *T02220211 50012=*

This report indicates that 50 hundredths of an inch of rain (**P0050**) fell since the previous remark in the last scheduled hourly message and a total of 1.34 inches of rain was reported over the previous 3 hours (**60134**). Cumulative precipitation accumulations are calculated for 3- and 6-hour intervals and are presented using the “6RRRR” precipitation accumulation remark, which is similar in format to the “7RRRR” precipitation accumulation remark discussed earlier. Three-hour totals are reported in the METAR reports issued closest to 0300, 0900, 1500, and 2100 UTC while the six-hour totals are shown in the reports issued closest to 0000, 0600, 1200, and 1800 UTC. This scheduled hourly report was made at 0256 UTC (190256Z), which is nearest to 0300 UTC, so the 3-hour precipitation total was given.

The third METAR report is as follows:

KMIA 190156Z 05007KT 360V080 3SM ***-RA*** *SCT003 BKN015CB OVC025 22/22 A2998 RMK AO2 TSB31E55RAB23 SLP153 CB VC NE-SE MOV NE* ***P0084*** *T02220217 $=*

Light rain (**-RA**) was falling at the time this report was issued and 0.84 inches (**P0084**) of rain had fallen during the previous hour.

The last report is shown below:

KMIA ***190131Z*** *35015G24KT 1/2SM* ***+TSRA*** *FG SCT003 BKN015CB OVC026 22/21 A2999 RMK AO2 TSB31RAB23 PRESRR OCNL LTGICCG OHD TS OHD MOV NE* ***P0019*** *$=*

The last report is actually a SPECI report as it was unscheduled (**190131Z**). It was issued 31 minutes, as opposed to 56 minutes for the other reports, after the top of the hour. A thunderstorm producing heavy rain (**+TSRA**) was identified in this report. The **P0019** code indicates that 0.19 inches of rain was recorded between the last scheduled METAR report and the time this report was issued (a period of 35 minutes), but does not represent the hourly precipitation total. Further understanding of METAR/SPECI reports can be obtained on the Internet. The Texas A&M University Department of Atmospheric Sciences maintains a website that provides a comprehensive guide for the complete decoding and interpretation of METAR/SPECI reports ("Decoding METAR").

3.2 Radar

Weather Surveillance Radar 1988 Doppler (WSR-88D), also known as NEXRAD, have been installed at 164 locations across the U.S. as part of the modernization and office restructuring of the NWS ("NWS Doppler Radar"). Radar allows forecasters to detect and track storm movement and type, facilitating earlier warnings and enhanced predictions. In addition, NEXRAD provides high resolution spatial and temporal precipitation information. Both of these items are critical to predicting areas susceptible to flash flooding. Ground truth rain gage data are still needed, however, to accurately adjust raw radar rainfall estimates, which are estimates of rainfall aloft, to surface estimates. Additional processing is needed to remove contamination caused by anomalous propagation and hail and also to account for range effects, drop size distribution, and beam blockage. Combined with rain gage based rainfall estimates, NEXRAD based rainfall estimates can significantly improve the accuracy of forecast predictions (Shed 2000).

Radar operates in either clear air mode or precipitation mode. Radar reflectivity indicating 'significant' precipitation initiates a radar switch from clear air mode to precipitation mode, which tunes the radar to ignore non-precipitation clutter such as dust, bugs, and birds. This transition is around 30 dBZ (“Radar in Meteorology”). Radar reflectivities greater than 53 dBZ are typically ignored due to potential contamination by hail (Rees 2001). The WSR-88D outputs four sets of raw precipitation data: one hour rainfall totals, three hour rainfall totals, storm total rainfall, and hourly digital precipitation array. Raw data can be processed to produce finer resolution data, but this cannot typically be done in “real-time.” Graphs are used to depict the horizontal distribution of rainfall for the one-hour rainfall totals, three-hour rainfall totals, and storm total rainfall. Although the numerical data may not be accurate, it has been shown that areal distribution of rainfall presents a good indication of regions receiving the most rain (“Radar in Meteorology”).

3.3 Agencies/Vendors

The following sections highlight some of the various weather products offered by several agencies and vendors through the Internet as well as discuss some pros and cons about each website.

3.3.1 Automated Flood Warning Systems

The Integrated Flood Observing and Warning System (IFLOWS) website presents stage and precipitation data for 13 states whose Automated Flood Warning Systems (AFWSs) fall under the IFLOWS network (“IFLOWS”). Connecticut and Massachusetts, however, are the only two New England states that have AFWSs that are part of the IFLOWS network. Real-time gage data can be pulled up for an entire state or by individual county. Archival data are also available, but only for 2000 and 2001. As with numerous other sites, a direct link to IWIN is provided. Real-time gage data from the Connecticut AFWS, or ALERT system, is available through the IFLOWS website, but the Connecticut DEP is working to set up a server on the Internet that would also report ALERT data (Glowacki 2001). Real-time Massachusetts gage data posted on the IFLOWS website are limited to six rain gages in Hampden County ("IFLOWS"). It should be noted that erroneous or missing data are often relayed on the IFLOWS website and therefore use of the website to obtain real-time gage data is not recommended.

3.3.2 United States Geological Survey

The United States Geological Survey (USGS) operates in many different capacities, but without question, one of the agency's strengths is its monitoring and reporting of real-time hydrologic data. Specifically, the USGS has established networks of automated rain and stream gages that have proved invaluable for purposes of stream monitoring and flood forecasting, although the USGS does not issue forecast information itself. New technologies such as satellite telemetry have allowed the agency to make gage information available on the Internet, which has "…enhanced the value of the data and also the demand and expectations about its availability and reliability…" ("Streamflow Information"). It should be noted that the USGS has often collaborated with DOTs on the collection of scour data in the field and evaluation of predictive scour methods.

The USGS provides two separate websites for real-time hydrologic data: the *USGS Real Time Water Data* website ("USGS Real-Time") and the *Water Resources Data for USA* website ("Water Resources Data"). Historical and real-time streamflow data are posted on both sites for active stream gages in each state. Depending on the website, historical data may include daily, monthly, and annual flow statistics along with peak flow measurements. Historical data is more readily available through the *Water Resources Data for USA* website. Real-time data refers to data collected every 15 to 60 minutes, depending on the gage. Both stage and discharge values are displayed graphically and in tabular format on both websites. Real-time data are available through the websites for approximately one week after they are recorded, depending on the state. The data are then archived, but can still be retrieved for up to three years by contacting the local USGS office. These data are useful in the event that they can be accessed post-flood to correlate with data collected by scour monitoring devices. Historical data from past active stream gages are also available.

Real-time rain gage data are presented on both websites along with total precipitation accumulations over various intervals, depending on the site. The data reported by these rain gages are used by the USGS as input into hydrologic models. There are significantly fewer rain gages than stream gages operated by the USGS, though, which limits use of the websites for obtaining rainfall data. USGS rain gages represent a small fraction of the total rain gages throughout any state. It should be noted that USGS rain gages are not sited by the NWS, and therefore should not be considered a primary source of real-time precipitation data (Shed 2000).

Beyond the above similarities, the two USGS websites are suited for different purposes. The *USGS Real-Time Water Data* website is more conducive to this project because it is geared towards alerting individuals to significant flow events. Although the main purpose of the USGS is not as an emergency warning body, the site does offer direct hyperlinks to the Hydrologic Information Center (HIC) and the Interactive Weather Information Network (IWIN), which both provide current hydrologic conditions with an emphasis on extreme events such as floods. Flood stage and/or discharge thresholds are provided for some gages ("USGS Real-Time"). The *Water*

Resources Data for USA website is far more powerful in terms of its capabilities, particularly in terms of data selection and presentation, and was developed to include all water resources information measured at gages, not just streamflow. The flexibility of the site is also superior in that it has convenient interactive features and enhanced querying capabilities ("Water Resources Data").

Data collection systems operated by the USGS include DCPs, as described earlier, and telephone gage-height telemeters. Depending on the device, stage data are typically recorded at 15 to 60 minute intervals and then relayed to USGS offices every 1 to 4 hours via radio, satellite, or telephone. During critical events, however, data may be recorded and transmitted more frequently ("Water Resources Data"). Rating curves, developed by the USGS through more detailed analyses, are used to convert the stage data to discharge values.

Recently, a third USGS website called StreamStats was introduced, which provides streamflow statistics for waterways in Massachusetts. Streamflow data and basin characteristics are available from a database composed of records from more than 700 locations in the state where streamflow data were collected. A Java applet acts as the interface through which a GIS software system is used for querying purposes, calculations, and displays of text, tables, and images. While streamflow statistics serve a variety of needs, the statistics on the website that are most relevant to this project are the flood flow frequency statistics, which include the mean annual flood and the 10-, 25-, 50-, 100-, and 500-year recurrence interval floods ("MA StreamStats"). The significance of these statistics will be discussed in Chapter 5.

3.3.3 United States Army Corps of Engineers, New England District

The United States Army Corps of Engineers, New England District (NAE) is another source for real-time hydrologic data in New England. Both rain and stream gages are owned and operated by the NAE. The Reservoir Regulation Team (RRT), a division of the Water Management Section, monitors real-time water data at NAE Corps flood control dams and along rivers and streams in major drainage basins throughout New England. The RRT website, though, is limited in its focus and scope. The focus of the RRT is flood control, so their gages are located to collect hydrologic data for this purpose. Their scope is restricted to major drainage basins only, leaving out large areas of several states including all of Maine ("Reservoir Regulation Team"). It should be noted that many of the gages listed on this site are also presented on the USGS website. The user should recognize these limitations and therefore use data collected by the RRT to supplement data from other sources.

All of the data collection systems owned and maintained by the NAE are DCPs. The types of sensors on each DCP are conveniently listed in a table on the website, making it easy to quickly identify gages with precipitation and/or stage sensors. DCP data are typically recorded every 15 minutes, but transmitted every four hours, although data can be disseminated more frequently during a critical event ("Reservoir Regulation Team").

There are several attractive features of the NAE website. Interactive maps provide real-time data regarding not only streamflow conditions at gage sites, but also reservoir conditions. Maps depict the locations of both gages and dams, offering the user visual insight as to which dams impact stream gage records. Summary tables supply simple, organized reports of current and forecast conditions, including CSM values, or cubic feet per second per square mile, which give an overall sense of river conditions. CSM values are determined by normalizing discharge by drainage area and are useful for comparing the magnitude of streamflow conditions in drainage basins of various areas. Another nice feature of this site is that warning and flood values for stage and discharge are shown in conjunction with the concurrent real-time data for each gage. Finally, numerous links are available to connect the user to other sites with hydrological and meteorological data, including NERFC and NWS offices, although some weather products like snow and flood potential bulletins are issued by the NAE directly on their website ("Reservoir Regulation Team").

3.3.4 Hydrometeorological Automated Data System

The Hydrometeorological Automated Data System (HADS) website reports data collected from DCPs nationwide, which compose the backbone of the USGS and USACE gage networks. Nearly all of the DCP data from those two websites are found on the HADS page. Real-time DCP data are available for all DCPs (and all types of sensors), but only in graphical form. Additionally, the data are not archived for retrieval on this site. The website presents a GIS demonstration that includes the locations and attributes of DCP sites throughout the U.S. Attributes for these sites can be pulled up by clicking on them, but the specific SHEF product codes provided by the sites are not listed. Therefore, the map cannot be directly used to determine the locations of sites that collect stage and/or precipitation data ("Hydrometeorological").

Within each state page, HADS definitions exist for each site. ASCII files for DCPs in each New England state were copied into MS Excel from the website and then sorted based upon their SHEF codes to identify relevant DCPs. As previously mentioned, multiple SHEF parameter codes may be reported by a DCP, but only those sites transmitting stage data (HG) and precipitation data (PC) were considered. The real-time precipitation data on this site are useful, but without corresponding discharge values, the river stage data can really only be used for qualitative purposes for flood warnings ("Hydrometeorological").

The author has observed some inconsistencies with the website, ranging from inaccurate data to missing DCPs. Efforts have been made to identify and correct these discrepancies with HADS officials, but the reader should be aware of these past problems.

3.3.5 Northeast River Forecast Center

As the name implies, the Northeast River Forecast Center (NERFC) website is a source of river forecast information and provides all information relevant to the evaluation and prediction of river conditions. Since the NERFC is a product of the National Weather Service, links are provided to numerous sources of hydrological and meteorological data. Interactive maps present current and forecast river conditions at stream gages, including flood conditions. NERFC web-based interactive maps offer a wider range of data than provided by the maps on the NAE website described earlier. Stream gage data are shown both graphically and as text, and additional gage information is available through links such as USGS webpages and the latest local NWS river statement. As with the HADS website, actual streamflow values are not incorporated into the NERFC data, but these data can be obtained through the corresponding USGS website. Other useful information includes maps of soil moisture conditions and snow/precipitation totals. No real-time precipitation data from individual automated rain gages are available, however ("River Forecast Center").

Maps and tables of quantitative precipitation forecasts (QPF) are available through the NERFC, which provide forecast estimates of precipitation in 6-hour blocks over a 24-hour period. These estimates are used in models to forecast river conditions, allowing river stage forecasts to be made up to 48 hours in advance. The two main assets of QPFs are they improve river forecast reliability and allow earlier dissemination of information to emergency agencies and the public ("River Forecast Center").

The NERFC is also a valuable source of information regarding flash flood forecasting. Flash flood guidance (FFG) maps are available for 1-hr, 3-hr, 6-hr, 12-hr, and 24-hr periods, which present the average rainfall, in inches, needed for rivers to reach flood stage over a certain time period. This information would be particularly helpful when used in conjunction with ASOS precipitation data. Forecast precipitation could be quickly verified in the field using ASOS sites and compared to FFG maps, providing earlier warning of potential flash flood conditions ("River Forecast Center").

3.3.6 Emergency Managers Weather Information Network

Typically, weather information is disseminated passively across the Internet. It is made publicly available, but requires active participation by interested parties to get the information, such as surfing the Internet. The Emergency Managers Weather Information Network (EMWIN) is a service designed to actively disseminate near real-time NWS weather products to emergency managers and public safety officials. The network provides a live data stream of weather forecasts, watches, warnings, and other products, which is sent via Internet, radio, or satellite broadcasts. Specialized hardware and/or software are necessary to receive the EMWIN feed, depending on the method of transmission, but there are no additional charges beyond these capital costs. IWIN is the Internet weather venue that represents one method of obtaining NWS weather products through EMWIN. It should be recognized, however, that Internet access may not always be immediately available to the user ("EMWIN Homepage").

3.3.6.1 Interactive Weather Information Network

The NWS's Interactive Weather Information Network (IWIN) is the premiere Internet source of weather products for the U.S. with more than 10,000 websites directly linked to it. Virtually every possible weather product is available through this site, from forecasts to warnings, precipitation data to QPFs, and local to national weather, although its primary purpose is the dissemination of active warnings, which is evident as soon as the user opens the website. Even precipitation data from ASOS sites are offered at this site, although the data are summarized and not as detailed as the raw data found on the ADDS website. The one feature lacking from the IWIN are interactive maps of stream gages to visually get a sense of current or forecast stream conditions ("Interactive Network").

A unique feature of IWIN is the NOAA/NESDIS Rainfall AutoEstimator, currently an experimental product that graphically displays radar-like images of estimated rainfall rate, either as individual snapshots or as a 6-hour loop of sequential snapshots. Doppler radar images on the Internet are typically presented using reflectivity values, making it difficult to understand the doppler images in terms of quantitative precipitation rates ("Satellite Estimated"). A product like the Rainfall AutoEstimator would help DOTs and emergency agencies because it takes raw radar data and translates them.

3.3.7 Aviation Digital Data Service

Real-time precipitation data can be acquired through the Aviation Digital Data Service (ADDS) website, which provides weather information for aviation purposes. The website reports real-time precipitation data measured by ASOS sites. METAR messages are displayed for all ASOS sites in either standard or translated format. Standard METAR messages do require some translation, as was discussed earlier in Section 3.1.3. The main advantage of this website is the frequency at which the data are reported. Messages are reported every hour regardless of weather conditions, but can be issued more frequently if there are changing conditions. They also can be accessed over a specified interval, anywhere from the latest message issued to all messages issued over the previous 24 hours (“Aviation Digital”). Some websites present updated precipitation data once every four hours, whereas other websites only report the most recent precipitation data.

An interactive METAR Java tool is offered on this website, which allows users to view geographic locations of ASOS sites while overlaying real-time METAR messages on the sites. Forecast and radar information along with a link to the NWS homepage are also provided on the ADDS website, but it should be noted that the operation and presentation of this site is funded by the FAA. The NWS does not endorse any of the experimental weather products on this website, although this statement does not refer to precipitation data reported by ASOS sites (“Aviation Digital”).

3.3.8 Regional Weather Forecast Offices

Although the NWS homepage offers weather products for the entire US, the user will find it easier to obtain pertinent, local information from regional NWS forecast offices. A total of six regional NWS forecast offices cover forecasting responsibilities for various parts of New England and they are listed as follows: NWS Burlington, VT, NWS Albany, NY, NWS Boston, MA, NWS Brookhaven, NY, NWS Caribou, ME, and NWS Gray, ME. These offices offer current weather, forecast information, and historical data. In addition to standard weather products, each office website has its own unique features. For example, the NWS Burlington website includes a map of all cooperative observer locations, which will be discussed in the next section, and operates a MESONET, which lists all automated devices in its jurisdiction that record weather data, including DCPs, ASOS sites, and data loggers ("NWS Burlington").

3.3.8.1 NWS Volunteers

While networks of automated real-time gages are clearly the best way to record and disseminate real-time data, several communication networks established prior to the digital revolution are active and valuable sources of data. This is particularly true in the case of volunteer weather observers who are part of the NWS Cooperative Observer Program (COOP). The program, created in 1890, was designed to provide observational meteorological data for both real-time purposes (to support forecasts and warnings) and to record long-term climate changes. Currently 11,700 observers are part of the Cooperative Observer Program. Each NWS office enlists its own group of observers to record and report weather observations. The network of cooperative observers is much more dense and diverse than the automated systems described earlier. Cooperative observers typically record precipitation and temperature daily and send the results via telephone, Internet, or mail to the supervising NWS agency. Many cooperative observers also send their daily precipitation data to River Forecast Centers ("Cooperative Program").

There is no official website that provides public access to data reported by cooperative observers. The NERFC presents daily precipitation accumulations reported by cooperative observers ("NERFC Products"). Penn State University has developed a website where weather observers can submit weather observations online. Although these observations are entered at the cooperative observer's leisure, the site offers a central location where near real-time weather products can be submitted and then accessed by any individual ("User Weather Observations").

Another volunteer program, SKYWARN, is the NWS's network of trained severe weather spotters. This program was introduced nationwide in the early 1970's in response to several major tornado outbreaks. Spotters report severe conditions such coastal flooding, flash flooding, winter weather, etc. They should also be readily available in the event that the NWS needs to contact them about current weather conditions at their location. Each NWS forecast office operates its own SKYWARN program. A major asset of these spotters is that many of them are amateur radio operators, with about one-third of NWS Taunton's spotters capable of performing these dual roles. In the event of power outages or downed phone lines, they can maintain critical communication with weather forecasting or emergency agencies. The real-time data provided by these volunteers, when used in conjunction with doppler radar and other data, enhance the ability of the NWS to issue quick and accurate severe weather reports, particularly for small, localized areas. ("How to Become a NWS Spotter").

3.3.9 Commercial Weather Vendors

It should be mentioned that in addition to weather products made available by public agencies, there are also private meteorologists and private weather service companies that offer weather services within the U.S. While the NWS does not specifically endorse any of these individuals or companies, it has compiled a list of these providers, which can be accessed by state. Service code keys are assigned to each provider to identify the weather service(s) that they offer (“Commercial Weather Providers”).

3.3.10 State Emergency Management Agencies

State Emergency Management Agencies are not a direct source of weather products, but they often provide links to this information. The Federal Emergency Management Agency provides a website with links to emergency management agency websites for all 50 states (“Emergency Management”).

4.0 GIS APPLICATIONS

The scope of this project requires the assimilation of data from a variety of sources. An assessment tool, such as a GIS, not only allows the user to integrate and analyze the data, but more importantly, see the data presented in space. Several GIS components were developed for this project: bridges, gages, and dams. Examined individually, the components are meaningless. When considered as a whole, the reality of a scour monitoring network and its capabilities are quite lucid. A visual tool like GIS provides the user with a better understanding of the relation of data that are normally stored in spreadsheets and databases.

All GIS work was performed using either ARC/INFO v7.2.1 on a Sun workstation at the SAGE laboratory at UMass Amherst or ArcView 3.1 on a Windows-based personal computer. ARC/INFO v7.2.1 uses a UNIX operating system, which is command prompt oriented, and is augmented by a digitizer. ArcView 3.1 is a Windows-based program that was not used in conjunction with a digitizer. ARC/INFO was initially used exclusively, but since many of the required coverages were already obtainable through the Internet, no digitizing was necessary. Coupled with its cumbersome nature, ARC/INFO was relegated in favor of ArcView. ArcView is much more user-friendly in terms of a person's ability to learn and operate the application. Analyses are conducted easily and map displays are produced quickly. Newer versions of both ARC/INFO and ArcView are now available, but they were not used because it was not desirable to upgrade software during the middle of the project.

