Report No. K-TRAN: KU-14-1 ▪ FINAL REPORT ▪ September 2016

Developing a Bridge Scour Warning System

C. Bryan Young, Ph.D., P.E.

The University of Kansas

AD ASTRA PER ASPERA
Kansas
Department of Transportation

1 Report No. K-TRAN: KU-14-1	**2 Government Accession No.**	**3 Recipient Catalog No.**
4 Title and Subtitle Developing a Bridge Scour Warning System		**5 Report Date** September 2016 **6 Performing Organization Code**
7 Author(s) C. Bryan Young, Ph.D., P.E.		**7 Performing Organization Report No.**
9 Performing Organization Name and Address The University of Kansas Department of Civil, Environmental and Architectural Engineering 1530 West 15th St Lawrence, Kansas 66045-7609		**10 Work Unit No. (TRAIS)** **11 Contract or Grant No.** C1978
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Topeka, Kansas 66611-1195		**13 Type of Report and Period Covered** Final Report October 2013–March 2016 **14 Sponsoring Agency Code** RE-0629-01
15 Supplementary Notes For more information write to address in block 9.		

Flooding and scour can be major threats to the integrity of bridges. During flood events, scour at bridge piers and abutments can undermine the foundations of the bridge, causing significant damage or even total structure loss. Because scour occurs below the water level during a large flood event, it can be difficult to detect and may go unnoticed unless a targeted inspection is performed.

The Kansas Department of Transportation (KDOT) is required by federal mandate to establish and maintain a bridge scour plan of action for all scour-critical bridges in the state. A plan of action can include the implementation of scour countermeasures to protect and stabilize a bridge and/or scour monitoring. Bridge scour monitoring presents multiple challenges for bridge owners, including state Departments of Transportation (DOTs).

This research project surveyed in situ and ex situ monitoring options with particular attention on warning system options in the public domain. In situ monitoring can include portable and/or fixed devices for detecting bridge scour. Ex situ monitoring implies a statewide system that issues scour alerts to trigger bridge closures and/or inspections based on hydrologic conditions (rainfall and/or streamflow).

A systematic statewide system would be preferable for monitoring scour-capable events at bridges across the state. KDOT could leverage existing United States Geological Survey (USGS) and National Weather Service (NWS) tools to monitor scour-critical bridges or pursue a vendor to offer a turn-key solution. For critical locations, additional measures could be implemented at specific sites to offer more information or a higher level of monitoring.

17 Key Words Bridge Scour, Flooding, Scour Monitoring, In Situ Monitoring, Ex Situ Monitoring, Warning System		**18 Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov.	
19 Security Classification (of this report) Unclassified	**20 Security Classification (of this page)** Unclassified	**21 No. of pages** 50	**22 Price**

Form DOT F 1700.7 (8-72)

This page intentionally left blank.

Developing a Bridge Scour Warning System

Final Report

Prepared by

C. Bryan Young, Ph.D., P.E.

The University of Kansas

A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

and

THE UNIVERSITY OF KANSAS
LAWRENCE, KANSAS

September 2016

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

The authors and the state of Kansas do not endorse products or manufacturers. Trade and manufacturers names appear herein solely because they are considered essential to the object of this report.

This information is available in alternative accessible formats. To obtain an alternative format, contact the Office of Public Affairs, Kansas Department of Transportation, 700 SW Harrison, 2nd Floor – West Wing, Topeka, Kansas 66603-3745 or phone (785) 296-3585 (Voice) (TDD).

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or the policies of the state of Kansas. This report does not constitute a standard, specification or regulation.

Abstract

Flooding and scour can be major threats to the integrity of bridges. During flood events, scour at bridge piers and abutments can undermine the foundations of the bridge, causing significant damage or even total structure loss. Because scour occurs below the water level during a large flood event, it can be difficult to detect and may go unnoticed unless a targeted inspection is performed.

The Kansas Department of Transportation (KDOT) is required by federal mandate to establish and maintain a bridge scour plan of action for all scour-critical bridges in the state. A plan of action can include the implementation of scour countermeasures to protect and stabilize a bridge and/or scour monitoring. Bridge scour monitoring presents multiple challenges for bridge owners, including state Departments of Transportation (DOTs).

This research project surveyed in situ and ex situ monitoring options with particular attention on warning system options in the public domain. In situ monitoring can include portable and/or fixed devices for detecting bridge scour. Ex situ monitoring implies a statewide system that issues scour alerts to trigger bridge closures and/or inspections based on hydrologic conditions (rainfall and/or streamflow).

A systematic statewide system would be preferable for monitoring scour-capable events at bridges across the state. KDOT could leverage existing United States Geological Survey (USGS) and National Weather Service (NWS) tools to monitor scour-critical bridges or pursue a vendor to offer a turn-key solution. For critical locations, additional measures could be implemented at specific sites to offer more information or a higher level of monitoring.

Acknowledgments

This work was supported by the Kansas Department of Transportation (KDOT). Mike Orth, P.E., of KDOT served as the project monitor. The author sincerely appreciates Mr. Orth's contributions and guidance.

Table of Contents

List of Tables

List of Figures

This page intentionally left blank.