4.1 Available State GIS Coverages

While GIS coverages can be drawn with the aid of a digitizer, oftentimes the work has already been done. Such was the case for New England, where each state has its own GIS webpage. GIS coverages for a single state are created using the same coordinate system, making them easy to overlay. In addition, feature attributes are included in each coverage that describe characteristics or parameters associated with each feature. These attributes can be linked to similar attributes in other layers as well as queried to narrow the focus to a smaller, specific group of features. Metadata, which provides data about the data, is usually available to view or download along with its corresponding coverage. The state GIS websites used for this project are listed below:

Table 2. State GIS websites.

State	URL Address
Connecticut	http://magic.lib.uconn.edu/
Maine	http://apollo.ogis.state.me.us/
Massachusetts	http://www.state.ma.us/mgis/massgis.htm
New Hampshire	http://www.granit.sr.unh.edu/
Rhode Island	http://www.edc.uri.edu/rigis/
Vermont	http://geo-vt.uvm.edu/

While numerous coverages are available for download from each state GIS website, the ones of interest are those containing state boundaries, county boundaries, major river basins, and streams and rivers. For this project, statewide coverages were used, where available, to avoid piecing together smaller coverages. State boundaries were included because they represented the political extent of bridges to be considered. County boundaries were incorporated because flood warnings and watches typically are issued on a county-by-county basis. Stream and river coverages were selected to supplement the other coverages as well as ensure that bridge locations fell on waterways. These coverages help users observe the relation of bridges with physical features (e.g. dams and gages) and political and geographical boundaries. A list of downloaded coverages is presented in Table 3.

In some instances, modifications of the existing coverages were performed where the coverage detail was more precise than needed. This typically occurred for watershed coverages, where the features were drawn so densely that it was not presentable as is. Attributes were thus queried and new coverages created that contained broader, more identifiable features. Existing state GIS coverages were predominately downloaded as ARC/INFO export files (extension .e00), but ESRI shapefiles were available in some instances. Shapefiles can readily be brought into ArcView, but export files have to be imported first using the Import 71 utility as part of the ArcView GIS software before they can be used.

4.2 Bridge Data

Bridges entered into the GIS developed for this project were selected based upon their Item 113 codes, which were assigned by the DOTs. The objective was to input all bridges that were either scour susceptible or had not undergone some type of scour analysis. State DOTs were contacted to obtain lists of bridges, which were queried to extract only those with Item 113 codes of 0-3, 6, and U unless additional codes were requested by DOTs for inclusion within the their GIS. Although several bridge attributes were included later in the project, initially the main objective was to acquire just two attributes for each bridge: a unique id and the bridge location. The unique id made it simple to insert additional attributes at a later time while the bridge location was important for spatially locating the bridge within the coverage.

Bridge locations were often provided in geographic coordinates (latitude and longitude), whereas existing state GIS layers were created with a stateplane coordinate system. In order to

Table 3. Downloaded state GIS coverages

State	Coverage Name	Coordinate System	Datum	Units
Connecticut	County Boundaries Hydrography Subset Major Basins	Stateplane	NAD27	Feet
Maine	MEDRDVD METWP250	UTM Zone 19	NAD83	Meters
Massachusetts	Counties Major Basins Major Streams and Rivers	Stateplane	NAD83	Meters
New Hampshire	Political Boundaries Major Basins	Stateplane	NAD83	Feet
Rhode Island	State of RI Rhode Island Basins Major Rivers & Streams	Stateplane	NAD83	Feet
Vermont	CNTY250 RIVBAS	Stateplane	NAD83	Meters

overlay the existing state GIS layers with bridge locations, bridge coordinates were converted to appropriate units for their respective state. This was accomplished using Corpscon, Version 5.11.08, a MS-Windows based program developed by the US Army Corps of Engineers. Corpscon allows the user to convert between Geographic, State Plane, and Universal Transverse Mercator (UTM) systems on the North American Datum of 1927 (NAD 27), the North American Datum of 1983 (NAD 83) and High Accuracy Reference Networks (HARNs) ("Corpscon").

Bridge data sent by the state DOTs were typically transmitted via Microsoft (MS) Excel files. In the event that more than one attribute file was sent, MS Access was used to link information for the same bridges from multiple files. The DOTs were asked to send bridge attributes they believed to be relevant for inclusion in the bridge scour database, including descriptors (town, county, id), bridge characteristics, stream characteristics, and rankings. There was some difficulty in obtaining the information from DOTs; complete bridge lists were received from Connecticut, Massachusetts, New Hampshire and Vermont. The two most important bridge attributes to collect are a unique bridge id and a bridge location. Any and all other attributes can easily be added or modified at a later time. Emphasis was placed upon including attributes pertinent to bridge scour equations as well as parameters that could be manually queried by the DOTs that would help identify and prioritize bridges generally more susceptible to scour, such as foundation type, scour indices, critical flow events, countermeasures installed (if any), and average daily traffic (ADT). The ability to see the locations of these bridges and use attributes to identify bridges most susceptible to scour during a storm event are vital to earlier and better preparation and response by DOTs and emergency management agencies. Attributes may also be queried to identify trends in infrastructure weakness as well as establish prioritization for bridge remediation.

Once the bridges were entered into the GIS, a cursory check was made to ensure that the sites fell within the state boundaries. In cases where they didn't, the coordinates were checked, and if a discrepancy existed, the DOT was notified and a correction was made.

4.3 Stream and Rain Gage Data

Although real-time hydrological data are an important component to this project, the data are not very useful without spatial knowledge of the gage locations. Whether the gage data are monitored throughout the course of a storm or forecast offices provide estimates of precipitation totals or river stages at various gage locations, the user must be aware of gage sites in relation to scour susceptible bridges and dams. Therefore, it was crucial that locations of all active real-time rain and stream gages were identified and entered into a GIS for each state.

An extensive search of the Internet revealed no comprehensive website that included all rain and stream gage networks. Websites with information regarding gage networks typically had their own GIS map showing gage locations, but the map was usually not available to download. The multiple coordinate systems and map formats used by various agencies on their websites also posed difficulties for integrating them within each state GIS. It was thus easier to extract the gage locations and attributes manually and then insert them as new GIS coverages.

Relevant stream gage attributes included general descriptors as well as drainage area into gage. Warning and/or flood thresholds were available for some gages, but were not included as part of the gage attributes. Rain gage attributes were similar to the ones for stream gages, but gage elevation was also added as a parameter.

4.4 Dams

Although not initially discussed in the proposal, it was decided that it would be also useful to incorporate the locations of dams into the GIS, due to their potential impact on the accuracy of stream gages during a significant storm event. This would serve dual purposes: (1) identify gages with regulated flows and (2) aid in the placement of future gages. While thousands of dams have been constructed in New England, only a fraction of these significantly affect the stream gages. The National Inventory of Dams, which is maintained by the Army Corps of Engineers, is available online and contains database information on thousands of dams nationwide ("National Inventory of Dams"). Due to the large number of dams in each state and that fact that no one dam attribute directly impacts bridge scour, all of the dams in the inventory were incorporated into the GIS for the time being. It is better to have too much information than too little and the data can easily be queried to eliminate dams from consideration.

5.0 SYSTEM ARCHITECTURE

The system architecture for the model of the real-time scour monitoring system integrates existing scour analyses with utilization of Internet resources and GIS tools. The system should operate in a number of capacities, including spatial feature display, data storage, and analytical tool. This versatility emphasizes that the strength of the system is its flexibility. Its purpose is to aid DOTs in their understanding, recognition, and evaluation of scour as well as their preparation and response to scour-induced problems.

A web-based approach using a spatial decision support system (SDSS) would be adopted for development of the monitoring system. A SDSS is a software application that can be used as both a decision and research tool. The SDSS code could be written in Sun Microsystems Java 1.2. Java is platform independent and can be run on any operating system. Java was selected for the approach as a result of its algorithmic flexibility, its ability to be accessed from the web by all parties, and the familiarity of the authors with it (Miles et al, 1999).

This chapter covers the development of the conceptual model and illustrates its application within a scour monitoring system. Components of the GUI are discussed, including scour parameters and scour algorithms to be integrated within the spatial modeling framework. Different methods for obtaining real-time scour parameters such as flow variables are also presented. Examples are given as to how existing analyses could be used in the model. Finally, the framework of a real-time scour monitoring system is outlined.

5.1 Graphical User Interface

5.1.1 Graphical User Interface Components

The graphical user interface (GUI) components serve the purpose of making the SDSS user-friendly. This is accomplished by masking the complexity of the user tasks and the differences between the numerous underlying components. Through direct-manipulation, the GUI will include several components for use in managing spatial data requirements (input parameters), model configuration (algorithms/analyses), and analysis output (Miles et al, 1999). Direct-manipulation refers to performing computing tasks through physical action instead of syntax. Several advantages of direct-manipulation are cited by Schneiderman (1988), such as control-display compatibility, reduced error rates, faster learning, longer retention, and more user explanation.

The GUI will be based upon a tree model similar to the file structure for Windows, Macintosh, and Unix operating systems. As a result, the tree model will be familiar and comfortable for most users. Its structure will not only aid in the understanding of information such as model configuration and input parameters, but also in the structure of the information in terms of organization and relation. The flexibility of the tree will also permit modification of spatial data parameters, such as in the instance where a model component is added or changed (Miles et al, 1999).

An example of an SDSS prototype for seismic landslide analysis is shown in Figure 2. The three components of the GUI include the Spatial Data Manager, the Model Manager, and the Output Manager. The Spatial Data Manager will contain all spatial data requirements, which will be represented by branches of the tree in the GUI. The Model Manager will list all of the models (algorithms) that can be selected for analysis, permit editing of model parameters, and

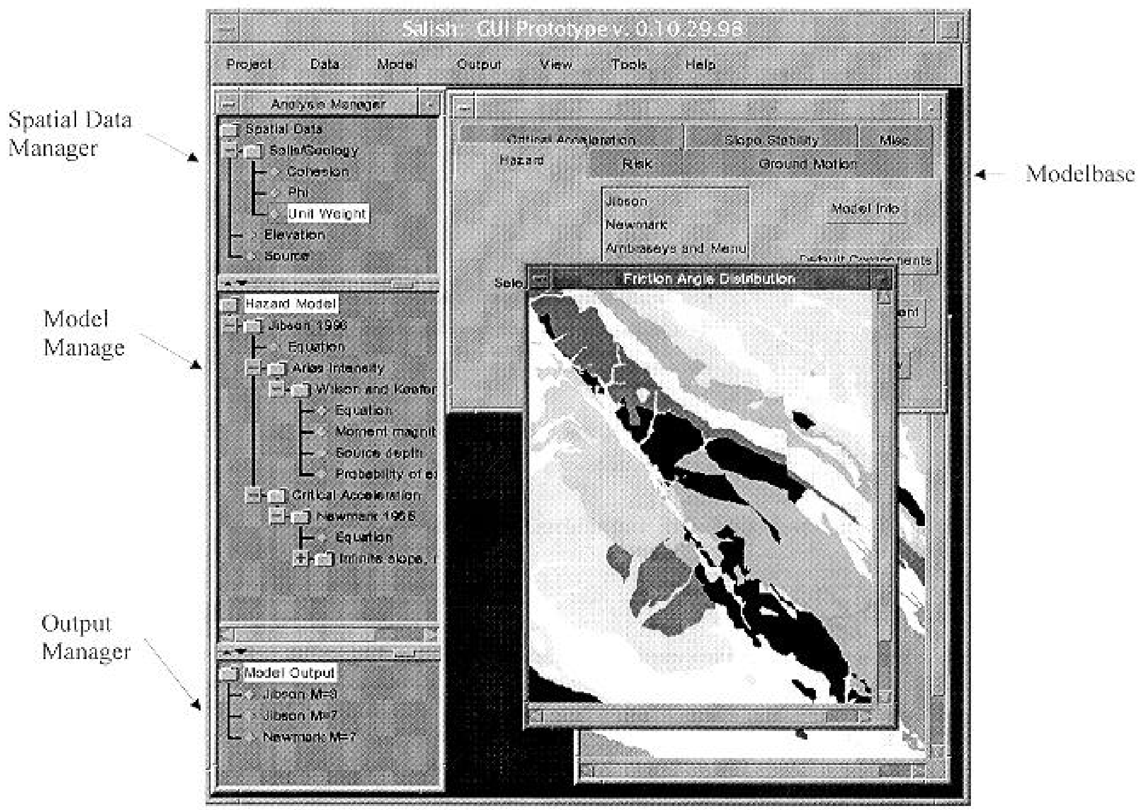

Figure 2. Conceptual prototype of spatial decision support system for seismic landslide analysis (from Miles and Ho, 1999a)

perform the analysis through direct-manipulation. The Output Manager will have the same configuration as the Spatial Data Manager, except that it will organize and present the results of the analysis (Miles et al, 1999). A flowchart is shown in Figure 3 to provide a visual reference of the scour monitoring system components:

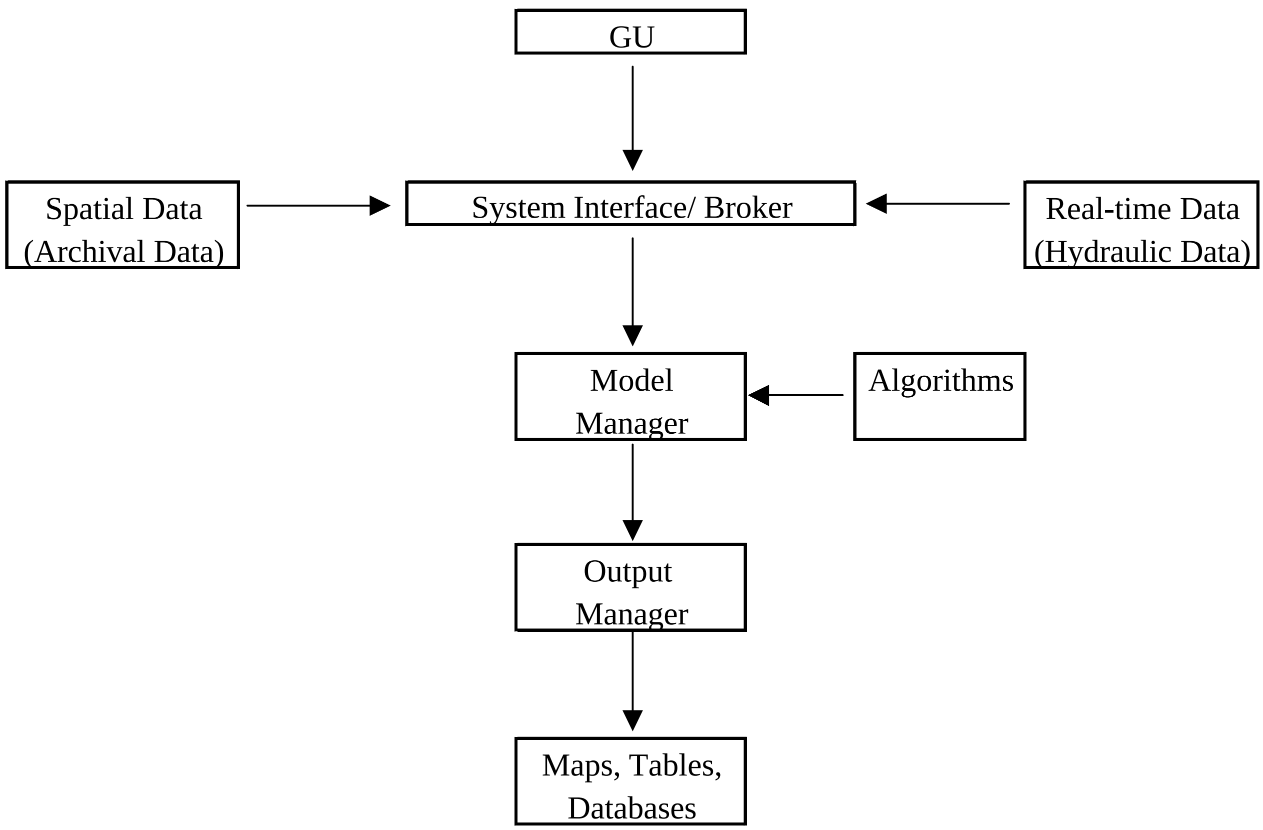

Figure 3. Proposed system architecture of spatial decision support system (SDSS) for scour monitoring

5.1.2 Spatial Data Manager

Scour parameters for bridge sites within the Spatial Data Manager will consist of archival data and real-time data necessary for input into scour equations, although other site attributes (e.g. town name, waterway, Item 113 code, etc.) should be included in the manager as well. The parameters included in the manager, therefore, are largely dependent upon the algorithms chosen for analysis, which are ultimately selected by the DOTs. Archival data refers to data that will remain relatively constant, although the data could change over time as periodic bridge inspections may reveal gradual transformations (e.g. channel movement). Bridge geometries, foundation characteristics, channel characteristics, and bed material are all considered archival data. Real-time data refers to currently acquired transient hydraulic data (e.g. discharge). Although hydraulic variables such as flow depth and velocity are considered real-time data, they too will be stored within the Spatial Data Manager for each bridge. These variables (discharge, velocity, and flow depth) will be predetermined for several flow return intervals to avoid calculating them (and scour depths) during a significant flow event; instead, real-time discharge values from active stream gages will be compared to the gages' historical flow data to assess the magnitude of the event. The function of the Spatial Data Manager will be better understood within the context of a scour monitoring system, which is explained in detail in Section 5.4.

5.1.3 Model Manager

Despite extensive research into scour processes in recent years, accurate scour models remain elusive, as evidenced by the conservative nature of scour equations. It is therefore crucial that the model manager be developed to allow the user to choose from a number of different algorithms. The flexibility of the model would permit algorithms to be easily added, removed, or modified to keep up with future scour research. This approach will allow scour depths calculated from different equations to be compared and give interested parties a better understanding of which scour equations work best under certain conditions. The model does not have to be limited to strictly numerical algorithms for scour depth calculations. Qualitative algorithms such as the comparative scour analysis could also be added to the Model Manager to help assign Item 113 codes to those bridges with unknown foundations or for which no scour evaluation has been conducted.

USGS offices in several states, in cooperation with their respective state DOTs, have released Water-Resources Investigations (WRI) Reports that evaluated the accuracy of scour measurement methods and predictions with observed scour at bridge sites (Hayes 1996, Jackson 1997, and Boehmler and Olimpio 2000). These reports considered numerous scour equations in the literature, mostly for pier scour, and compared scour estimates using these equations with scour measurements in the field.

Boehmler and Olimpio (2000) conducted an investigation of pier scour at 20 bridge sites throughout New Hampshire. The objective of their report was to assess the accuracy and reliability of predicted scour depths using several different pier scour equations when compared with scour depths measured using fixed instrumentation (FI), field teams (FT), geophysical methods (GM), or any combination of the three. These bridges had initially been designated as scour critical in a previous study, but the low occurrence of historical damage incurred by them was inconsistent with the study's results as the bridges had withstood events greater than their respective scour critical event. As a result, a joint effort was made by New Hampshire DOT and USGS to evaluate streambed scour at piers using a variety of monitoring and predictive methods. Ten different pier scour equations, many of which are documented in the literature, were selected for comparison. Table 4 lists these ten equations and provides definitions for variables in each equation. The methods used to monitor and predict scour in their study are likely applicable to all New England states.

Table 4. Equations reviewed and used for pier-scour computations (from Boehmler and Olimpio 2000)

[Definition of variables for equation HEC-18, CSU, and Simplified Chinese are used for other equations listed in this table]

Equation name and reference(s)	Equation	Variables, units, and other notes
HEC-18 Richardson and Davis (1995)	$y_{sp} = 2.0 y_0 K_1 K_2 K_3 K_4 \left(\frac{b}{y_0}\right)^{0.65} F_0^{0.43}$ where $K_4 = \sqrt{1 - 0.89(1 - V_R)^2}$ $V_R = \left(\frac{V_0 - V_i}{V_{c(D90)} - V_i}\right)$ $V_i = 0.645\left(\frac{D_{50}}{b}\right)^{0.053} V_{c(D50)}$ and $F_0 = \frac{V_0}{\sqrt{g y_0}}$	NOTE: The HEC-18 equation is not dimensionless; y_{sp} is the depth of pier scour below the ambient bed elevation, in meters. y_0 is the depth of flow immediately upstream of the pier, in meters. K_1 is a coefficient based on the shape of the pier nose (table 4). K_2 is a coefficient based on the angle of attack of the approaching flow and the ratio of the pier length to the pier width, L/b, (table 5). L is the pier length, in meters. b is the pier width, in meters. K_3 is a coefficient based on the bed condition (table 6). K_4 is a coefficient to correct for armoring by large particles in the bed material. V_R is a dimensionless velocity ratio. V_i is the incipient-motion velocity for bed material particles at the pier, in meters per second. D_{50} is the median diameter of bed material particles, in millimeters. $Vc(D_n)$ is the critical velocity for the D_n particle diameter, in meters, for which n percent of the particle diameters are smaller. F_0 is the Froude number for the flow immediately upstream of the pier. V_0 is the flow velocity immediately upstream of the pier, in meters per second. g is the acceleration due to gravity (9.81 meters per second squared).
CSU Richardson and others (1990)	$y_{sp} = 2.0 y_0 K_1 K_2 \left(\frac{b}{y_0}\right)^{0.65} F_0^{0.43}$	NOTE: The CSU equation is not dimensionless; Same as HEC-18 equation without K_3 and K_4 coefficients.

Table 4. Equations reviewed and used for pier-scour computations – continued (from Boehmler and Olimpio 2000)

Equation name and reference(s)	Equation	Variables, units, and other notes
Ahmad Ahmad (1953)	$y_{sp} = K V_0^{2/3} y_0^{2/3} - y_0$	NOTE: The Ahmad equation is not dimensionless. y_{sp} and y_0 are in feet, and V_0 is in foot per second. K is a factor, which is a function of the boundary geometry, pier width, pier shape, and angle of the approach flow. Whereas recommended K values range from 1.7 to 2.0, it was assumed to be 1.8 for pier-scour computations in this study.
Blench - Inglis II Blench (1951, 1962, 1969) and Inglis (1949)	$y_{sp} = 1.53 b^{0.25} V_0^{0.5} y_0^{0.5} D_{50}^{-0.125} - y_0$	NOTE: The Blench-Inglis II equation is not dimensionless; as b, y_{sp} and y_0 are in feet, V_0 is in foot per second and D_{50} is in millimeters.
Simplified Chinese Gao and others (1993)	$y_{sp} = 0.78 K_s b^{0.6} y_0^{0.15} D_m^{-0.07} \left(\frac{V_0 - V_c'}{V_{c(Dm)} - V_c'}\right)^c$ where $V_{c(Dm)} = \left(\frac{y_0}{D_m}\right)^{0.14} \sqrt{17.6\left(\frac{\rho_s - \rho}{\rho}\right) D_m + 6.05X10^{-7}\left(\frac{10 + y_0}{D_m^{0.72}}\right)}$ and $V_c' = 0.645\left(\frac{D_m}{b}\right)^{0.053} V_{c(Dm)}$	NOTE: The Simplified Chinese equation is not dimensionless; The variables y_{sp}, y_0, b, and D_m are in meters, V_c is in meters per second, and c is 1.0 for all piers examined (clear-water scour). Ks is a simplified pier shape coefficient defined as 1.0 for cylinders, 0.8 for round nosed, and 0.66 for sharp-nosed piers. Dm is the mean particle diameter of the bed material. The median diameter particle size was used as a proxy for the mean for all computations. $V_{c(Dm)}$ is the critical velocity for the mean diameter-size particle. V_c'is the approach velocity acciociated with the critical velocity and incipient scour in the accelerated flow region at the pier. ρ_s is the density of sediment assumed to be 2.65 for all computations. ρ is the density of water.

Table 4. Equations reviewed and used for pier-scour computations – continued (from Boehmler and Olimpio 2000)

Equation name and reference(s)	Equation	Variables, units, and other notes
Melville-Sutherland Melville and Sutherland (1988)	$$y_{sp} = K_I K_d K_y K_1 K_2 b$$ where $$K_I = 2.4\left\|\frac{V_0-(V_a-V_c)}{V_c}\right\| \text{ when } \frac{V_0-(V_a-V_c)}{V_c} < 1.0$$ $$K_I = 2.4 \text{ when } \frac{V_0-(V_a-V_c)}{V_c} > 1.0$$ $$V_c = 5.75u_{*c}\log\left(5.53\frac{y_0}{D_{50}}\right)$$ $V_a = 0.8V_{ca}$ when $V_a > V_c$, otherwise $V_a = V_c$ $K_d = 1.0$ when $b/D_{50} > 25.0$ and $K_d = 0.57 \log(2.24\ b/D_{50})$ when $b/D_{50} < 25.0$ $K_y = 1.0$ when $y_0/b > 2.6$ and $K_y = 0.78\ (y_0/b)^{0.255}$ when $y_0/b < 2.6$	K_I is a coefficient for flow intensity. u_{*c} is the critical shear velocity in meter per second from Shields diagram in figure 4 for a D_{50}, which is less than 60 millimeters. Otherwise, the critical shear velocity is computed as $0.03\sqrt{D_{50}}$. V_a is the critical velocity of the armor layer. V_{ca} is the critical velocity for the median diameter particle of the armor layer material, D_{50a}, which is computed by replacing the D_{50} with the D_{50a} in the equation for V_c. D_{50a} is defined as $0.556\sigma^{1.65}D_{50}$ where σ is the standard deviation of the bed material. K_d is a coefficient for sediment size. K_y is a coefficient for the flow depth.
Shen Shen and others (1969)	$$y_{sp} = 0.00073\boldsymbol{R}_p^{0.619}$$	$\boldsymbol{R}_p$ is the pier Reynolds number defined as $\frac{V_0 b}{\nu}$, where ν is the kinematic viscosity of water.
Shen-Maza Maza and Sanches (1964), and Shen and others (1969)	$y_{sp} = 11.0b\boldsymbol{F}_p^2$ for $F_p < 0.2$ $y_{sp} = 3.4b\boldsymbol{F}_p^{0.67}$ for $F_p > 0.2$	Fp is the pier Froude number defined as $\frac{V_0}{\sqrt{gb}}$.

Table 4. Equations reviewed and used for pier-scour computations – continued (from Boehmler and Olimpio 2000)

Equation name and reference(s)	Equation	Variables, units, and other notes
Jain-Fischer Jain and Fischer (1979)	For live-bed-scour conditions [for example, $(F_0 - F_c) > 0.2$]: $y_{sp} = 2.0b(F_0 - F_c)^{0.25}\sqrt{\frac{y_0}{b}}$ and for maximum clear-water scour conditions: $y_{sp} = 1.84bF_c^{0.25}\left(\frac{y_0}{b}\right)^{0.3}$ where $F_c = V_c/\sqrt{gy_0}$ $V_c = 2.5u_{*c}\ln\left(11\frac{Xy_0}{D_{50}}\right)$ and $u_{*c} = \sqrt{\tau_c/\rho}$	NOTE: The Jain-Fischer equation is not dimensionless; b is the pier width, in meters; Y_o is the depth of flow immediately upstream of the pier, in meters; D_{50} is the median diameter of bed material particles, in millimeters. Fc is the critical Froude number at the threshold of bed material motion. X is Einstein's Factor obtained from Richardson and others (1990, fig. 2.3.5, p. II-24). τ_c is the critical tractive force for the D_{50} size particle obtained by use of Lane's diagram from Richardson and others (1990, figure 3.5.2, p. III-41).
New York 1996 Welch and Butch, U.S. Geological Survey, written commun., 1999)	$y_{sp} = 6.21 \times 10^{-7}\frac{p}{D_{84}} - 0.07$ where $p = \rho y_0 w V_0^2$	NOTE: The New York 1996 equation is not dimensionless; p is the local momentum of a 1-meter-wide column of water immediately upstream of a pier. D_{84} is the diameter of the particle for which 84 percent of the bed material particles are smaller than D_{84}, in meters. w is assumed to be 1.0 meter. ρ is assumed to be 1,000 kilograms per cubic meter. Y_{sp} is in meters.

Results from the study are shown in Figures 4 and 5. All results in the report were presented as residual depth of pier scour, or the difference between the measured scour depth and predicted scour depth at a pier. Negative scour residuals indicate that the equation overestimated the actual scour depth as the predicted scour was greater than the measured scour, giving a conservative result. Conversely, positive scour residuals mean that the scour depth was underestimated. In general, all of the equations were conservative to some degree. Residual pier scour depths calculated using predictive HEC-18 equations and field measurements ranged from –5 to –15 feet. It was acknowledged that for the large majority of sites, the equations were evaluated by comparing residuals to zero scour since no scour was measured at these sites. However, for sites where there was measurable scour, it was concluded that the Shen, Blench-Inglis II, and Simplified Chinese equations provided the most accurate estimates of bridge scour. It was surmised that the reason for the small range of residual scour depths determined using the Simplified Chinese equation was its incorporation of the velocity-ratio variable, which accounts for the "competence" of flow and was not included in any other equation (Boehmler and Olimpio, 2000).

While these three equations provide the most accurate predictions of pier scour depth at selected bridges in New Hampshire, they are not necessarily the best equations to determine bridge scour in other New England states nor do they represent all of the scour equations available. Different equations may be better suited to predict scour depths at other bridges within a state based upon stream characteristics or local geology. This reaffirms the central idea that several algorithms to predict scour should be included in the model.

The Bridge Scour Evaluator (BSE) is a computer program developed by Dave Mueller of the USGS that serves as a database of scour equations (Mueller 2001). Currently, the program,

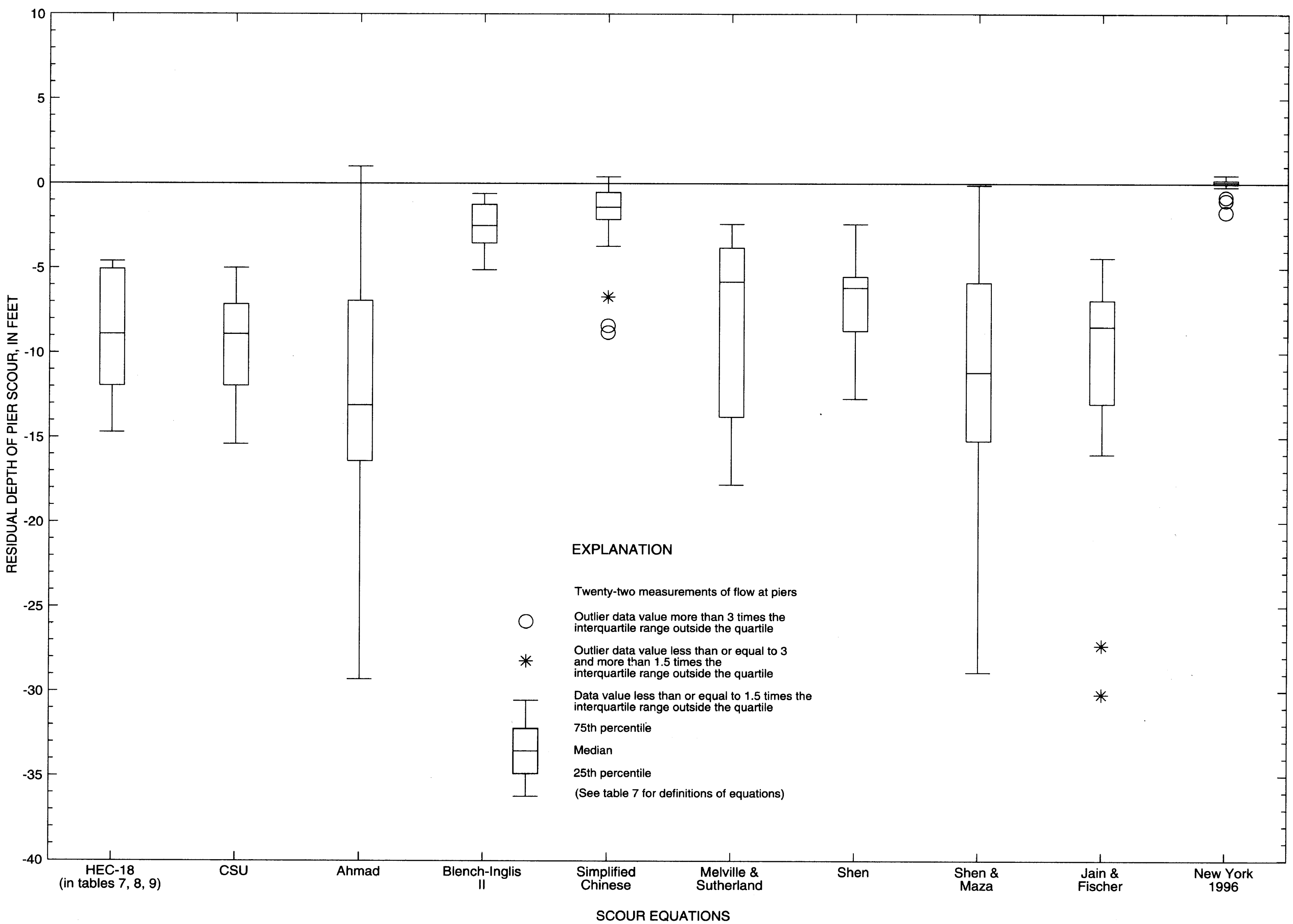

Figure 4. Residuals of pier-scour depths estimated/predicted by indicated equation and measured by field teams at five bridge sites in New Hampshire (from Boehmler and Olimpio 2000)

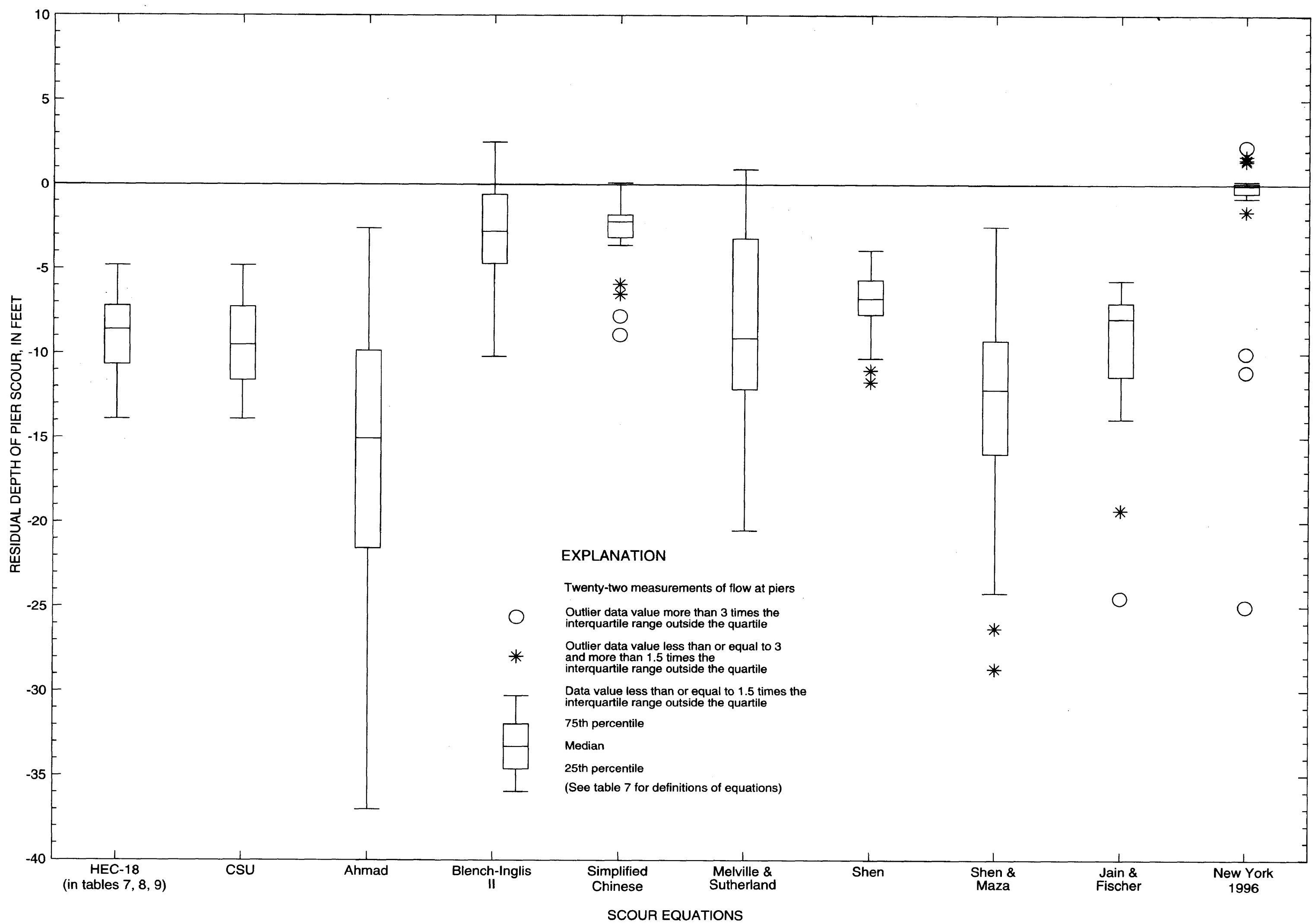

Figure 5. Residuals of pier-scour depths estimated/predicted by indicated equation and measured by Ground-Penetrating Radar and fixed instruments at 20 bridge sites in New Hampshire (from Boehmler and Olimpio 2000)

which is written in FORTRAN code, calculates approximately 25 pier scour equations and the abutment and contraction scour equations from HEC-18. While not officially released, the source code of the BSE has been shared with many USGS officials. This program, at the very least, provides a good reference for available scour equations.

5.2 Real-time Parameters

Real-time flow parameters, such as stream velocity and flow depth, are the most difficult parameters to calculate for input into scour equations. Unlike archival data, which remain fairly constant, flow variables are affected by continuously changing conditions, whether it be channel or stream dynamics. Although they can be measured in the field, these variables are typically derived using hydraulic modeling programs such as WSPRO or HECRAS for Level 2 scour analyses. Such hydraulic modeling programs are time-consuming, costly, and hamper rapid completion of full scour investigations for all bridges that need them. Coupled with the conservative nature of scour equations, DOTs are reluctant to continue intensive scour analyses using these programs, especially since the coding process (Item 113 codes for bridges) is nearly complete.

If scour depths can be calculated quickly and reasonably without the aid of hydraulic modeling programs, then DOTs would push to finish the intensive scour analyses for the non-assessed bridges, including those assigned temporary codes or that have unknown foundations. This would also be useful for bridges at which flow conditions change over time, from natural or man-made processes, thus requiring that new scour analyses be performed. Bridges that have already been evaluated would benefit as well from a faster procedure for scour analysis, particularly if the proposed monitoring system outlined in Section 5.4 is implemented. In addition, if scour depths are calculated for a number of significant flow events instead of just the scour critical event, officials will have a better grasp of scour conditions at a bridge. It is thus important to consider simplified methods of determining hydraulic scour variables.

5.2.1 Prediction of Flood Magnitudes

Since required hydraulic scour variables such as flow depth and velocity can be determined from discharge values using procedures such as the rapid-estimation method, methods of estimating discharge were reviewed in the literature. There are two scenarios to consider when estimating discharge at a bridge. One is the presence of an active stream gage near a bridge site. In this instance, it can be inferred that the flow reported at the gage is the same at the bridge and the data can be found at real-time websites. The second possibility is that no gage is stationed near a bridge site, for which prediction of discharge is much more critical. It is the estimation of discharge values for the second scenario that will be addressed in the following sections. Methods of discharge estimation using channel geometry and basin characteristics will be presented as well as the UMass approach.

5.2.1.1 Literature

Dingman and Palaia (1999) recently developed and evaluated three regression models for estimating flood quantiles at ungaged stream reaches in New Hampshire and Vermont that were not affected by flow regulation or land-use alteration. Model development was divided into three classes: channel geometry predictors, basin-characteristic predictors, and drainage area only as a predictor. These empirical predictors included drainage area, average drainage-basin elevation, main-channel slope, basin-average 2-yr return interval, 24-hr rainfall, bankfull values of channel width, average depth, and stream cross-sectional area. Bankfull width and basin area were determined to be the best channel geometry and basin characteristic predictors, respectively, with bankfull width the best single predictor of flood quantiles. These conclusions were in agreement with the results of many previous studies. The incorporation of basin elevation with basin area was found to largely improve predictions over area alone, although flood quantile predictions were reported to be noticeably better using bankfull width than the best basin-characteristic predictors.

Prediction errors and time-sampling errors were compared to evaluate the various empirical discharge models. Prediction errors associated with empirical models using bankfull width, basin area and elevation, and basin area alone were determined by comparing predicted discharges with measured discharges. Time-sampling errors were estimated at gages with a range of record lengths using statistical analyses. Prediction errors for the empirical models were then contrasted with time-sampling errors for gages of varying record lengths. It was found that prediction errors for the bankfull width model were not much greater than time-sampling errors for a gage with a record length of approximately 20 years, particularly as the 100-year flow event was approached. Prediction errors for other empirical models were greater than those for the bankfull width model, while time-sampling errors were reduced for gages with longer record lengths (Dingman and Palaia 1999).

Predictive discharge equations can be affected by several factors that could limit their application. Holnbeck and Parrett (1997) cite some limitations to channel-geometry equations, such as upstream flow regulation, the alteration of natural channel geometry near bridges by construction activities and hydraulic conditions, and use of the equations in regions where channel geometry is poorly defined. For application of the rapid-estimation method in Montana, discharge was estimated in the foothill regions using channel-geometry equations, whereas drainage area was used to predict discharge in the flatter, prairie regions where channel geometry is more difficult to define. While the equations by Dingman and Palaia (1999) were developed using data from New Hampshire and Vermont, it is foreseeable that they would be applicable in regions with similar geologies and elevations, such as western Massachusetts and northwest Connecticut.

5.2.1.2 UMass Approach

As Dingman and Palaia (1999) and Holnbeck and Parrett (1997) both reported, many authors have investigated the relation between basin characteristics and flood magnitude. For the UMass approach, the relation between discharge and drainage area was examined using historical gage data from active real-time stream gages. Although data were collected and plotted for all New England states, only Massachusetts was selected for demonstrational purposes with the intent that the methodology could also be applied to the other states. This method offers another approach to estimating flood magnitudes for various recurrence intervals, particularly for regions where channel geometry is not as well defined.