Chapter 1: Introduction

1.1 Background

Flooding and scour can be major threats to the integrity of bridges. During flood events, scour at bridge piers and abutments can undermine the foundations of the bridge, causing significant damage or even total structure loss. Because scour occurs below the water level, it can be difficult to detect and may go unnoticed unless a targeted inspection is performed. Scour due to flooding is the number one cause of bridge failures in the United States (Arneson, Zevenbergen, Lagasse, & Clopper, 2012).

Bridge scour can cause damage and/or failure, leading to (worst case) the loss of life, as well as economic losses including repair costs, replacement costs, and/or traffic delays due to prolonged route closures (possibly critical routes for schools, hospitals, or others). The cost of a statewide bridge scour monitoring system could be offset many times over by the failure of one bridge.

The Kansas Department of Transportation (KDOT) is required by federal mandate to establish a bridge scour plan of action for all scour-critical bridges in the state. The bridge scour plan of action (POA) is a useful tool in helping to identify bridges deemed most susceptible to scour during a flood event. POAs generally contain information for monitoring specific sites during an event and when to close the bridge to traffic to protect the public. Other information in the POA includes site geology and other characteristics, as well as hydraulic information. Figure 1.1 shows the locations of scour-critical bridges. KDOT has classified 323 bridges as scour critical at the time of this report. Site monitoring can be time-consuming during a large event.

The Federal Highway Administration (FHWA) has produced three Hydraulic Engineering Circulars (HECs) that are designed to be used in concert for bridge scour assessment. These HECs provide guidance on how to identify scour-critical bridges, evaluate countermeasure control options, and implement countermeasures and inspection protocols:

HEC-20, “Stream Stability at Highway Structures” (Lagasse, Zevenbergen, Spitz, & Arneson, 2012): HEC-20 provides background on stream stability and geomorphic assessment of bridges, and is used to identify bridges that are susceptible to scour.

HEC-18, “Evaluating Scour at Bridges” (Arneson et al., 2012): HEC-18 provides methods for hydrologic, hydraulic, and scour analysis to determine whether scour countermeasures are necessary and/or feasible.

HEC-23, “Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance” (Lagasse et al., 2009)*:* HEC-23 covers scour countermeasure options and bridge monitoring techniques.

It is recommended for highway engineers involved with bridge scour analyses to become familiar with HEC-20, HEC-18, and HEC-23.

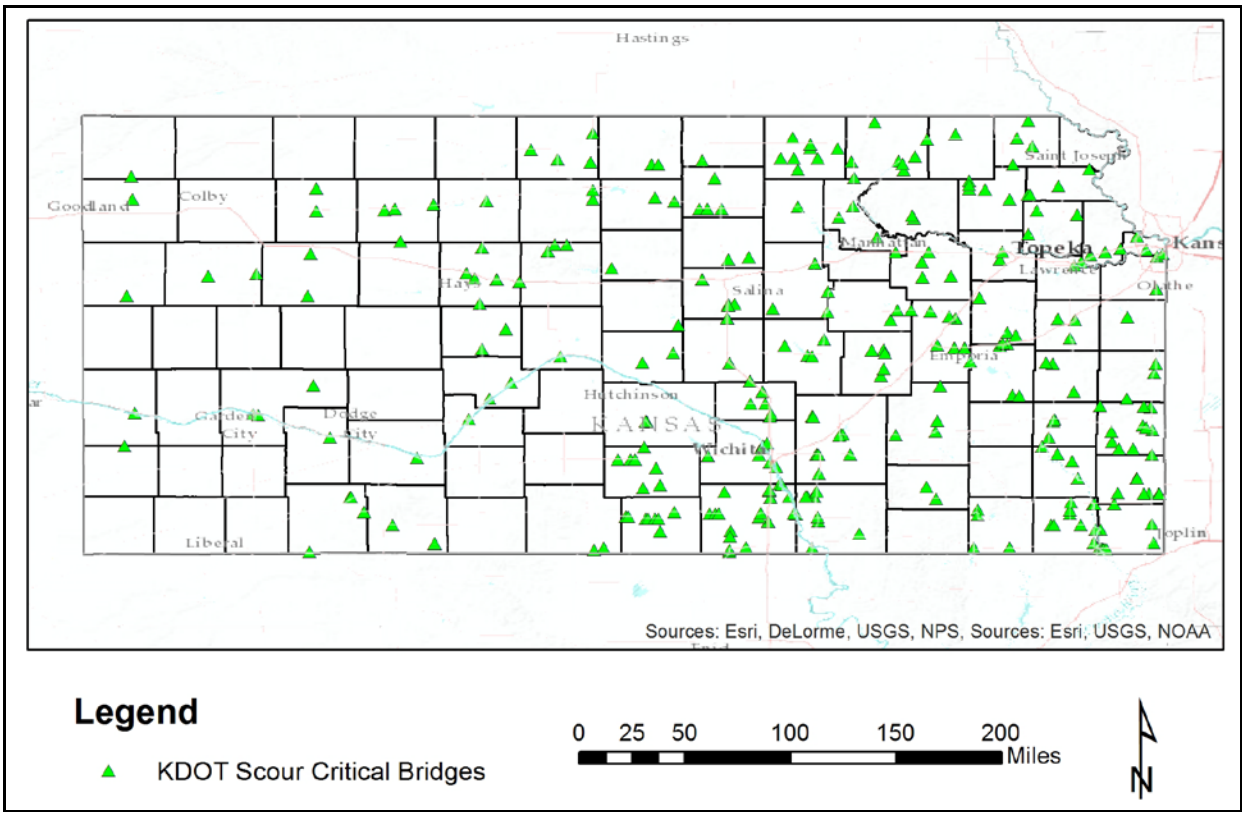

Figure 1.1: Locations of Scour-Critical Bridges in the State of Kansas

1.2 Bridge Scour Review

HEC-18 provides an excellent detailed overview of bridge scour conditions and considerations, including guidelines for estimating the depth of scour as a function of flow conditions, channel dimensions, streambed characteristics, and bridge geometry (Arneson et al., 2012). This section provides a brief overview of the factors contributing to scour and the methods for estimation of scour depth.