An algorithm encoded in standard FORTRAN 77 was used to extract annual flood peak data and gage attributes from historical USGS stream gage records and perform statistical analyses on them. The algorithm, based on L-moment analysis (Hoskings 1990), was modified for this project to obtain additional gage attributes such as latitude and longitude and drainage area and to estimate discharges for the 10-, 25-, 50-, and 100-year return interval flow events. A 10-year event typically is the catalyst for conducting post-flood bridge inspections by a state DOT, but it is important to predict scour depths for greater flow events since they are more likely to induce bridge failure. Historical annual peak flow data for all active real-time stream gages were downloaded in punchcard format from the USGS Real Time Water Data website. Data were not downloaded from gages that met either of the following two criteria: (1) those with drainage areas less than 10 square miles, and (2) those with 10 or fewer years of annual peak flow records. This criteria was established to improve the reliability of the records and minimize large variations in the data for small drainage areas. Initially, gages on regulated streams were eliminated from consideration, but were later included because they did not appear to impact the analyses and provided a greater number of points for the model.

Power functions are typically used for regression models relating discharge with drainage area. These functions take the following form:

$$Q = c\,(A)^{d} \qquad (1)$$

where

Q = discharge for x-year flow event, in cubic feet per second
A = drainage area, in square miles

Rearranging the equation, it can be written as:

$$\ln Q = \ln C + d \ln A \qquad (2)$$

This form of the equation is similar to a linear regression line, shown as:

$$y = b + m\,x \qquad (3)$$

From the input files consisting of historical gage data, the program generated an output file containing drainage area and estimated return interval discharges for each input gage, which was then entered into a spreadsheet. Plots were created for each return period for gages in each state. A sample plot is presented in Figure 6, which shows a log-log plot of discharge versus drainage area for Massachusetts stream gages.

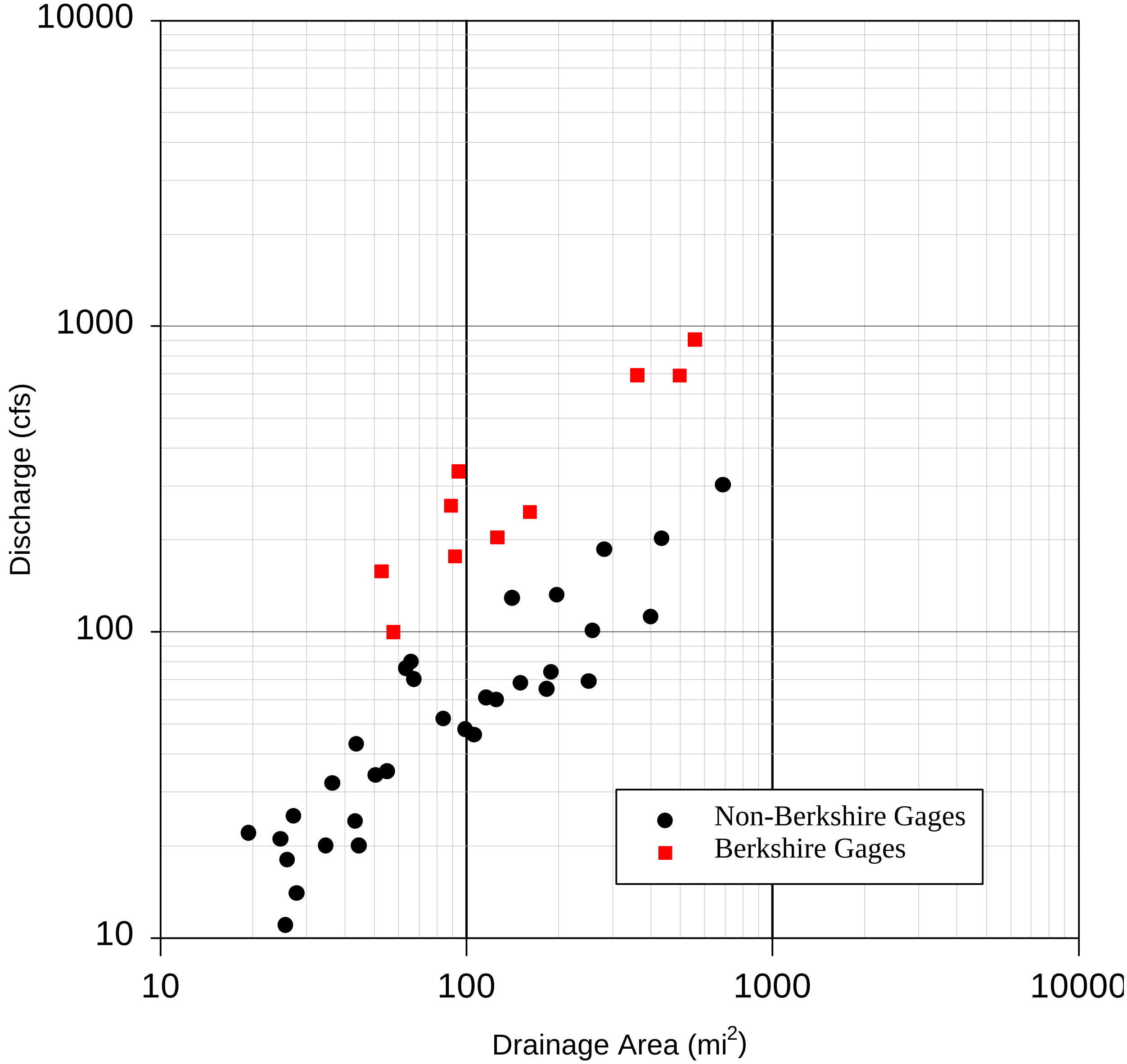

Figure 6. Discharge vs. drainage area for active real-time stream gages in MA (10-year return period)

From the plots, there appears to be scatter in the data, which could be attributed to varying gage record lengths, gage density and locations, and overlapping drainage areas. A bi-model trend, though, is observed as a group of several points consistently appear to fall outside the general population. These points in question are denoted by squares on Figure 6. Using the GIS created for Massachusetts, it was quickly realized that this group of points represented stream gages that were located in or near the Berkshires, a mountains range in western Massachusetts. This is consistent with the expectation that the hydrologic response of streams is accelerated at higher elevations, causing higher flow events at these gages than at gages with similar size drainage areas at lower elevations. It also confirms that models using drainage area and basin elevation together are better discharge predictors than drainage area alone.

To generate curves for the data, the natural log of discharge was plotted versus the natural log of drainage area and a linear regression line was fit to the data in the form of Equation 3 for the 10-, 25-, 50-, and 100-year flows. A plot of these data for the 10-year return period is shown in Figure 7. After converting the equations for all four return periods into power functions as shown in Equation 1, the functions were drawn on the same plot and are illustrated in Figure 8. These functions were developed using gage data from all active real-time stream gages in Massachusetts excluding those gages identified at higher elevations in the Berkshires.

This approach is another example of how prediction of flood magnitudes can be made. Given a particular flow recurrence interval and the drainage area into a bridge, the approximate corresponding discharge at a bridge can be extracted from the graph. The UMass approach was developed as one possible alternative to quickly estimate discharge at ungaged sites. USGS websites contain historical streamflow records for numerous gages in each state that were once active, regardless of whether they are currently real-time gages. Data from current, active, real-

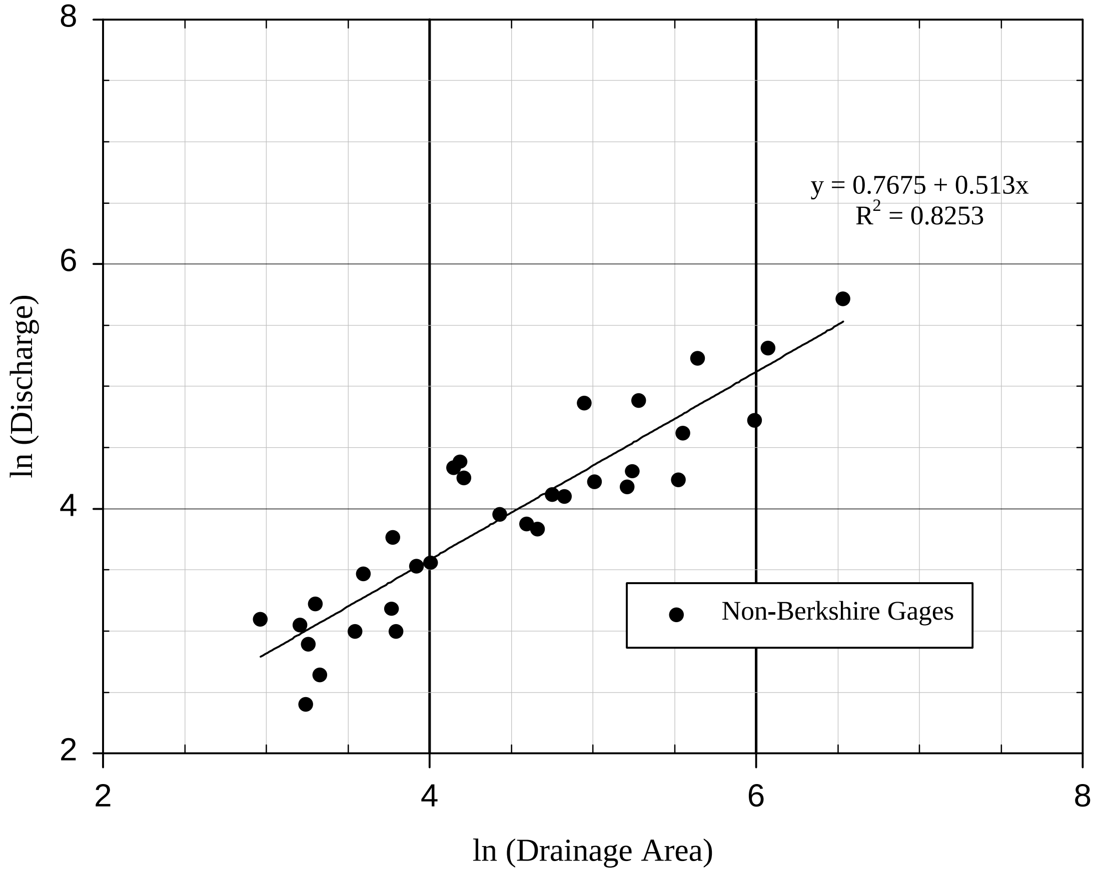

Figure 7. Linear regression of natural log transformation of discharge and drainage area for non-Berkshire gages (10-year return period)

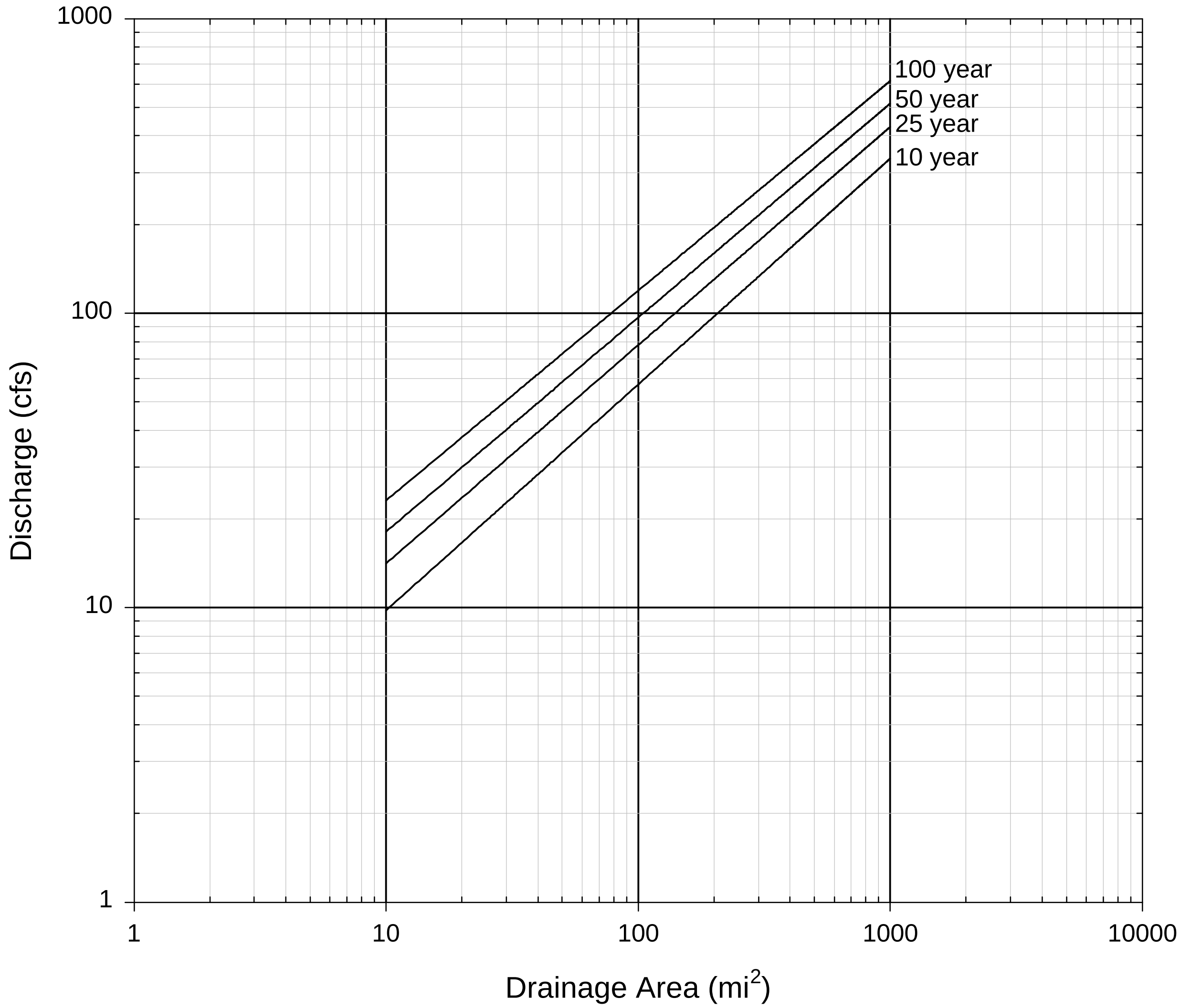

Figure 8. Discharge – drainage area functions for non-Berkshire gages in MA

time gages were chosen to develop the functions relating discharge and drainage area, but the resources are available on these websites to download data from other gages and use them to create new or revised discharge – drainage area models. Additional discharge – drainage area plots for MA gages at other flow return intervals are in Appendix B.

5.2.1.3 StreamStats

Regional regression models developed by the USGS are also available for purposes of flood magnitude prediction. These models are based upon the same principals as the UMass approach, but incorporate more variables. As mentioned earlier, a cooperative effort between the USGS, MassGIS, and Syncline, Inc. produced the StreamStats website, which provides a database of streamflow statistics along with an automated procedure that measures basin characteristics and uses regression equations for estimates of streamflow statistics at ungaged sites. This program enables the user to acquire streamflow statistics for any location along a stream in the state (Ries and Friesz 2000). USGS offices in other New England states, as well as nationally, are also working on projects that would achieve similar goals in the next few years (Toppin 2001).

5.2.2 Prediction of Flow Variables

Once discharge is estimated, a simplified method for obtaining hydraulic variables such as velocity and flow depth is necessary to facilitate quicker scour analyses that still provide results comparable to Level 2 analyses. This can be accomplished through the procedure outlined in the rapid-estimation method. The rapid-estimation method offers a way to quickly generate flow variables knowing only the discharge at any bridge site without the need for a full hydraulic analysis. It should be noted here that the method is not intended to replace more detailed hydraulic analyses and engineering judgement should be used to determine if the application is warranted for each bridge site. Given the time-intensive nature of hydraulic modeling programs, though, the method does offer a way to reasonably estimate flow variables in a short period of time until more thorough analyses can be performed.

When the Montana USGS developed this procedure (Holnbeck and Parrett 1997), the relationships between flow variables were based upon WSPRO hydraulic data from Level 2 analyses. Once an estimation of discharge was made, the flow was normalized to compare bridges with varying spans and discharges, creating a unit discharge value, as follows:

$$q_2 = Q_2/W_2 \qquad (4)$$

where

q_2 = unit discharge in cubic feet per second per foot-width of main channel at the contracted section
Q_2 = x-year discharge through bridge opening, in cubic feet per second
W_2 = estimated top width of x-year flow at the downstream face of the bridge opening, adjusted for any skewness to flow and for effective pier width, in feet

Using data from regional Level 2 bridges, the logarithm of unit discharge was then related to the logarithm of average main-channel velocity at the bridge contraction, V_2, at the downstream bridge opening. The form of this equation is presented below:

$$V_2 = c(q_2)^d \qquad (5)$$

where

V_2 = average main channel velocity at the bridge contraction at the downstream bridge opening
c, d = region-specific coefficients

The authors suggested that equations for velocity – unit discharge relationships throughout the U.S. could be developed in a similar fashion using region-specific coefficients derived from Level 2 data from the respective regions (Holnbeck and Parrett 1997).

Flow depth at the bridge contraction (y_2) was then calculated by dividing the unit discharge (q_2) by the average velocity at the bridge contraction (V_2). For purposes of estimating flow depth, the difference in water-surface elevation (Δh) from the approach section to the bridge opening was also taken into account by the rapid-estimation method for sites at which flow measurably contracted at the bridge. The effects of channel slope and backwater were attributed to this difference in water-surface elevation, which was developed as a function of V_2^2, and were based on the results of Level 2 bridges. The complete flow depth equation, then, is shown below:

$$y_1 = y_2 + \Delta h \qquad (6)$$

where

y_1 = flow depth in the approach section
y_2 = flow depth at the downstream face of bridge
Δh = difference in water surface elevation

and

$$\Delta h = c\,(V_2)^2 + d \qquad (7)$$

Equation 4 was based upon a similar equation for flow through an orifice. If contraction is insignificant at the bridge opening, then the approach depth can be estimated using y_2 alone (Holnbeck and Parrett 1997).

5.3 Applications of the Strategy

5.3.1 Engineering Application

Some states have expressed satisfaction with the scour codes assigned using the HEC-18 scour equations. With the understanding that the equations can be overly conservative, they have met the requirements that were established by the FHWA regarding scour analyses (Nardone 2000). Other states have indicated interest in identifying new equations that could more accurately predict measured scour depths in the field (Antoniak and Levesque 2000). Such equations could reduce the number of bridges determined to be scour critical. Revising codes for bridges initially coded as scour critical could significantly impact the allocation of new monitoring devices, the routing of traffic during an evacuation, and the prioritization of bridges for remediation.

Connecticut has already taken this initiative of adopting new equations by amending the local abutment scour equation by Froehlich, as presented in HEC-18, Third Edition. The current formula is as follows:

$$Y_s / Y_a = 2.27 K_1 K_2 \left(\frac{L^1}{Y_a} \right)^{0.43} Fr^{0.61} + 1 \qquad (8)$$

where

K_1 = coefficient for abutment shape (See Table 6, Section 4.3.6 in HEC-18 Third Ed., dated Nov. 95)
K_2 = coefficient for angle of embankment to flow (Refer to Section 4.3.6, Figure 16 in HEC-18, Third Ed., dated Nov. 95)
L^1 = the length of abutment projected normal to flow
Y_a = average depth of flow in the floodplain = A_e/ a'
A_e = the flow area of the approach cross section obstructed by the embankment
Fr = the Froude number = $V_e/ (g\ y_a)^{0.5}$
$V_e = Q_e/ A_e$
Q_e = the flow obstructed by the abutment and approach embankments
Y_s = scour depth

CDOT reported that the +1 value was initially intended as a factor of safety, but was not in Froehlich's original paper. This value increases the predicted scour depth by the depth of the overbank flow. Considering predictive scour algorithms are conservative in nature when compared with field measurements of scour, CDOT, after consulting with researchers, chose to replace the +1 value with a value of +0.05 and reanalyze their bridges using this revised equation. The predicted scour depth is now referred to as the *amended scour depth* (CDOT 1999). Therefore, the amended local abutment scour equation is:

$$Y_s / Y_a = 2.27 K_1 K_2 \left(\frac{L^1}{Y_a} \right)^{0.43} Fr^{0.61} + 0.05 \qquad (9)$$

Connecticut plans on using the equation to reevaluate the 287 rated (full Level 2 scour analysis) bridges that served as the sample of bridges with which unrated bridges were compared. The state's goal is to reduce the number of scour critical bridges and it is hoped that the revised equation can predict more accurate and less conservative scour depths (CDOT 1999).

In the event that a new equation is developed or modified, such as the one presented above, it could very easily be added as an algorithm. For this equation, no additional spatial data requirements would be necessary, but an additional branch of the tree would be added to the Model Manager. A flowchart representing the system architecture for the engineering application is shown below in Figure 9:

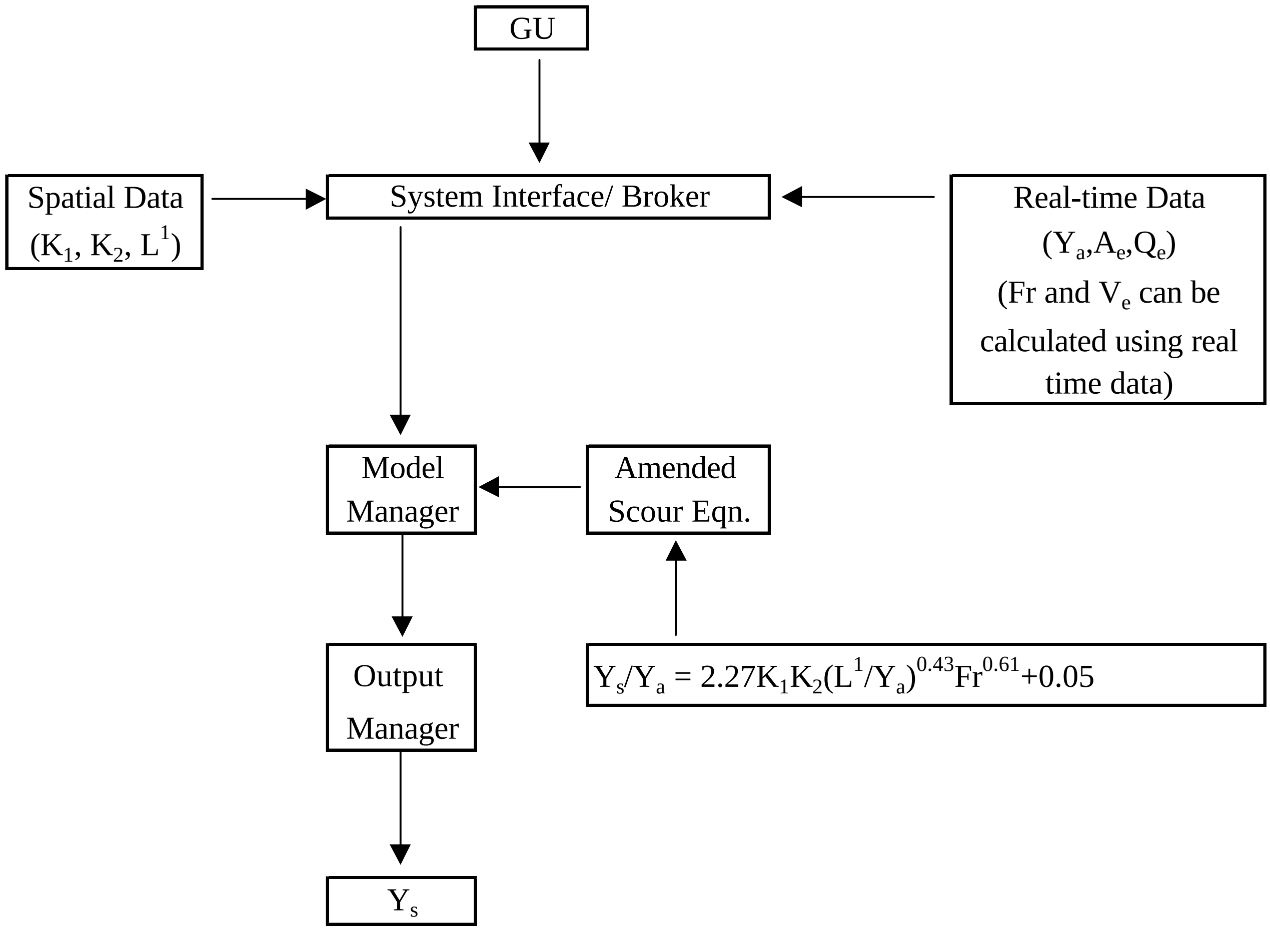

Figure 9: Flowchart of system architecture for engineering application

The output would contain, among other things, the calculated value of Y_s. Instead of going back through all of the scour critical bridge files in order to recalculate predicted scour depths using the new model, the scour analysis can immediately be conducted through the GUI. The new results can then be compared with scour depth results using existing models. The more models that are available for analysis, the more informed DOT officials will be regarding the scour susceptibility of a bridge.

5.3.2 Comparative Application

Algorithms such as the comparative scour analysis could also be introduced and used in the web-based approach. The spatial data, which contains the bridge attributes, would have to include the primary and secondary criteria established for the rated bridges. Queries could be used to identify rated bridges that are similar to unrated bridges according to matching criteria. If flows at the structure evaluated by the comparative scour analysis approach magnitudes similar to critical flows for its corresponding rated bridge, the system could warn the user of the potential hazard. Many commercial means exist to distribute such warnings via automated notification systems and updated webpages. A flowchart representing this application is shown in Figure 10:

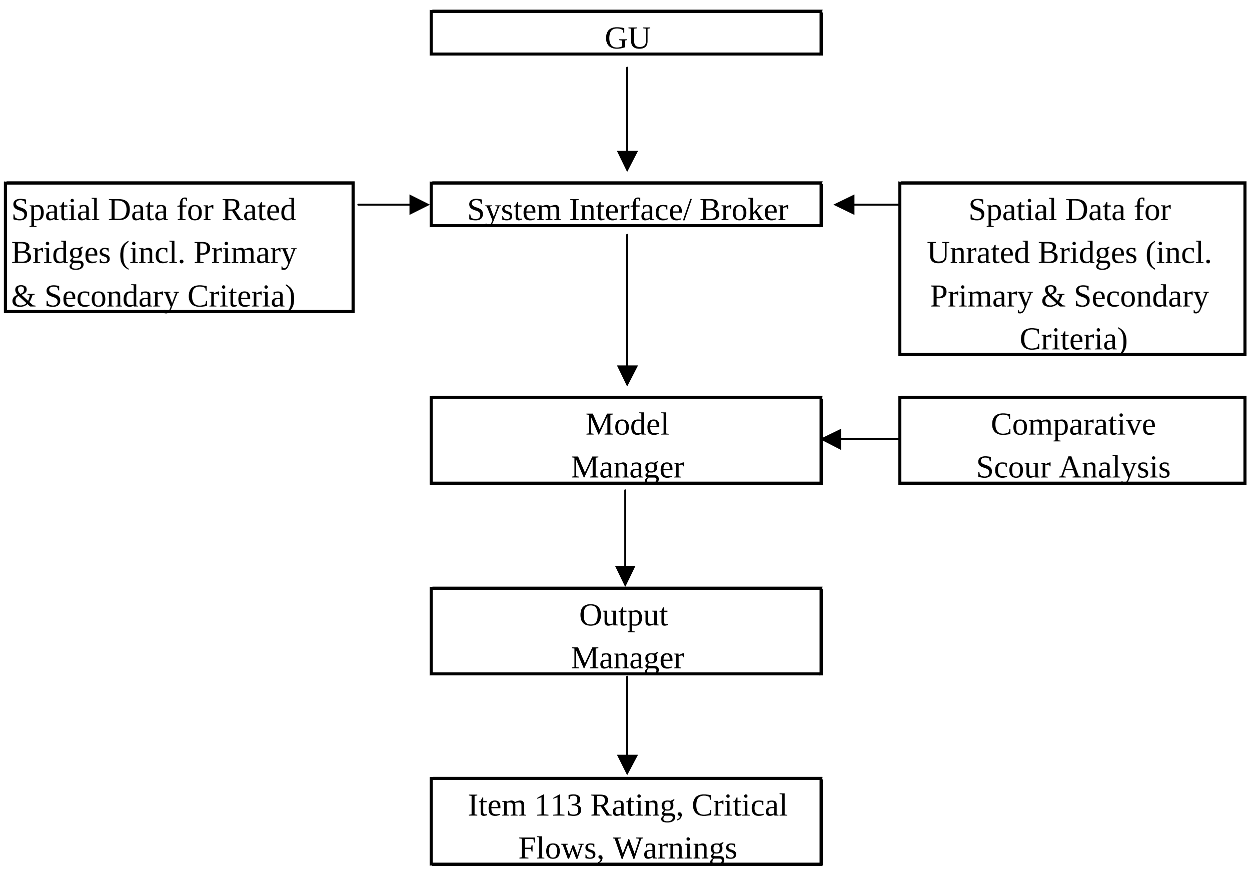

Figure 10: Flowchart of system architecture for comparative application

In the event that bridge or stream conditions drastically changed, a bridge could quickly be reanalyzed using the comparative analysis, assuming it was initially analyzed using the same method. If this occurred to a Level 2 bridge, however, there would be two options. It could be placed back into the group of rated bridges used for comparison only if another Level 2 analysis was performed or it could be removed altogether from the sample group and be reassigned a code as an unrated bridge through a comparative analysis.

5.4 Monitoring System Framework

Monitoring systems should be designed not only for observation purposes, but also to alert people when established thresholds are surpassed and to relay information quickly in emergencies. The idea behind this scour monitoring system is to rely on forecasts and gage data to determine when those thresholds have been exceeded. A web-based model offers the best method to collect, analyze, and disseminate information during a critical storm event.

Figure 11 presents the flowchart diagram for the monitoring system. DOT personnel would access forecast weather information via the Internet. Based upon the forecasts, gages and bridges in regions potentially impacted by an approaching storm would be identified. A figure such as Figure 12 could be used to identify the locations of automated stream and rain gages in Vermont. In this figure, the stream gages are sorted by gage drainage area, whereas the rain gages are distinguished by gage network. Bridges would then be queried in the GIS using certain attributes to establish which bridges will most likely be jeopardized by a coming storm. An example of this is shown in Figure 13, which queried all multiple span, scour critical bridges in Massachusetts. It should be noted that this querying procedure is simply intended to distinguish bridges from each other based upon their archival data, regardless of flow conditions.

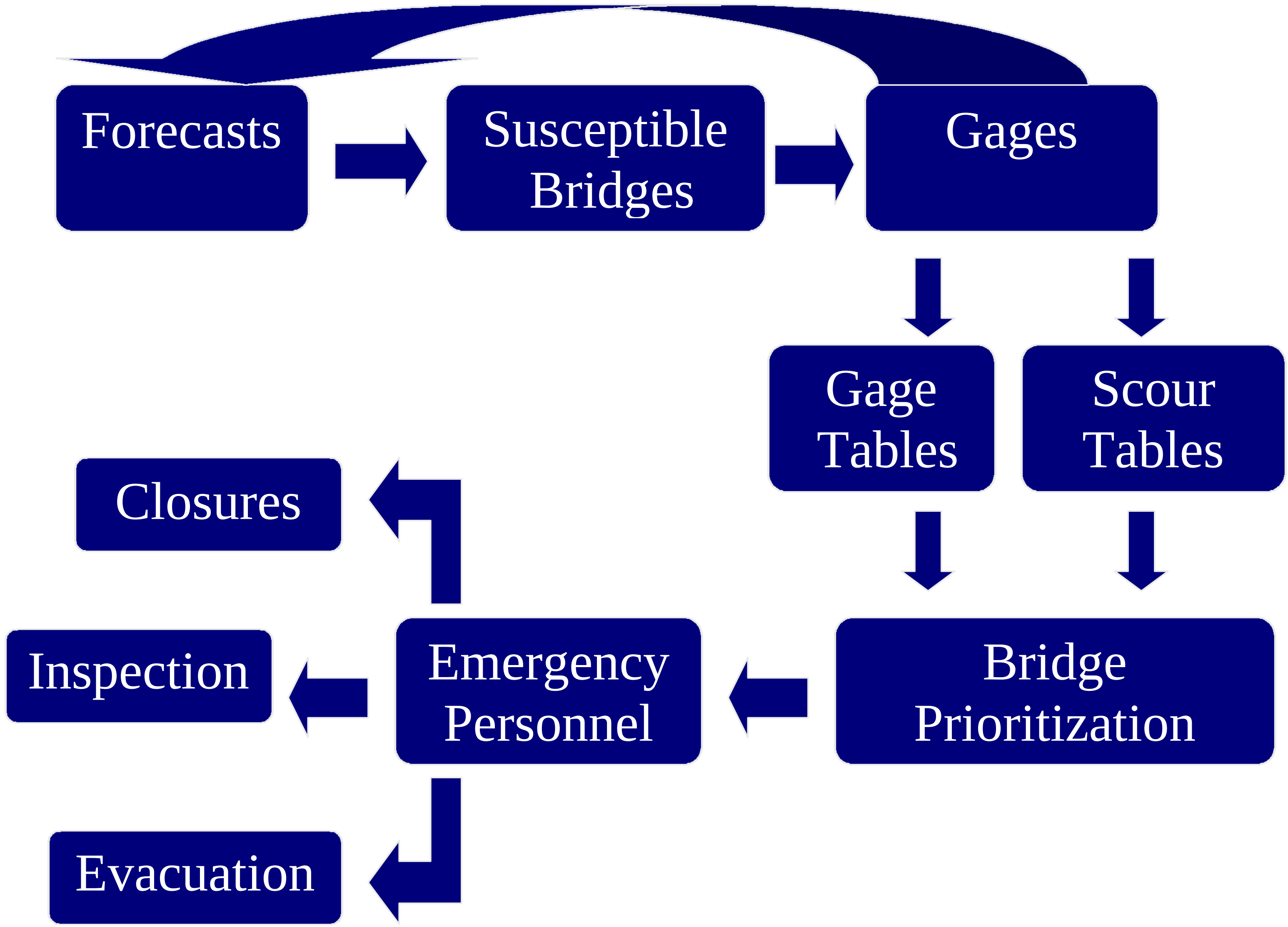

Figure 11. Flowchart of conceptual model for scour monitoring system

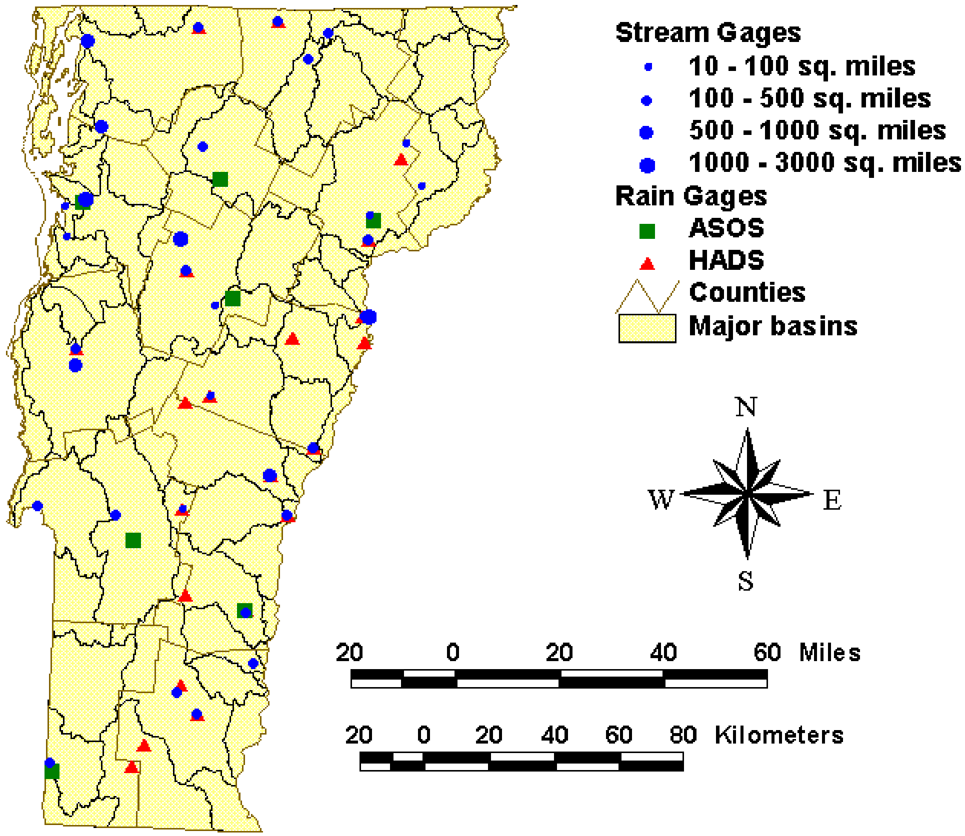

Figure 12. Automated stream and rain gages in VT

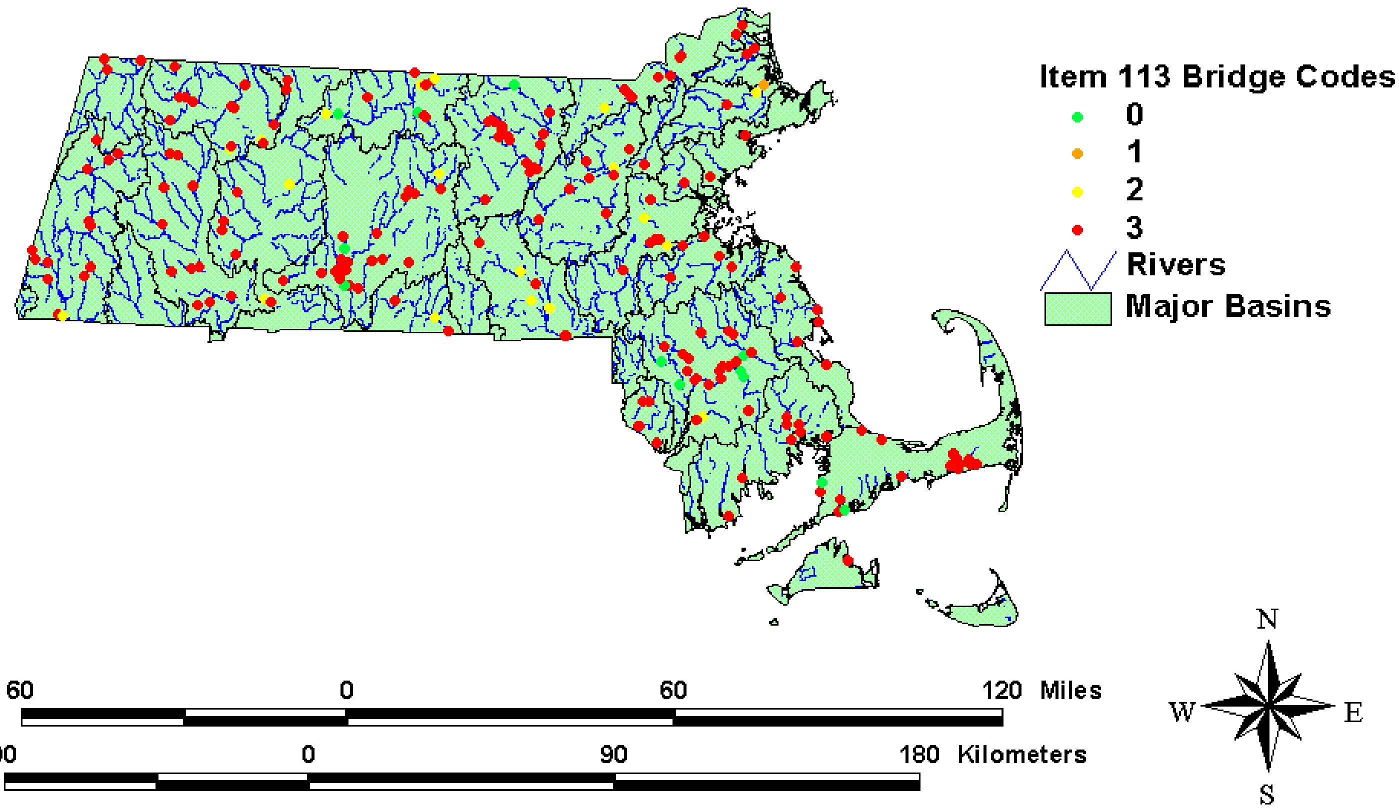

Figure 13. Multiple span, scour critical bridges in MA

These data may include bridge age, foundation type, average daily traffic, rip-rap placement (if any), bridge history, or stream history. These attributes, however, are selected for analysis at the user's discretion. Running multiple analyses allows the user to observe how querying various combinations of parameters alter the group of bridges identified. This procedure also serves as a preliminary method to determine how and where resources will be allocated for preventive measures.

The second step of the monitoring system takes advantage of the real-time data provided by stream and rain gages. While forecasts provide early predictions of weather conditions caused by a storm event, actual conditions can be verified through automated gages. The real-time gage data could be monitored either manually or downloaded periodically to a server where the information could be stored for comparison to historical gage data. The real-time gages thus provide insight into the path and severity of the storm as well as the hydrologic response of streams. This is particularly useful for prioritizing, whether it is for closure, evacuation, or inspection. It becomes important, therefore, to develop a scour monitoring system that utilizes real-time data.

A solution to this is the creation of "gage tables" and "scour tables", which, when used in conjunction with real-time gage data, allow the user to assess scour conditions at bridges in real-time. Instead of calculating bridge scour depths directly from the gage data as reported in real-time, depths could be estimated and catalogued in a database in advance based upon predicted discharges for several return periods. The predicted scour occurring in "real-time" would then be verified using real-time data from nearby gages. Scour depth estimates for bridges will be predetermined and stored in tabular format for a number of flood flow events along with the bridges' scour critical events. Real-time gage data for each gage near a bridge of interest will be referenced to its own "gage table" to ascertain the magnitude of the event. That event will then be referenced with the "scour table" to approximate the corresponding scour depth at the bridge and determine if the bridge is experiencing its scour critical event.

These "gage tables" and "scour tables" would be compiled from existing gage and bridge attributes already stored within the GIS. The intent of these "tables" is to summarize relevant scour attributes for presentation purposes. The user could look at these tables without pulling up extraneous attributes that overall may be important to the gage or bridge, but unimportant within the context of these "tables." These "tables" are of course subject to modification by DOTs.