Erosion of bed material occurs when the bed shear stress (τ_b) reaches the critical shear stress required to mobilize bed material (τ_c). Bed shear stress is a function of flow velocity, fluid density, and bed friction. The critical shear stress required to move material is a function of material cohesiveness, particle density, and the particle size of the bed material.

Scour occurs at bridges due to a combination of factors, including bed degradation, contraction scour, and local scour. Total scour is the sum of these three components. While contraction and local scour are functions of site conditions and bridge geometry, bed degradation is subject to the overall geomorphology of the stream.

Streambed degradation can occur due to a wide range of influences, including changes to the stream channel or hydrologic and/or sediment transport characteristics of the stream. Degradation is common in areas across Kansas due to historical stream straightening, degradation downstream of reservoirs, and head-cutting due to degradation somewhere downstream. Bed degradation can be a long-term process or can occur rapidly during the course of a large flood event. Estimation of future degradation can be accomplished through extrapolation of long-term records from bridge inspections or gaging stations, geomorphological analysis (as presented in HEC-20), and/or computer modeling.

The depth of contraction and/or local scour is affected by whether the site is subject to clear-water or live-bed scour. Clear-water scour occurs when bed material has not been mobilized in the stream channel upstream of the bridge. Clear-water scour will continue as long as the bed shear stress due to flow exceeds the critical shear stress needed to mobilize the bed material. Live-bed scour occurs when bed material in the upstream channel has been mobilized. Live-bed scour will continue as long as the quantity of bed material leaving the bridge site is greater than the quantity of bed material entering the bridge opening. In both clear-water and live-bed scour, scour leads to an increase in the area of flow, which decreases flow velocity and shear stress. Changes in bed material may slow or halt further scour if, for example, larger particles are exposed by the removal of fine-grained sediment.

Contraction scour occurs at bridges due to the reduction in cross-sectional area of the channel at the bridge (see Figure 1.2). The smaller cross-sectional area results in acceleration of flow into the bridge opening and higher velocities. The higher velocities in the contracted area increase the bed shear stress, resulting in movement of more material and larger particles than at the upstream stream segment. Chapter 6 in HEC-18 presents equations for estimating contraction scour. Estimation of contraction scour depth depends on flow characteristics, whether clear-water or live-bed scour is occurring, bridge geometry, bridge location (main bridge or relief bridge), and channel characteristics including bed material.

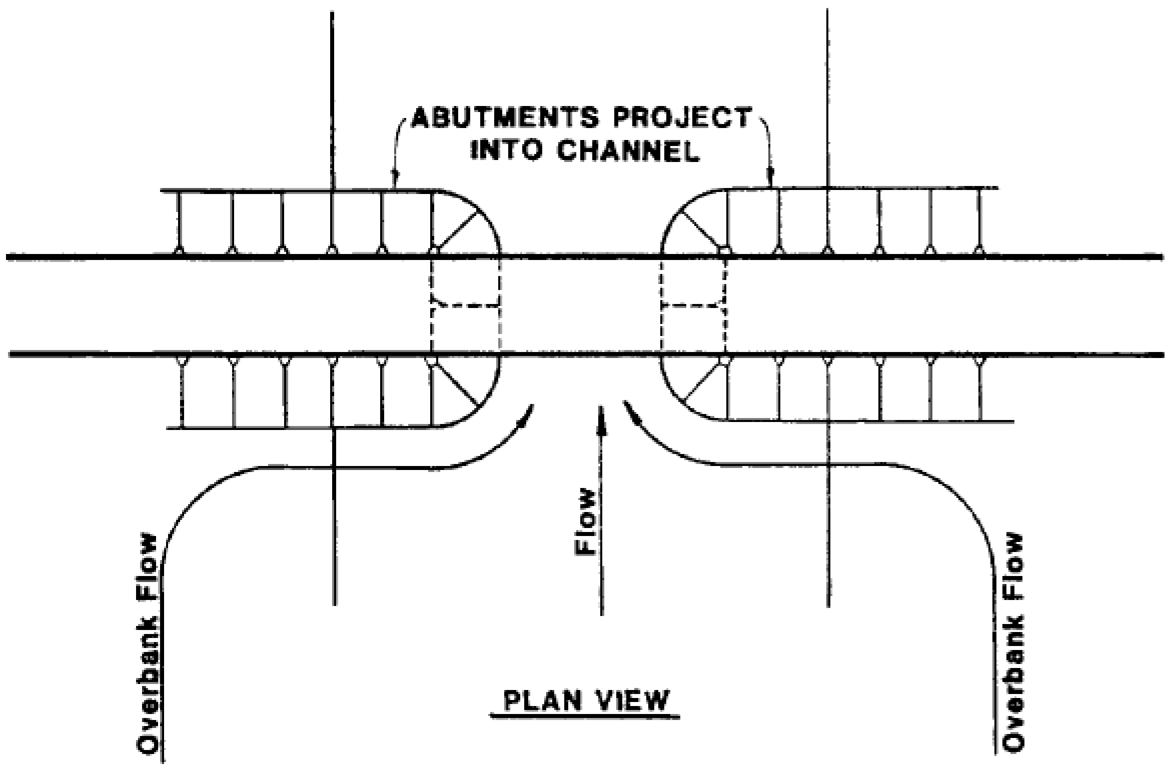

Figure 1.2: Contraction Scour Caused by Reduction of Cross-Section
Source: Arneson et al. (2012)

Local scour is caused by the acceleration of flow around objects or obstructions in the flow path such as bridge piers or abutments. Flow accelerates around the obstruction and causes vortices that contribute to scour. Chapter 7 of HEC-18 covers the estimation of pier scour depth. Chapter 8 of HEC-18 covers the estimation of local scour depth at abutments.

Figure 1.3 illustrates the hydraulic factors at play in pier scour, including downflow at the face of the obstruction and vortices. The depth of pier scour is affected by multiple factors, including individual pier geometry and proximity of neighboring piers; flow angle of attack, depth, and velocity; and bed characteristics (which can be affected by history of scour at a location). In addition, debris or ice can collect at the bridge pier during a flood event, effectively changing the geometry of the pier and altering scour characteristics.

Figure 1.4 shows the hydrodynamic factors that contribute to local scour at abutments. The acceleration of flow around the abutment and the formation of vortices along the embankment contribute to scour hole development that can undermine the abutment. Chapter 8 of HEC-18 presents three equations for estimating scour hole depth for abutments. The depth of the scour hole depends on the shape and length of the abutment; flow characteristics including the angle of attack, velocity, and depth of flow; and soil characteristics.

Detailed scour analysis following HEC-18 for a particular bridge site can indicate the flow rate of concern for that location. Scour warning alerts can be triggered based on observed scour at the bridge site, observed or predicted flow rates approaching the flow rate of concern, or observed or predicted rainfall intensities capable of producing the flow rate of concern.

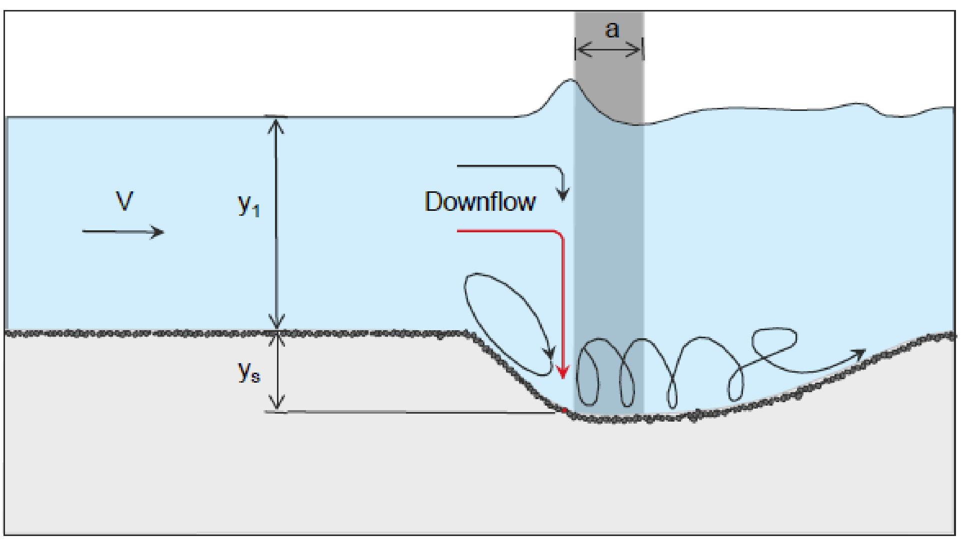

Figure 1.3: Bridge Pier Scour
Source: Arneson et al. (2012)

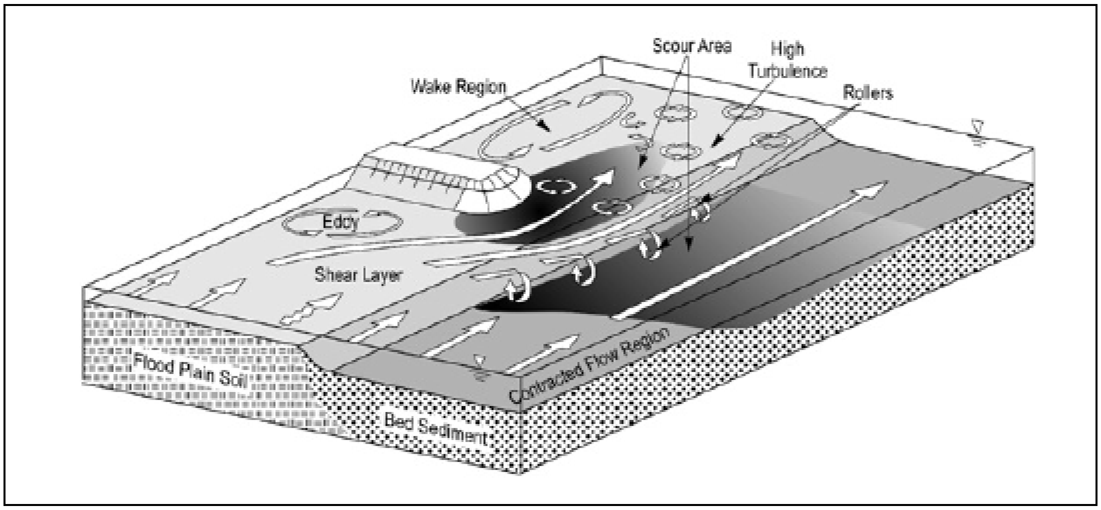

Figure 1.4: Local Scour at Abutments
Source: Arneson et al. (2012)