"Gage tables" would be compiled from statistical analyses of historical gage data, which was explained earlier in Section 5.2.1.2, or from streamflow statistics made available by websites such as StreamStats. These data would be stored within each gage's attributes in the GIS. "Gage tables" should at least contain various flow return intervals and their corresponding discharge values. Real-time streamflow data from active gages could then be compared to their respective "gage tables" to assess the current magnitude of flow.

"Scour tables" can easily be generated for bridges that have already undergone a full Level 2 analysis in which scour depths were calculated for certain flow events. These "tables" should include various flow return intervals along with corresponding discharge values, predicted scour depths, and determination if the event is scour critical. Many bridges did not receive these intensive analyses, however, meaning scour depths and scour critical events would need to be calculated for hundreds of bridges. This task is made difficult by the cumbersome nature of existing analyses, especially since they require the use of hydraulic modeling programs. A tool like the rapid-estimation method, though, would allow DOTs to quickly and reasonably estimate scour depths at bridges for flow events of different recurrence intervals. Discharges at bridges could be estimated using a variety of methods as described earlier and the rapid-estimation method would again be used to generate hydraulic variables. Figure 14 presents an envelope curve for estimation of pier scour using the rapid-estimation method. Pier scour can be calculated using this figure along with knowledge of bridge geometry and hydraulic variables, both of which are determined in the field using this method. Even if scour depths are not calculated using the rapid-estimation method, the method can still be used to quickly estimate flow variables for input into different scour algorithms. Regardless of how "scour tables" are created, it is emphasized that if these tables are not available for all bridges, then the potential of this monitoring system is limited.

Figures 15 and 16 show a picture of a bridge (D06003) in Deerfield, MA and the bridge's spatial location with regard to nearby active real-time stream and rain gages. Table 5 provides a possible real-time scenario in which three stream gages near the bridge are used to assess current scour conditions at the structure. The bridge and three stream gages are represented by a brown square and red dots, respectively, in Figure 16. There are no formal guidelines for choosing which gages to monitor when evaluating flow conditions at a bridge, other than using engineering judgement. The gages in this example were selected by the researcher due to their proximity to the bridge and the fact that two of them are stationed on the same river as the bridge (one upstream and one downstream). The gages could also have been selected by including all that fall within a particular radius of the bridge. The gage tables were compiled from the actual results of an output file generated using the UMass approach. The "actual" flows and values within the scour table were fabricated for demonstrational purposes. "Actual" flows represent the reported flow conditions at the time the comparison is conducted.

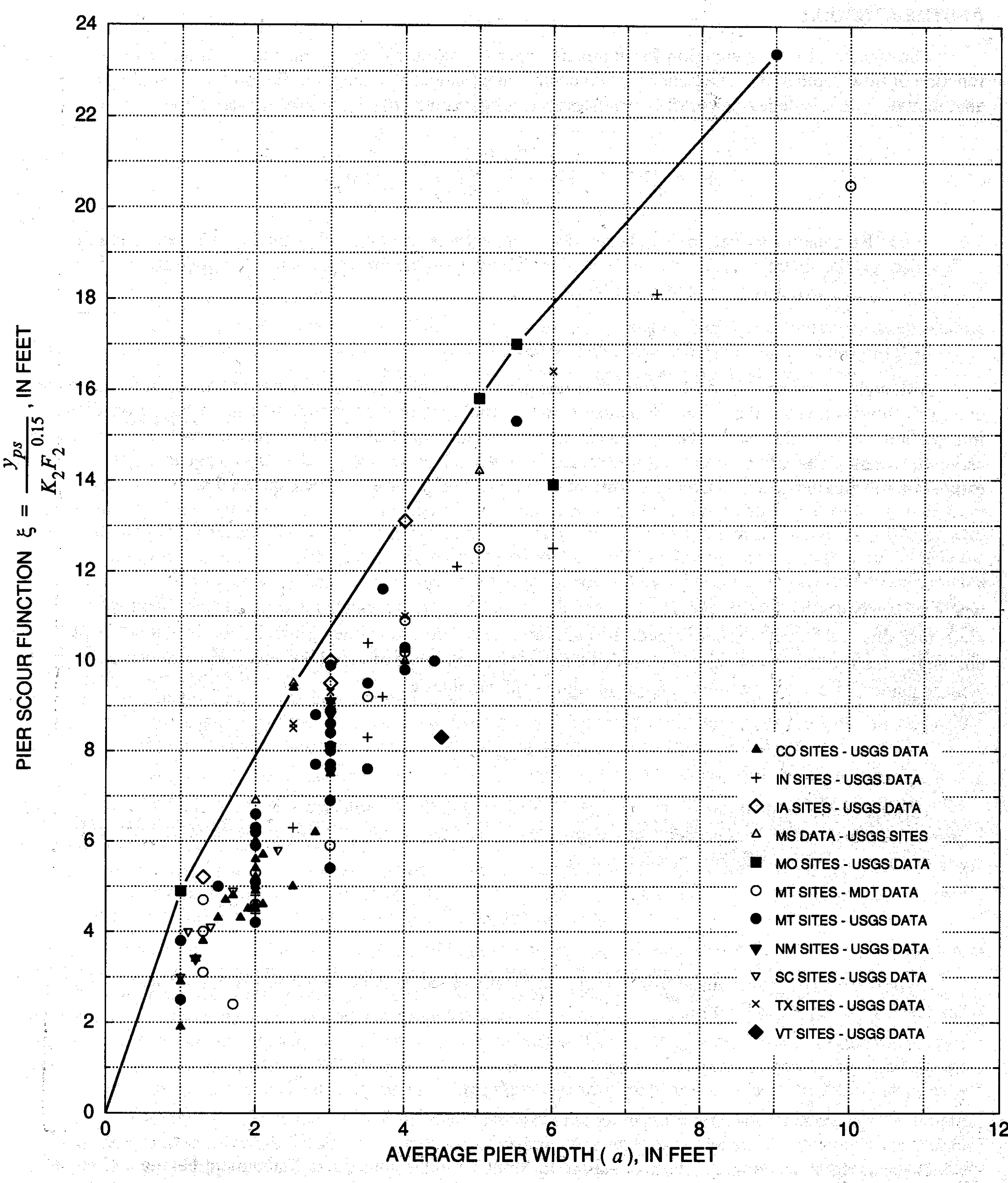

Figure 14. Envelope curve for estimation of pier scour (from Holnbeck and Parrett 1997)

Figure 15. Rte. 116 Bridge (D06003) in Deerfield, MA

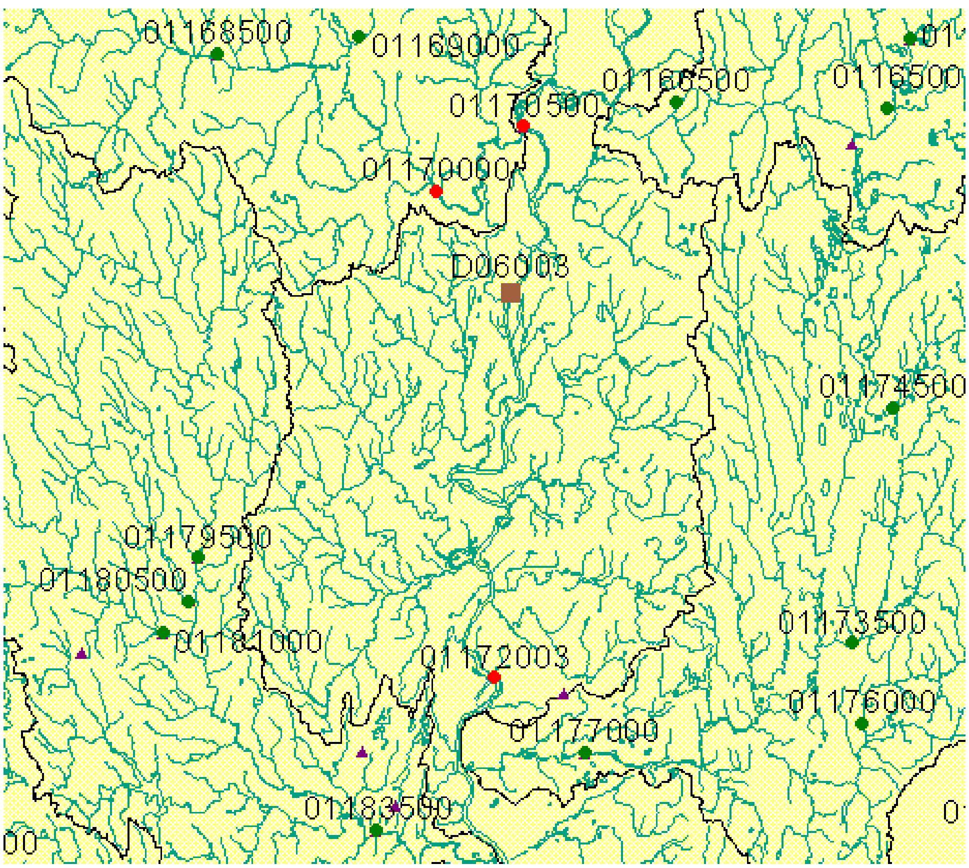

Figure 16. Gage infrastructure surrounding Rte. 116 bridge (D06003)

Table 5. Example use of gage tables to evaluate bridge scour conditions in real-time

Station ID: 01170000
Deerfield River
West Deerfield, MA

Event (yr)	Flow (cfs)
10	904
25	1207
50	1478
100	1795
Actual:	1421

Station ID: 01170500
Connecticut River
Montague City, MA

Event (yr)	Flow (cfs)
10	3694
25	4369
50	4892
100	5431
Actual:	4917

Station ID: 01172003
Connecticut River
Holyoke, MA

Event (yr)	Flow (cfs)
10	3496
25	3981
50	4307
100	4604
Actual:	4182

Bridge: D06003
Connecticut River
Deerfield, MA

Event (yr)	Flow (cfs)	Scour (ft)	Scour Crit?
10	3214	1.4	N
25	3599	2.7	N
50	3802	5.1	Y
100	4258	7.4	Y

If real-time stream gages are showing approximately 50-year flows upstream and downstream of Bridge D06003, it could be presumed that the bridge is also experiencing about a 50-year flow event. Since the scour depth for a 50-year flow has already been determined for this bridge, it is then predicted that the "real-time" scour depth at this bridge is approximately 5.1 feet. These estimated scour depths are useful because they could be used as markers that would help indicate the extent of scour and the scour susceptibility of the bridge. More importantly, if the 50-year flood event was determined as the scour critical event, then this would alert DOT personnel to closely monitor the bridge or take even more aggressive measures.

The versatility of the model is highlighted in this example. Scour depths and scour critical events for bridges have largely been calculated using the HEC-18 equations. Figure 17 presents a map of Connecticut bridges displayed according to their scour critical event determined using HEC-18. The user, though, may want to evaluate the bridges using another

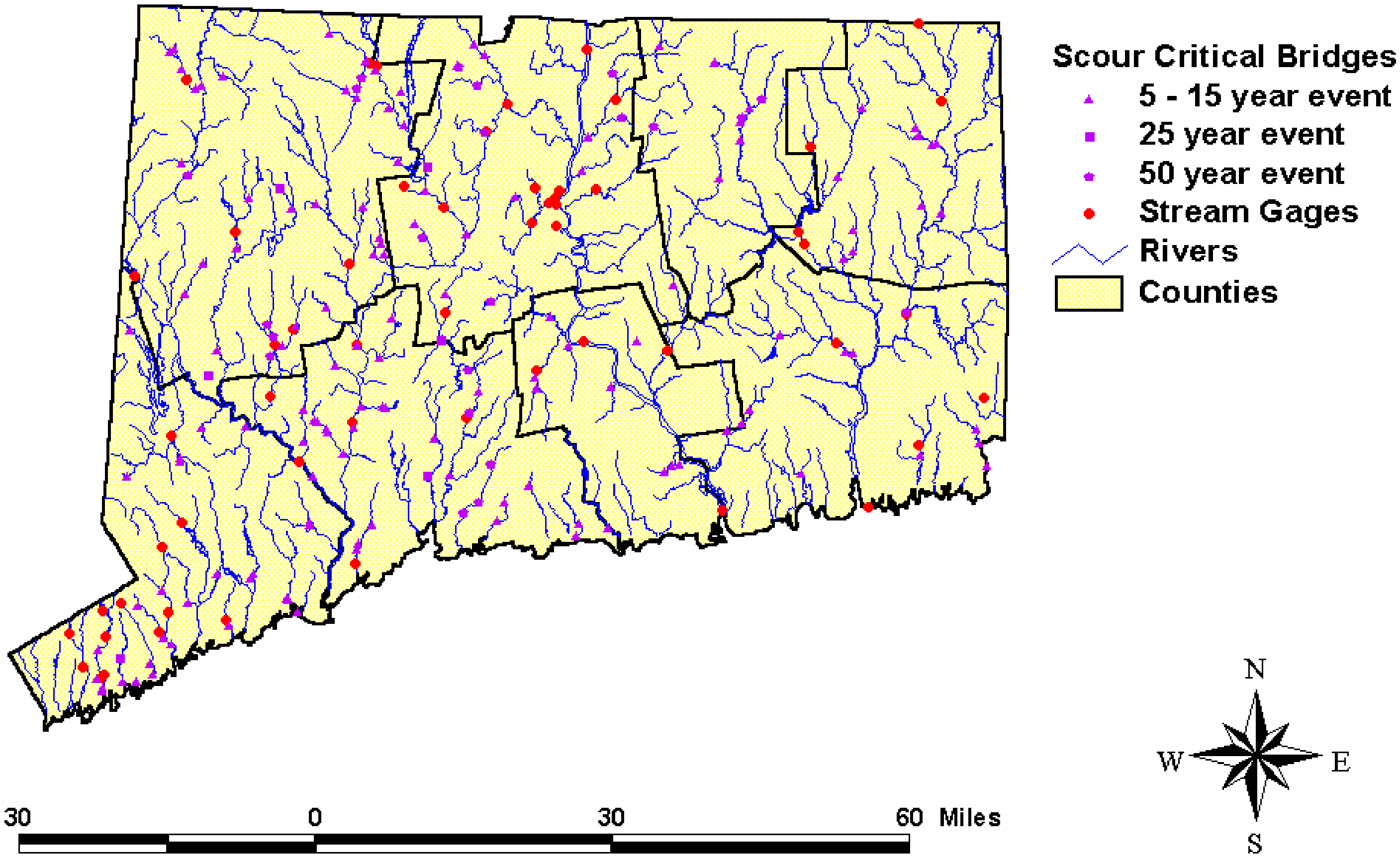

Figure 17. Scour critical bridges in CT (50-year event or smaller)

equation within the model manager. With equation parameters already stored in the bridge attributes (including flow variables), scour depths can be recalculated (and "scour tables" revised) using the new equation. Regardless of the scour equation, though, the scour depth that would cause factors of safety to fall below acceptable limits would have to be known for each structure. After applying the new equation, a new map would display the same bridges as the first, but the color or symbol scheme for the bridges would be different. The versatility of the model enables discretion to be used, permitting scour to be evaluated a number of different ways and allowing for a more complete analysis.

Analyses should not be limited to comparing bridges using the same equation, though, because equations may be better suited for application to certain bridges based upon the bridges' attributes. The NH USGS report demonstrated that the New York 1996 equation showed some promise as a predictive scour algorithm, but results were largely sensitive to decreases in bed material particle-size (Boehmler and Olimpio, p. 23, 2000). With this knowledge, the user could query all bridges with a minimum median bed particle size and evaluate them using the 1996 New York equation and then analyze the remaining bridges with a smaller median bed particle size using a different equation.

Engineering judgement should always be part of bridge scour analysis. Decisions should not be made solely using quantitative measures. The "gage tables" and "scour tables" are not intended to give exact scour conditions at any given time, but rather provide guidance as to the magnitude of the event and facilitate assessment of scour at bridges in real-time, particularly for prioritization purposes. The importance of engineering judgement is inherent in the SDSS, which allows the user to perform tasks at their discretion.

6.0 SUMMARY AND CONCLUSIONS

6.1 Summary

Bridge scour is a silent, yet viable threat to thousands of bridges across our nation's waterways. As the major cause of bridge failures, scour conditions must be vigilantly monitored at our nation's bridges. Efforts to assess and monitor scour conditions, however, are impeded by many problems, ranging from the nature of scour processes to lengthy, conservative scour analyses to involvement of several disciplines. It is difficult to predict the magnitude of scour during an event, let alone pinpoint the time at which scour-induced bridge failure is imminent. Scour conditions at a bridge can change over time, whether in the short-term as a result of stream dynamics or the long-term in response to stream evolution. Scour methodologies have been hampered by both conservative and time-intensive analyses. Detailed scour analyses, such as Level 2 scour analyses, can require significant time and resources, particularly if hydraulic modeling programs are used. Yet despite these rigorous, thorough analyses, predictive scour algorithms still have been unable to consistently provide accurate estimations of scour. As a result, efforts by DOTs to conduct full scour investigations for all bridges in their inventories have been hindered, leaving many bridges either unanalyzed or assigned temporary Item 113 codes.

An effective scour monitoring system is one that is flexible enough to cope with the dynamic nature of scour and requires the management and organization of data, people, and resources transcending several disciplines. The parts necessary for a monitoring system are available, but other than the ScourWatch™ product, little has been done to bring these parts together. Researchers, private firms, and government agencies alike have all seriously addressed the issue of scour over the past 15 years, but often from different angles. Much of their work to date has been limited to isolated aspects of scour. Scour monitoring instrumentation and technologies have been developed but have not been incorporated extensively into any real-time monitoring systems. Numerous scour methodologies have been developed to evaluate scour conditions at bridges, but less has been done to coordinate responses with emergency management agencies in dealing with scour-related problems. Sources of hydrological and meteorological data relevant to scour monitoring are ubiquitous on the Internet, but no one site provides all of the data. An effective, comprehensive monitoring system would draw upon all resources to assess and predict scour conditions, enabling DOTs and emergency agencies to identify, prepare, and respond to potentially destructive storm events.

In September 1999, a project was funded by the New England Transportation Consortium to research the creation of a scour monitoring system that would assist in the allocation of resources during potentially destructive flood events in New England. Several tasks were accomplished as a result of this project. Emphasis was placed upon the adoption and use of existing tools and infrastructure to accomplish these tasks. Potential components of the system were identified and reviewed, such as existing scour analyses, instrumentation, and automated gages. Internet websites were discussed in detail to familiarize DOTs with sources of available real-time weather products pertinent to the assessment of scour conditions. A GIS was created for each state to geographically integrate bridge, dam, and gage infrastructure in order to recognize the relation between them. Various scour models were presented along with methods for determining hydraulic input parameters to be entered into the models. The framework of a conceptual scour monitoring system was outlined and a potential scenario was used to illustrate the operation of the monitoring system for real-time warning and assessment of scour conditions.

The sum result of these tasks was the development of a prototype real-time scour monitoring and assessment tool that integrated web-based assessment tools, geographic information systems, and Internet resources.

6.2 Conclusions

The largest obstacle to a real-time scour monitoring system is a lack of communication between relevant disciplines. This problem mainly stems from the fact that several pertinent features of such a system were not originally developed for scour-related purposes. This lack of communication is clearly not the fault of the various agencies and parties brought together by this issue, as they each have their own objectives and responsibilities. Automated gage networks are operated and maintained by several agencies, but these agencies are less inclined to know about their counterparts' networks because each agency's gage network was implemented for a different purpose. Emergency personnel are familiar with floods in their discipline, but are not always aware of corresponding scour-related problems at bridges caused by these floods. As personnel and/or their products are assimilated under the context of a scour monitoring system, it is important that the parties understand not only their role and contributions to this system, but those of others as well. This forces everyone involved to become familiar with the monitoring system, exposing them to operations outside of their own and facilitating communication between people and agencies.

Several Internet sources of weather products, including real-time hydrologic and meteorological data, radar, and forecast products, were reviewed as part of this project. In the author's opinion, the best Internet sources of hydrological and meteorological data for scour-related purposes are as follows:

- Real-time stream data: USGS
- Real-time precipitation data: ADDS
- River, flood, and flash flood forecasting: NERFC
- All weather products: IWIN
- Local hydrological and meteorological data: Regional NWS office

These websites are listed based upon the author's personal findings and experiences. By no means should it be implied that these are the best and/or only websites of available weather-related information. It is suggested that readers of this paper review the websites listed, familiarize themselves with them, and determine the sites best suited for their needs.

A GIS is an enormously powerful and valuable tool to incorporate into any scour monitoring program. As previously discussed, the main strengths of a GIS are the ability to analyze, display, manipulate, store, and update geographically referenced information. A scour monitoring system requires such geographic referencing in order to observe the combined effects of individual system components. For instance, current scour data languish in DOT databases; fragmented gage data exist on several websites; and dam data are found on yet another website. A GIS enables the user to bring all relevant information together geographically in order to collectively analyze it, helping emergency and remediation decisions be made much more quickly and judiciously. These advantages can ultimately mitigate human and economic costs caused by storm events.

In terms of adequate real-time stream and rain gage coverages, there do not appear to be significant geographic "holes" in any New England state. Generally speaking, gage placement is slightly denser in populated areas than in rural areas. However, detailed GIS analyses that consider the geographic placement of features (e.g. dams, bridges, etc.) with respect to automated gages are strongly encouraged. Such analyses would better identify areas where data are lacking and help pinpoint the most advantageous locations for installation of additional automated gages. These analyses could also encourage DOTs to become proactive in decisions regarding gage networks, including the operation of current gages and the placement of future ones. Funding is often a major consideration in the operation of automated gages. A DOT may elect to continue funding for a gage slated to be discontinued by another agency or group if that gage serves an important role within its scour monitoring system. DOT input to future gage sites could include encouraging selection of a site near a group of bridges that have had a history of scour problems.

Several methods were presented for prediction of flood magnitudes at bridge sites. Channel width is considered one of the better predictors of flood magnitude, particularly for sites at higher elevations, although drainage area may be better suited for predicting flows at lower elevations where channel geometry is not as well-defined. It is noted that drainage area would be easier to obtain than channel width because drainage area could be determined using a GIS tool, whereas channel width would have to be measured in the field. The combination of drainage area and mean basin elevation has also demonstrated that it serves as a better predictor than drainage area alone. Although any method is valid, it is recommended that when state USGS offices complete their flood frequency projects, DOTs should use their regression equations for estimating flow at ungaged bridge sites. All USGS offices nationwide are working towards developing a web-based application similar to the StreamStats page provided by Massachusetts USGS office.

A web-based assessment tool is the perfect tool to address the variable, unpredictable nature of scour. The lack of a definitive scour equation demands that DOTs incorporate all scour models into their scour monitoring system. Although accepted scour algorithms such as those found in HEC-18 exist, it would be unwise to exclusively rely upon them given their conservative nature. The versatility of the SDSS gives DOTs the flexibility to assess and evaluate scour using multiple analyses. It also allows DOTs to easily manipulate and update components within the system such as database information or scour models. A web-based system also facilitates monitoring and assessment of real-time scour conditions and makes scour information universally available to all interested parties regardless of the platform and operating system being used.

6.3 Recommendations

The success of a scour monitoring system is contingent upon the accuracy and completeness of its data. DOTs must be diligent in maintaining and updating coverages and databases within their GIS that were developed as a component of this research. This is particularly true for automated stream gages, which are frequently added or removed from the network. Bridge databases should be periodically reviewed as conditions at bridges can change over time due to aging and flooding or bridge remediation. Updating GIS databases is not simply limited to filling in missing data, but may include the addition of entire data fields. Additional attributes, such as risk costs associated with bridge replacement, can only help with prioritization decisions. Failure to complete and revise information within the GIS will increase the likelihood of misinformed decisions, potentially leading to the misallocation of resources and further jeopardizing infrastructure and lives.

Future GIS work may include posting gage, bridge, and other statewide coverages on the Internet as well as adding peripheral features outside of a state's GIS coverages. DOTs may wish to make their coverages available for public use, whether posted on their own website or perhaps through their state GIS website. They may also want to incorporate additional features into their existing coverages that fall outside state lines, as all features within each state's GIS coverage, created for this project, currently fall within that state's boundary. Some gages, dams, and other features in Massachusetts, for example, are located outside of Connecticut's state boundary but have an impact on hydrologic conditions within Connecticut. It would be prudent to add these features to Connecticut's GIS to enhance Connecticut's ability to monitor a storm event.

Within the context of a scour monitoring system, it is recommended that "scour tables" and "gage tables" be generated for bridges and gages, respectively, and stored in the GIS to be used as guidelines for assessing real-time scour conditions. Using real-time data reported from automated gage networks, "gage tables" will enable the user to quickly reference current gage conditions with historical gage flows. Based upon the magnitude of current flows, scour conditions at nearby bridges can then be estimated from the "scour tables."

In order to incorporate the use of scour tables into a real-time scour monitoring system, it is important that DOTs finish their scour analyses for all bridges, if not just to finish assigning conclusive Item 113 codes to them. In theory, the only bridges that should be included in the GIS are those that are scour critical (Item 113 code of 0 to 3). Yet bridges with other Item 113 codes, such as 6 and U, were also included because the vulnerability of these structures to scour has not been ascertained. The bridges must be clearly defined as either scour critical or non-scour critical to enhance the system's capabilities; without definitive codes assigned to the bridges, the usefulness of the scour monitoring system is constrained and could result in poorer utilization of resources by DOTs. Money will have to be spent up front to complete analyses for all bridges, including the determination of foundations for bridges coded as U, but some of that money could later be recouped through better allocation of resources, whether for monitoring, remediation, or emergency purposes. The comparative scour analysis by CDOT and rapid-estimation method by the Montana USGS are two examples of abbreviated scour analyses that can help evaluate any remaining bridges.

The incorporation of "scour tables" is also contingent upon the development of a method to rapidly calculate scour depths that mirrors results typically found using more detailed analyses, as DOTs cannot afford to expend their energies conducting time-consuming scour analyses to create these tables. As discussed earlier, the rapid-estimation method is capable of fulfilling this requirement, generating scour estimates for a bridge site in a matter of hours rather than days. This method presents means for determining hydraulic variables such as flow depth and velocity without the use of hydraulic modeling programs. Even if the user elects not to employ this method to estimate scour depths, it can still be used to estimate hydraulic variables that can be entered into other scour algorithms. While this method must not supplant full detailed analyses, it has shown the ability to quickly distinguish between levels of scour susceptibility at bridges.

The comparative scour analysis will be a useful model to add to the Model Manager as another analytical tool, not only for Connecticut, but all New England states. Level 2 bridges in Connecticut were placed within the group of rated bridges for the comparative scour analysis. It would thus be advantageous to have a central, web-based database containing Level 2 bridge data for all of New England. A data clearinghouse could operate in this capacity as a secure, central location of scour data available to all parties. A site manager would be responsible for operation and maintenance of the clearinghouse. The proposed database of Level 2 bridges would provide a larger and even more representative group of rated bridges available for comparison via the comparative scour analysis. As discussed earlier, although it is not quantitative in nature (e.g. no scour depths are calculated), the comparative scour analysis is a tool that can be used to quickly assign Item 113 codes to bridges without the need for a full Level 2 analysis. Before this model is adopted, it is recommended that interested parties first contact the CDOT Hydraulic & Drainage Unit about the comparative scour analysis.

It is strongly recommended that instrumentation with real-time scour monitoring capabilities be further investigated. Instrumentation that uses wireless technology, such as the FM-CW reflectometry system, is well suited for implementation within a scour monitoring system. These devices can relay real-time bed scour data via radio or telephone telemetry to a monitoring system, similar to current data transmissions from automated real-time gages that are available on the Internet. Existing, in-place instrumentation such as “traffic cams” may also have some benefit within a scour monitoring system. Live, real-time camera feeds can transmit not only traffic views, but views of potential scour-inducing conditions at bridges such as the buildup of debris or ice jams around bridge piers and abutments.

While automated gage networks clearly are the driving force behind a scour monitoring system, it is recommended that cooperative weather observers be brought more directly in the fold as well, for both scour and non-scour related purposes. Many volunteers live in rural locations, where few automated gages are stationed, collecting valuable weather data for regional NWS offices. The precipitation data that they report would be relevant to a scour monitoring system, particularly during flash floods when warning time is minimal and real-time precipitation data are more important than real-time streamflow data. Maps of cooperative observer locations are already displayed on websites such as the NWS Burlington homepage and these locations could easily be added to existing state GIS coverages (“NWS Burlington”). Although the cooperative weather observers’ data reports are disseminated directly to the NWS, direct access to this data by DOTs and emergency personnel would be an asset. Providing cooperative observers with newer technology such as Internet access would allow their data to be reported much more quickly. With DOT funding, the NWS cooperative observer program could be expanded to include rainfall collection at sites near critical bridge sites, further assisting DOTs in determining scour conditions at bridges during storm events.

A DOT-specific cooperative observer network could be established to report scour relevant information such as river ice conditions and debris buildup around bridge piers and abutments in a more formal manner. These volunteers could be individuals or groups directly involved with scour monitoring or emergency response. General guidelines and procedures for reporting the information would need to be established. Such a network of observers could save DOTs considerable time and resources, particularly for bridge inspection teams, as well as alert officials much earlier to likely problems.

Creation of an online form to receive information from the public relevant to scour would also be useful to DOTs and emergency personnel, especially for unique circumstances. For example, the NWS Albany website has a hydrology link that brings the user to a river ice report ("River Ice Report"). Weather observers who observe river ice conditions fill out this report for online submission to the NWS Albany office. Although this report is not intended for scour purposes, given the exacerbated scour conditions under river ice, adoption and use of a similar online form by DOTs could be beneficial.

Commercial software packages such as ArcView GIS are available for analysis, dissemination, and presentation of data within a scour monitoring system. While ArcView 3.1 was a GIS tool chosen for this project, DOTs are strongly encouraged to purchase the latest GIS software, ArcView 8.1. The new software is available in Spring 2001 for personal computers running either Windows NT or Windows 2000. Enhancements associated with ArcView 8.1 include on-the-fly coordinate and datum projection, Microsoft's Visual Basic for Applications (VBA) for customization, and compatibility with Microsoft Office and other Windows applications ("ESRI News"). The software is also Internet-enabled, which offers the direct capability of linking to websites by clicking on map features (Trust 2001). This capability will be a valuable asset to a scour monitoring system because automated gages in the state GIS could be linked directly to their corresponding websites that report real-time conditions.

Action plans should be developed to assist DOTs and emergency agencies coordinate a swift, effective response to bridge emergencies caused by scour conditions. A Bridge Scour Action Plan (BSAP) was originally developed for scour critical bridges in Massachusetts to provide short-term and long-term guidance to protect bridges from damage and ensure public safety. Each bridge was to have had a BSAP that identified those officials responsible for monitoring or closing the bridge as well as information regarding the location the location and elevation of the foundations and the scour critical elevation ("Bridge Scour Summary Report"). These plans, however, never were implemented due to a lack of funds (Nardone 2000). This type of information will be more useful if stored in a GIS because contact and other critical information could easily be retrieved from a bridge's attributes if the monitoring system indicated that the bridge might be adversely affected by a storm.

In order to use the UMass approach to estimate discharge at a bridge, the area of the watershed draining into the point on the river where the bridge is located must be known. Some states may already have this attribute as part of their bridge data, but for states that do not, digital elevation models (DEMs) are capable of providing this information. DEMs reference vertical (Z) components (e.g. elevation) to areal components (X and Y coordinates) and can be overlain on a two-dimensional surface. These models are useful in determining the migration of water at any location and may be valuable coverages to add to the GIS at a later time.

DOTs should be aware of how gage locations can be better allocated within a scour monitoring system. The hydrologic response of streams is one thing to consider regarding placement of automated gages. Localized, flash flooding is probably the single greatest scour threat for DOTs because it is difficult to predict and occurs with very little warning. At higher elevations, peak stream discharges tend to occur more quickly after a precipitation event than at lower elevations. Knowledge of real-time streamflow data would be preferable in these situations, but given the rapid hydrologic response of streams in these locations, rain gage data will be more useful because of the earlier warning, particularly from either ASOS sites or cooperative observers.

The paper by Dingman and Palaia (1999) indirectly emphasized the importance of not discontinuing stream gages as well as the capabilities of some predictive empirical discharge models. As gage record length increases, time-sampling errors associated with gages decrease. At a 100-year flow event, it was found that error associated with an empirical model using bankfull width was only about 20 percent more than the error associated with a gage of approximately 20 years of record length. While there are many things to consider in terms of gage placement within a scour monitoring system, DOTs should recognize the value of a long-running gage, especially if a gage important to them is about to be discontinued.

Despite the stream gage data that are available in real-time, it is difficult for typical users to appreciate the implication of the data before them. Gages provide information such as stage and discharge, but clearly the magnitudes of these values largely depend on the size of the river basins. CSM, or cubic feet per second per square mile, provides a better sense of streamflow conditions because flows are normalized with respect to drainage area, thus eliminating the effect of drainage basin area. CSM is calculated as follows:

$$\text{CSM Values} = Q/\,DA \qquad (10)$$

where

Q = discharge for x-year flow event, in cubic feet per second
DA = drainage area into gage, in square miles

While other conditions also affect streamflow, such as topography, antecedent moisture conditions, land use, and porosity, advantages of this parameter include general assessment of overall river conditions, regional hydrologic awareness, identification of problems with the data, and estimation of flow in an ungaged basin or at a non-telemetered gage ("CSM").

The NERFC compiled a list of CSM values and qualitative basin characteristics for 76 river gaging sites throughout the Northeast. All CSM values were estimated assuming bankfull river conditions, which are conditions at flood stage, just prior to the water overtopping the flood banks. The table reveals that qualitative basin characteristics are largely correlated with CSM values. The highest values corresponded to basins that are small, hilly, urban, or rocky. Conversely, the lowest values originated from basins that are large, flat, and spongy ("CSM").

Future work may include the development of "scour functions" or "gage functions" as opposed to "tables", for which scour depths and streamflows at gages can be calculated for any magnitude event, not just for selected events. Additional work can also investigate multi-variable regression equations for prediction of flow since there presently are not enough data available on the USGS websites to perform such regressions. Methods to make better estimations of discharge from precipitation data would be useful in order to predict flows at bridges more accurately, thus giving DOTs and emergency agencies earlier warnings. The implementation of a real-time scour monitoring system based upon the recommendations made above would improve identification of and response to scour critical bridges jeopardized by a potentially destructive storm event.

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Appendix A – Item 113 Codes

(From the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges)

Item 113 - Scour Critical Bridges 1 digit

Use a single-digit code as indicated below to identify the current status of the bridge regarding its vulnerability to scour. Scour analyses shall be made by hydraulic/geotechnical/structural engineers. Details on conducting a scour analysis are included in the FHWA Technical Advisory 5140.23 titled, "Evaluating Scour at Bridges." Whenever a rating factor of 4 or below is determined for this item, the rating factor for Item 60 - Substructure may need to be revised to reflect the severity of actual scour and resultant damage to the bridge. A scour critical bridge is one with abutment or pier foundations which are rated as unstable due to (1) observed scour at the bridge site or (2) a scour potential as determined from a scour evaluation study.

Code Description

N Bridge not over waterway.

U Bridge with "unknown" foundation that has not been evaluated for scour. Since risk cannot be determined, flag for monitoring during flood events and, if appropriate, closure.

T Bridge over "tidal" waters that has not been evaluated for scour, but considered low risk. Bridge will be monitored with regular inspection cycle and with appropriate underwater inspections. ("Unknown" foundations in "tidal" waters should be coded U.)

9 Bridge foundations (including piles) on dry land well above flood water elevations.

8 Bridge foundations determined to be stable for assessed or calculated scour conditions; calculated scour is above top of footing. (Example A)

7 Countermeasures have been installed to correct a previously existing problem with scour. Bridge is no longer scour critical.

6 Scour calculation/evaluation has not been made. (Use only to describe case where bridge has not yet been evaluated for scour potential.)

5 Bridge foundations determined to be stable for calculated scour conditions; scour within limits of footing or piles. (Example B)

4 Bridge foundations determined to be stable for calculated scour conditions; field review indicates action is required to protect exposed foundations from effects of additional erosion and corrosion.

3 Bridge is scour critical; bridge foundations determined to be unstable for calculated scour conditions:
- Scour within limits of footing or piles. (Example B)
- Scour below spread-footing base or pile tips. (Example C)

(codes continued on the next page)

(From the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges - Continued)

Item 113 - Scour Critical Bridges (cont'd)

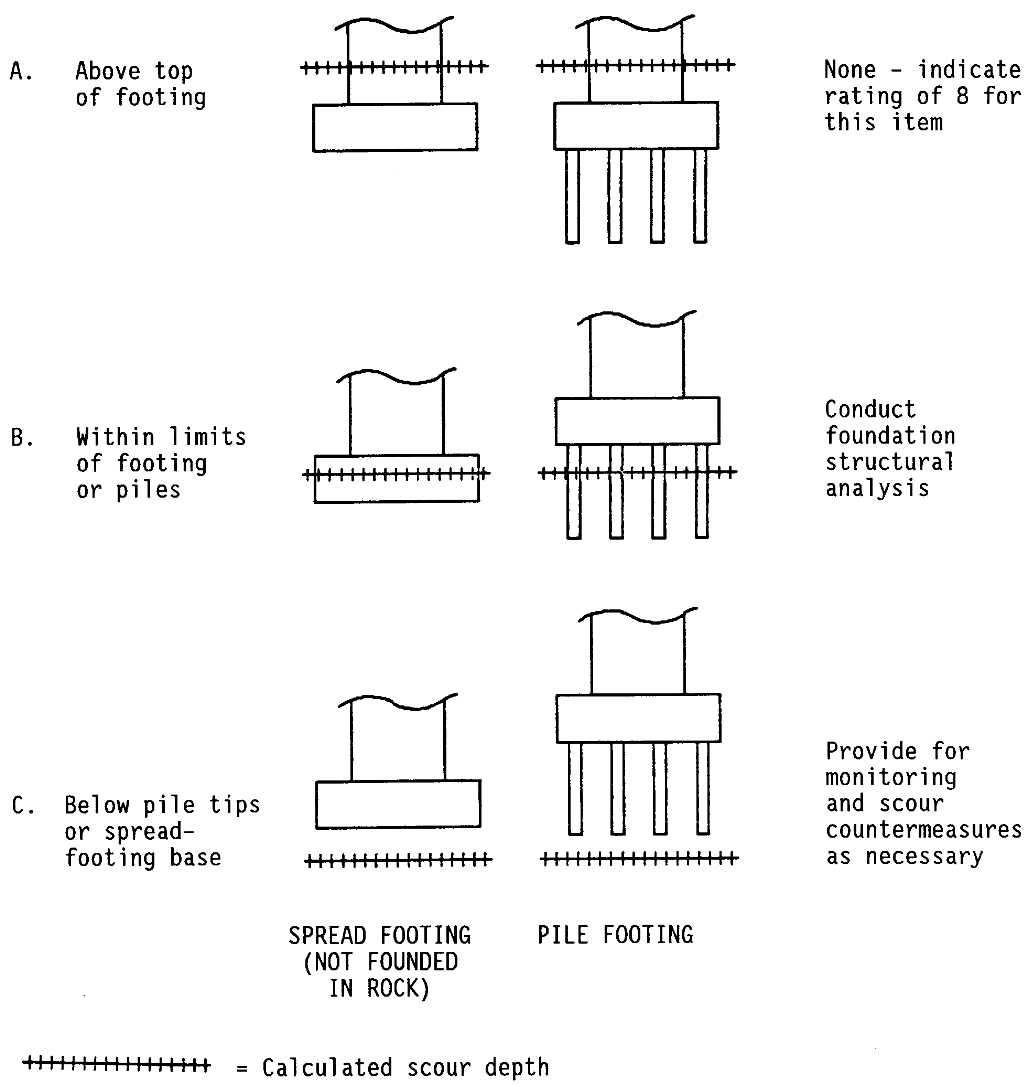
Code Description

2 Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations. Immediate action is required to provide scour countermeasures.

1 Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic.