1.3 Overview

The objective of this study was to explore options for a statewide scour and/or flood warning system for bridges in Kansas. This report provides an overview of in situ and ex situ bridge monitoring options. Chapter 2 describes portable and fixed options for in situ monitoring. Chapter 3 describes approaches for ex situ monitoring, including services provided by the National Weather Service (NWS) and the United States Geological Survey (USGS). Conclusions and recommendations are given in Chapter 4.

Chapter 2: Options for Bridge Scour In Situ Monitoring

2.1 Background on In Situ Monitoring

In situ monitoring entails physical measurement or observation of scour conditions at the bridge location. A wide variety of alternatives exist for in situ monitoring, and advances in technology continue to improve existing techniques and provide additional options. In situ monitoring can be performed using portable or fixed monitoring devices or some combination of the two.

2.2 Portable Monitoring Devices

Portable monitoring devices are suitable for bridge locations which do not require continuous measurement. Portable monitoring can be used to monitor streambed degradation or migration over time or soon after large flood events to evaluate the extent of scour. The advantage of portable instrumentation is the ability to provide measurements at multiple locations at any particular bridge site and, of course, the ability to survey multiple bridge sites. The disadvantages of portable devices include the lack of continuous monitoring, the necessary manpower associated with conducting surveys, and the fact that bridge scour holes frequently fill quickly after the peak of the flood hydrograph and the worst scour condition during a flood may be missed.

Portable devices are generally divided into three categories:

1. Physical probes: Weights, rods, or poles which are used to physically measure the elevation of the streambed.
2. Sonar devices: Sonar technology is used to remotely sense the depth of the river bed. Sonar devices can range from the ordinary fish finder to survey-grade devices.
3. Geophysical instrumentation: Seismic instruments or ground-penetrating radar (GPR) can be used to investigate the streambed. The primary advantage of geophysical investigation is that these instruments are sometimes capable of identifying the extent of scour holes that have filled in.

Chapter 9 of HEC-23 provides a brief overview of portable monitoring devices, including deployment techniques (Lagasse et al., 2009). Figure 2.1 (Table 9.4 from HEC-23) shows the approximate cost of instrumentation for physical probes, sonar, traditional survey, and GPS survey equipment.

	Instrument Cost	Cost for Installation or Use	Operation Cost
Physical Probes	< $500	varies by use	varies, minimum 2-person crew for safety
Portable Sonar	fish-finder - $500; survey grade - $15,000 +/-	varies by use	varies, minimum 2-person crew for safety
Traditional land survey	$10,000 +/-	varies	2-3 person crew
GPS	$5,000 for submeter accuracy, $20,000 + for centimeter	varies	1-2 person crew

Figure 2.1: Cost of Portable Instruments for Scour Measurement
Source: Lagasse et al. (2009)

2.3 Fixed Monitoring Devices

Fixed monitoring devices are usually mounted at the bridge abutment or pier of concern, and are used to monitor conditions continuously or are designed to trigger an alert if scour conditions occur. Fixed monitoring devices can be linked to a central server via radio, cellular, or satellite telemetry, and can be used to issue alerts in conjunction with weather and flow data. There are a number of fixed monitoring devices and technological innovation continues to provide more options and improve the reliability of existing instruments:

1. Sounding rods: Manual or mechanical probes used to measure the elevation of the streambed. Sounding rods can be mounted at a bridge location such that they rest on the streambed and drop as a scour hole develops. Figure 2.2 illustrates a fixed installation of a sounding rod at a bridge pier.

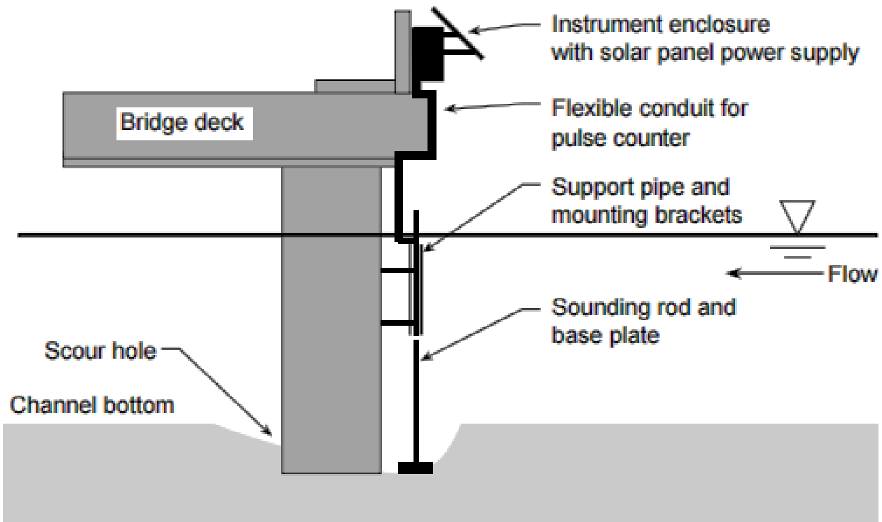

Figure 2.2: Sounding Rod Installation at Bridge Pier
Source: Haas, Weissmann, and Groll (1999)

2. Magnetic sliding collars: Consist of a buried rod with a sliding collar that falls as the streambed is scoured out from underneath. Electronics record and report the depth of the magnetic collar. Figure 2.3 illustrates a magnetic sliding collar installed at a bridge pier.

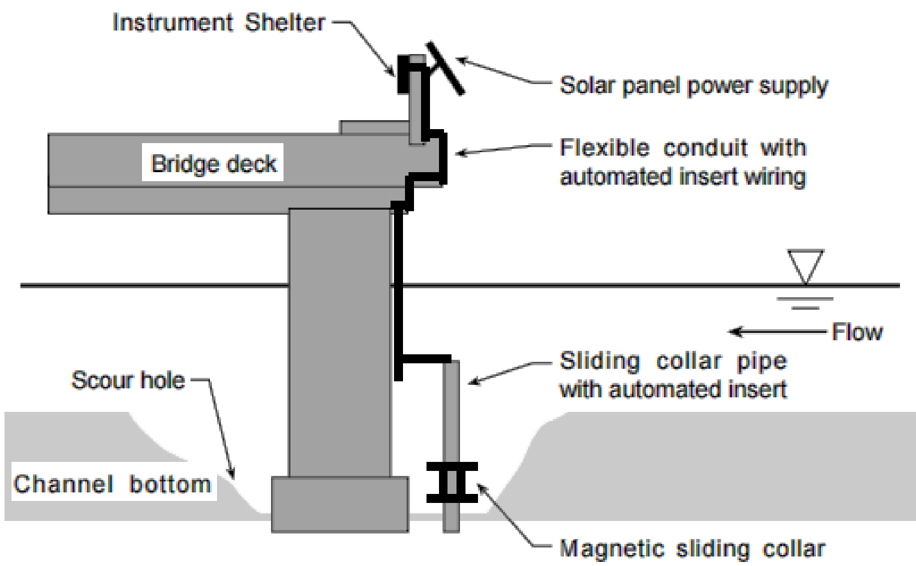

Figure 2.3: Sliding Magnetic Collar Installed at Bridge Pier
Source: Haas et al. (1999); adapted from NCHRP Report 21-3

3. Time-domain reflectometers (TDR): Use parallel pipes buried in the streambed. An electromagnetic pulse is sent through the pipes; sensors detect a change in the material characteristics between the pipes. Figure 2.4 shows a TDR probe with a sample signal on the left. The signal changes abruptly at the riverbed, allowing constant monitoring of the depth of scour.

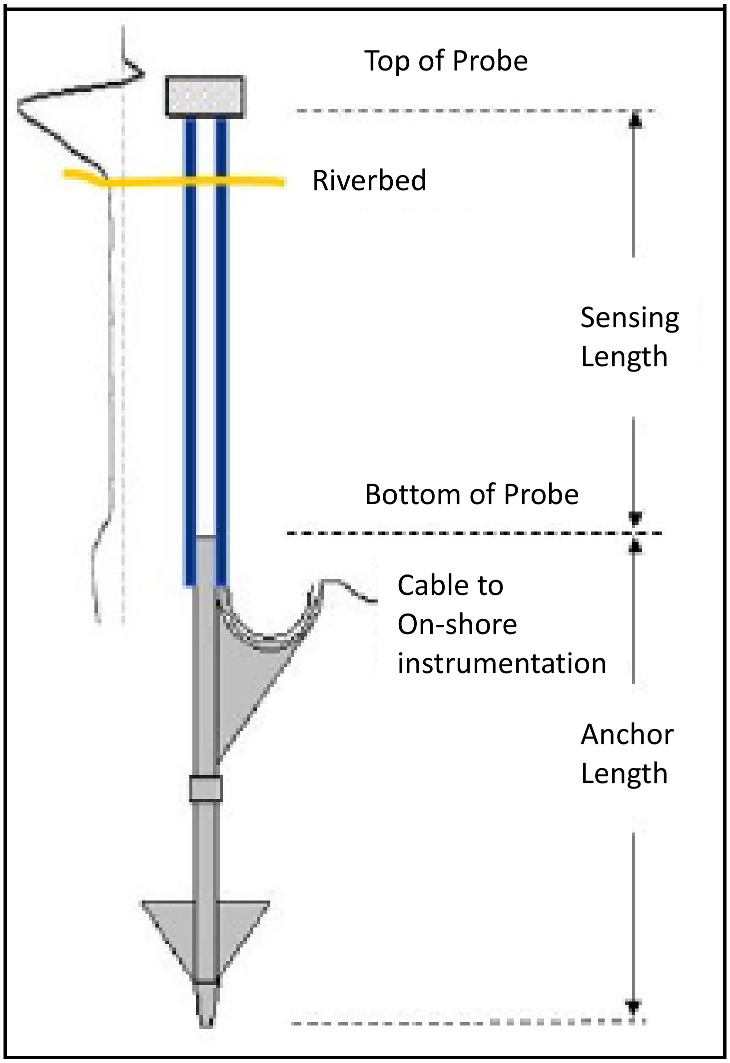

Figure 2.4: Time-Domain Reflectometer
Adapted from Lagasse et al. (2009)

4. Fathometers (sonar depth finders): Can be mounted on a bridge and used to monitor changes in bed elevation. KDOT had a fathometer mounted at one bridge location but encountered frequent problems with icing during winter months. Figure 2.5 shows a bridge-mounted fathometer.