0 Bridge is scour critical. Bridge has failed and is closed to traffic.

EXAMPLES: *CALCULATED SCOUR DEPTH* *ACTION NEEDED*



Appendix B – Additional discharge – drainage area plots for MA gages at other flow return intervals

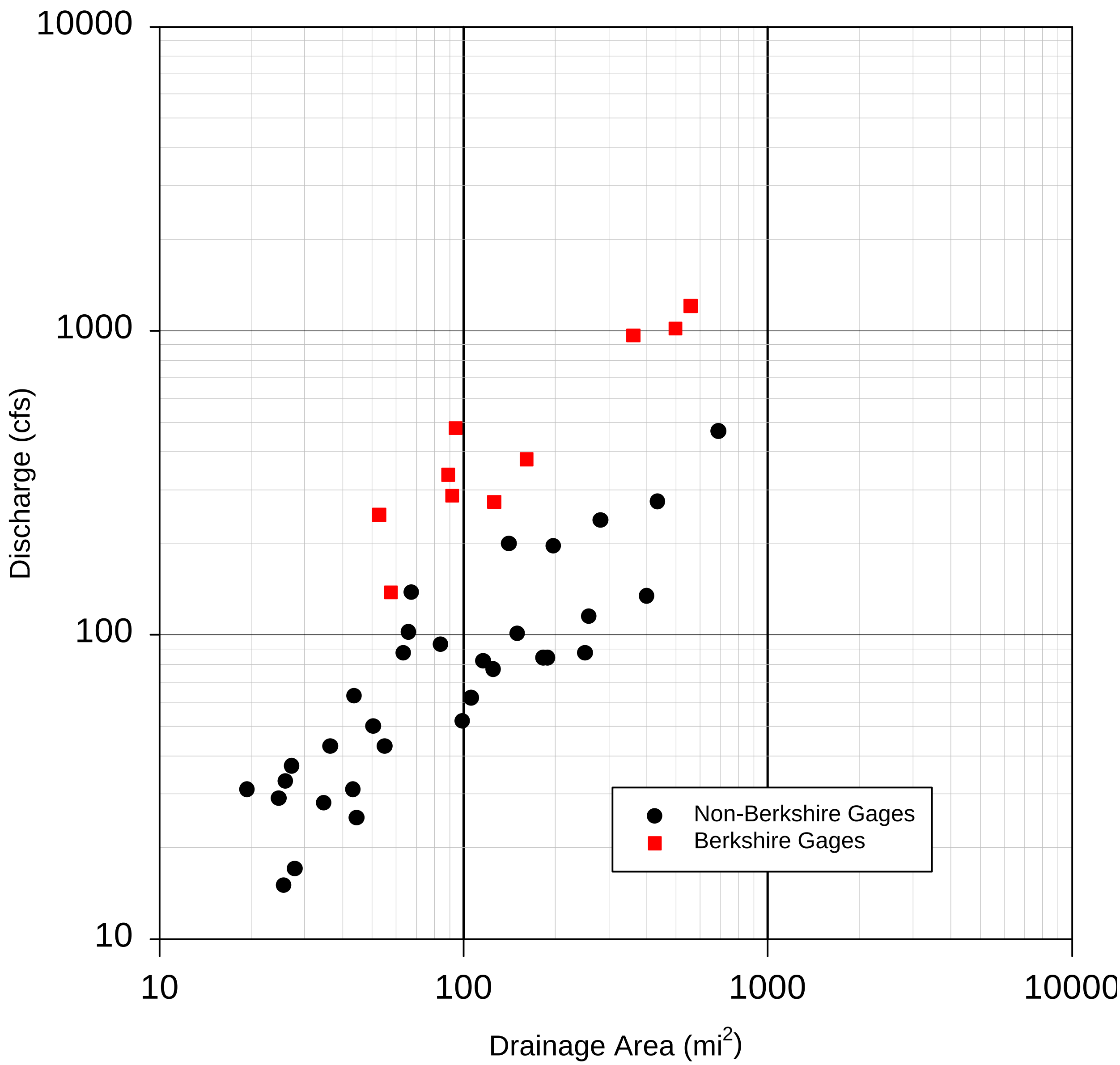


Figure B-1. Discharge vs. drainage area for active real-time stream gages in MA
(25-year return period)

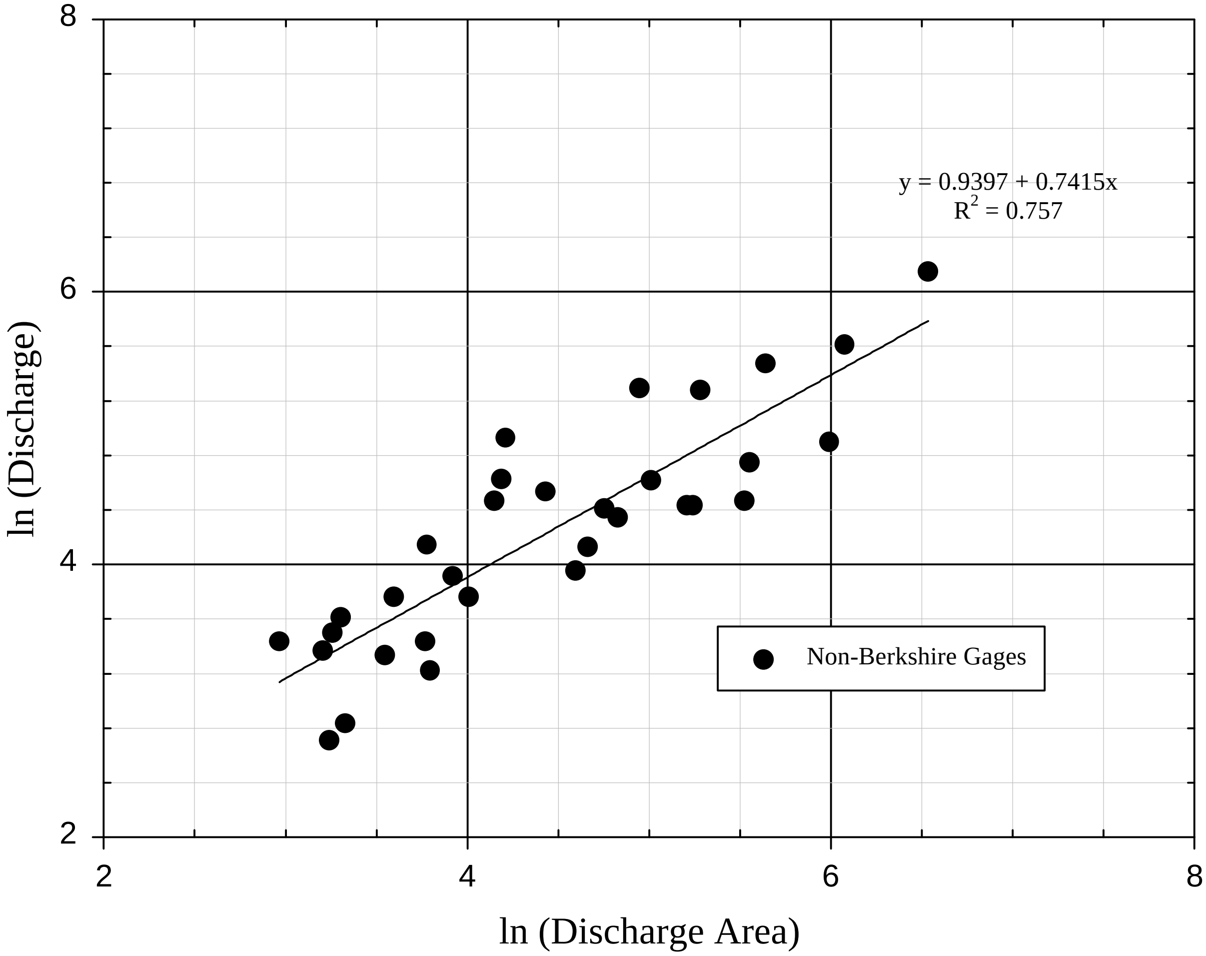


Figure B-2. Linear regression of natural log transformation of discharge and drainage area for non-Berkshire gages (25-year return period)

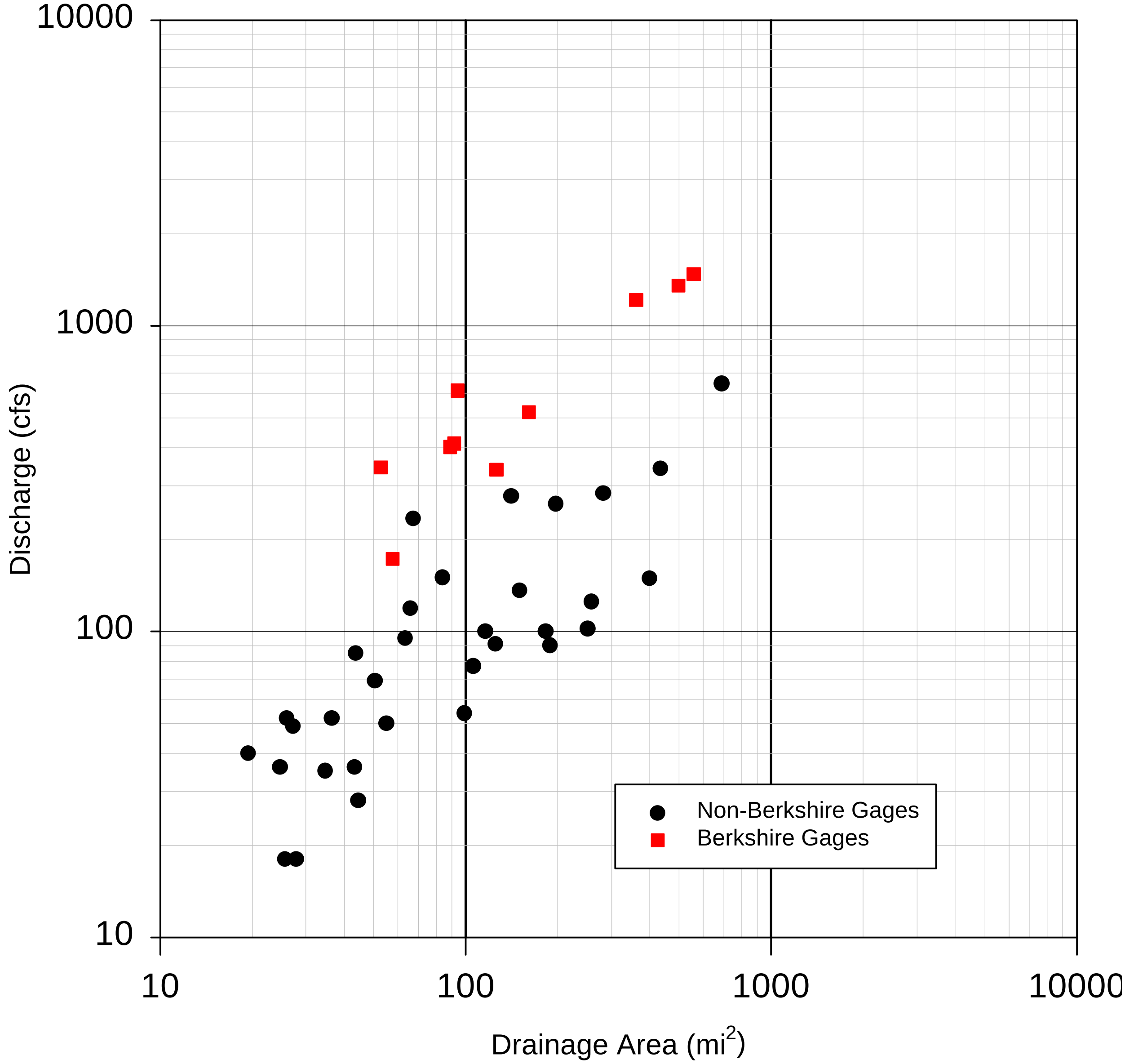


Figure B-3. Discharge vs. drainage area for active real-time stream gages in MA
(50-year return period)

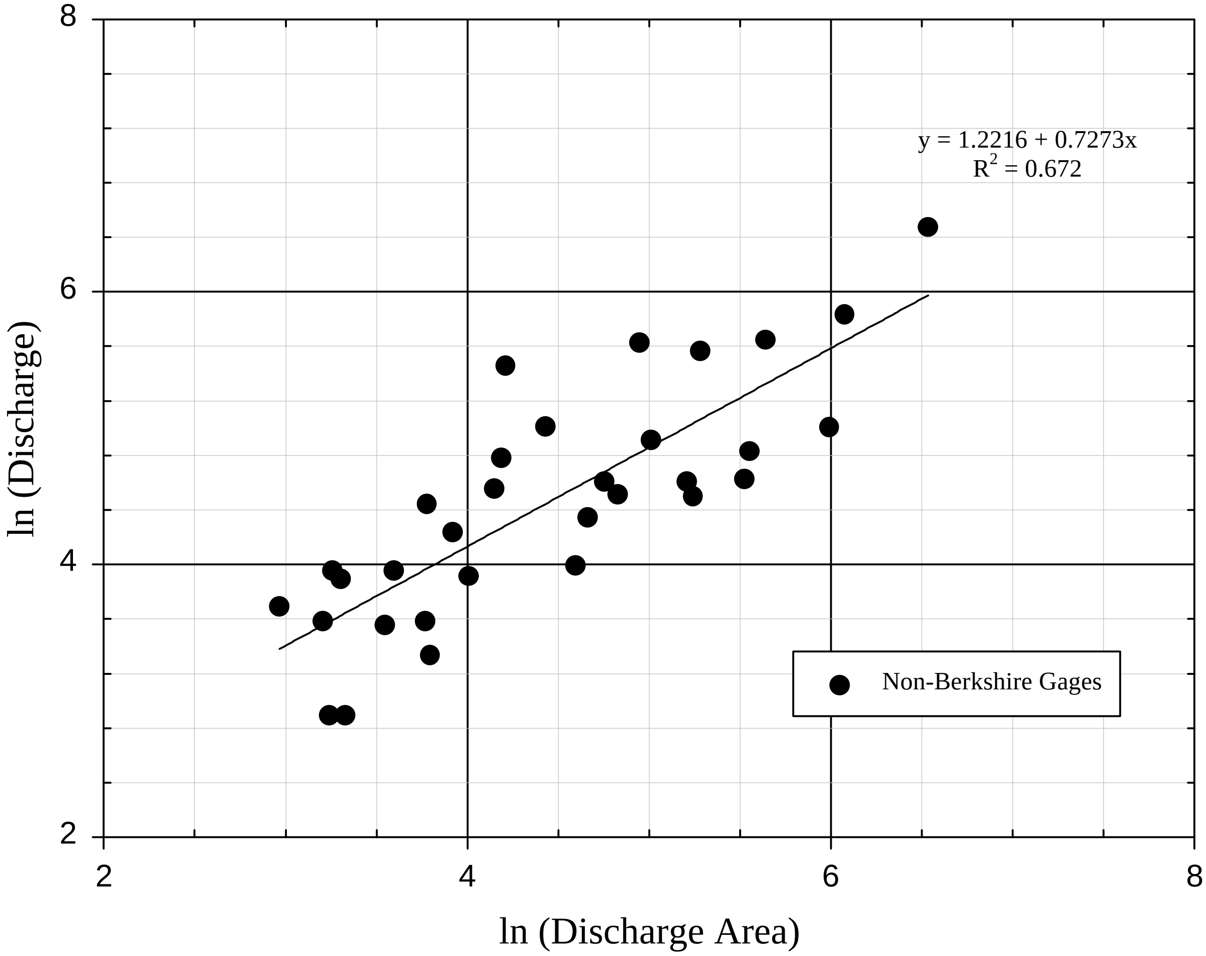


Figure B-4. Linear regression of natural log transformation of discharge and drainage area for non-Berkshire gages (50-year return period)

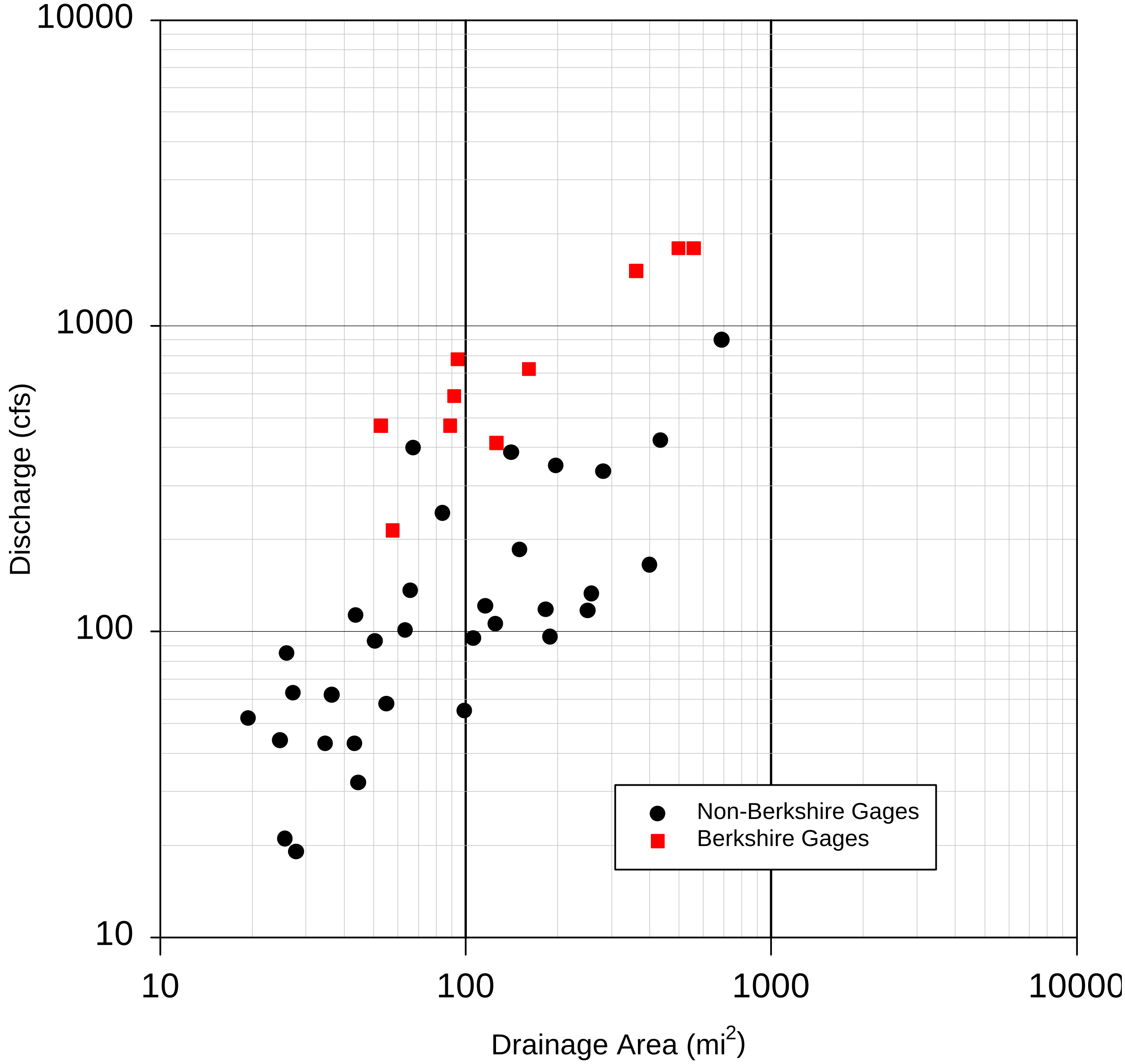


Figure B-5. Discharge vs. drainage area for active real-time stream gages in MA (100-year return period)

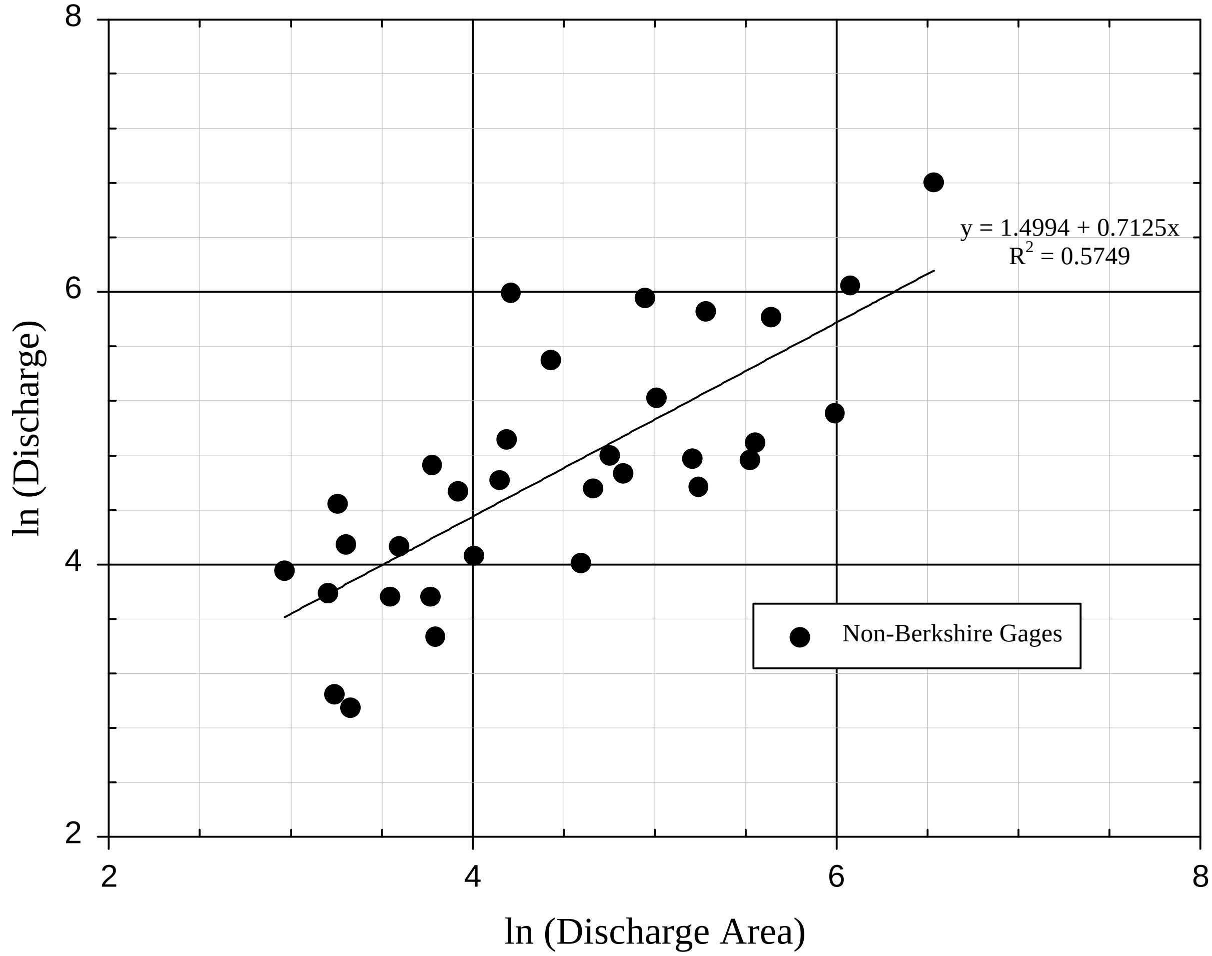


Figure B-6. Linear regression of natural log transformation of discharge and drainage area for non-Berkshire gages (100-year return period)