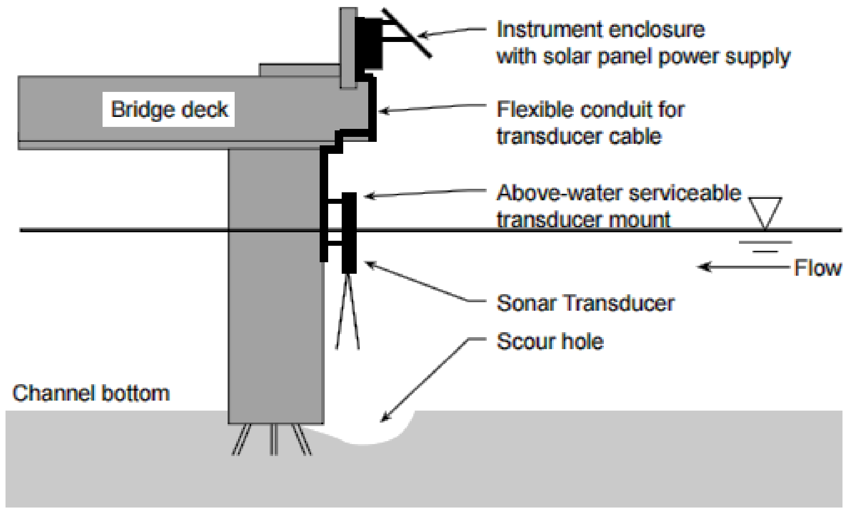

Figure 2.5: Fathometer or Sonar Device at Bridge Pier
Source: Haas et al. (1999); adapted from NCHRP Report 21-3

5. Buried sensors (float-out devices): Floating transmitters are buried in the streambed. When these devices float out and pass a receiver downstream, the receiver triggers an alert. Figure 2.6 shows a schematic of a float-out device. The antenna for detecting the float-out device can be mounted on the bridge or at a location downstream of the area of concern.

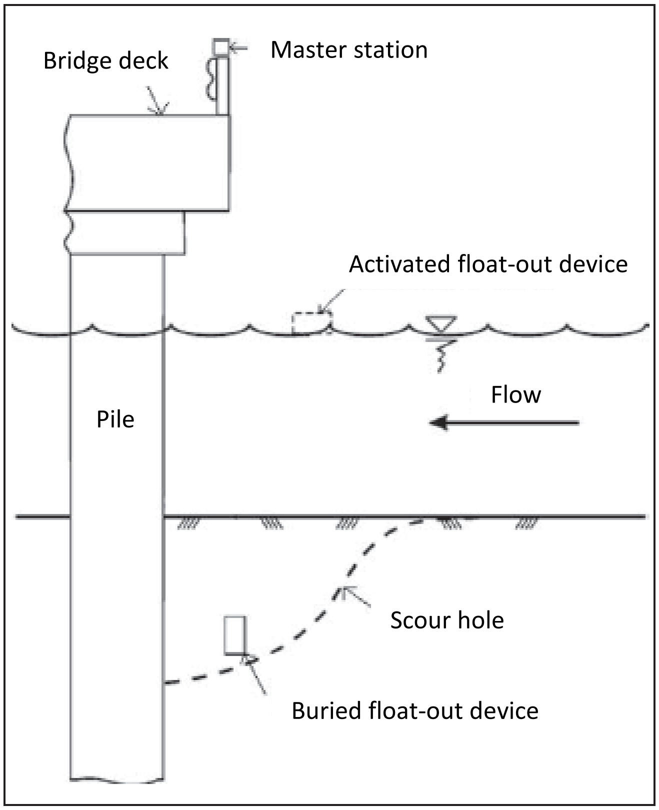

Figure 2.6: Float-Out Device
Adapted from Hunt (2009); further attributed to the Texas Transportation Institute

6. Structural sensors (tilt meters): Structural sensors can be deployed to monitor the structural health of a bridge. Tilt meters are often used for this purpose. Changes in the structure could indicate scour has undermined or threatened the foundation of the bridge. Structural sensors are also capable of detecting changes in the bridge caused by, for example, earthquakes, collision, fatigue fracture, or other bridge failure mechanisms. Figure 2.7 shows a schematic of a tilt sensor mounted on a bridge along with sample signals indicating normal and unhealthy patterns.

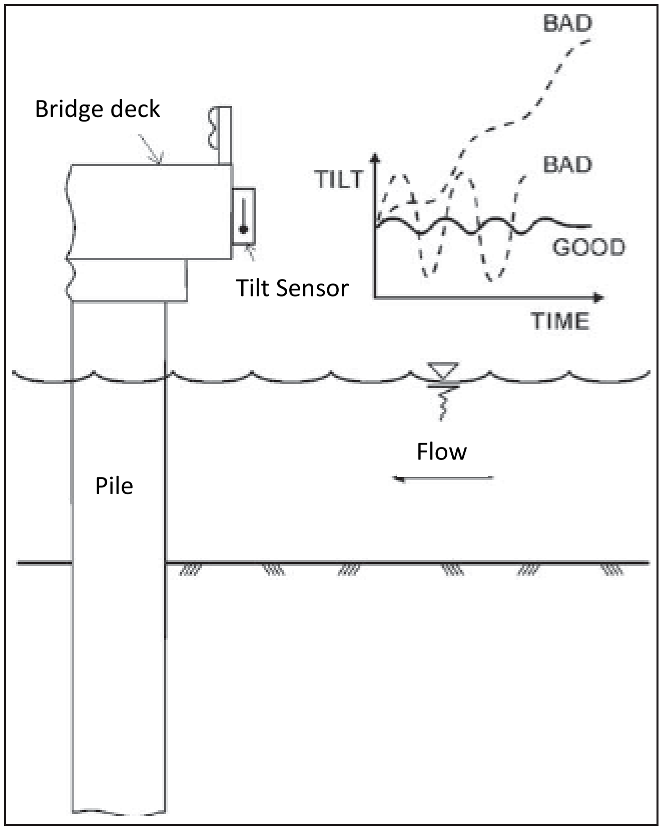

Figure 2.7: Tilt Meter
Adapted from Hunt (2009); further attributed to the Texas Transportation Institute

7. Stream stage gauges: Stream stage can be used to trigger alerts for bridge closure and/or inspection. Stage gauges are relatively inexpensive to install and operate (compared to other fixed monitoring options). KDOT would need to determine threshold stage values for each scour-critical bridge.

Chapter 9 of HEC-23 discusses the advantages and disadvantages of fixed scour monitoring instrumentation (Lagasse et al., 2009). The primary disadvantages are initial installation cost and ongoing monitoring plus maintenance. The challenges of monitoring continuously to detect infrequent events are enormous. Ensuring system reliability requires careful maintenance of the instrumentation and a failsafe reporting system.

Figure 2.8 (Table 9.5 from HEC-23) lists the advantages and limitations of various fixed instruments. The selection of instrumentation is highly site-dependent. Figure 2.9 (Table 9.7 from

HEC-23) gives approximate costs for various fixed instruments. These same costs are presented in NCHRP Synthesis 396 (Hunt, 2009). Both reports stress that scour monitoring systems must be carefully selected for each site, taking into account characteristics of the bridge, foundation, and streambed. It should be noted that these costs are estimates from 2009. Cost of deployment is highly dependent on site conditions.

NCHRP Synthesis 396, “Monitoring Scour Critical Bridges,” reports on the performance and effectiveness of fixed monitoring options (Hunt, 2009). The synthesis states that there are over 20,000 scour-critical bridges in the United States. Of these, only a vast minority have fixed scour monitoring in place (over 120). Sonar is by far the most common fixed instrument used in practice (71 bridges), with sliding collar devices a distant second (22 bridges). Many bridges require multiple instruments to monitor abutments and piers.

The fact that only a small fraction of the scour-critical bridges in the United States have fixed instrumentation demonstrates the challenges associated with fixed monitoring. Fixed instrumentation may be useful for locations of particular concern to KDOT (e.g., high volume, high risk bridges) as part of a more global, statewide monitoring system.

Type of Fixed Instrumentation	Best Application	Advantages	Limitations
Sonar	Coastal regions	Records infilling; time history; can be built with off the shelf components	Debris, high sediment loading, ice, and air entrainment can interfere with readings
Magnetic Sliding Collar	Fine bed channels	Simple, mechanical device	Vulnerable to ice and debris impact; only measures maximum scour; unsupported length, binding
Tilt Sensors	All	May be installed on the bridge structure and not in the stream-bed and/or underwater	Provides bridge movement data which may or may not be related to scour
Float-Out Device	Ephemeral channels	Lower cost; ease of installation; buried portions are low main-tenance and not affected by debris, ice or vandalism	Does not provide continuous monitoring of scour; battery life
Sounding Rods	Coarse bed channels	Simple, mechanical device	Unsupported length, binding, augering
Time Domain Reflectometers	Riverine ice channels	Robust; resistance to ice, debris, and high flows	Limit on maximum lengths for signal reliability of both cable and scour probe

Figure 2.8: Summary of Fixed Instrumentation
Source: Lagasse et al. (2009)

Typed of Fixed Instrumentation	Instrument Cost with Remote Technology ($)[1]	Instrument Cost for Each Additional Location ($)	Installation Cost	Maintenance/ Operation Costs
Sonar	12,000 - 18,000	10,000 - 15,500	Medium to high; 5 to 10-person days to install	Medium to High
Magnetic Sliding Collar	13,000 – 15,500	10,500 – 12,500	Medium, minimum 5-person days to install	Medium
Tilt Sensors	10,000 – 11,000	8,000 – 9,000	Low	Low
Float-Out Device	10,100 – 10,600	1,100 – 1,600	Medium; varies with number installed	Low
Sounding Rods	7,500 – 10,000	7,500 – 10,000	Medium; minimum 5-person days to install	High
Time Domain Reflectometers	5,500 – 21,700	500	Low	Medium
[1]Cost per device will decrease when multiple devices share remote stations and/or the master station.				

Figure 2.9: Cost of Fixed Instruments for Scour Monitoring

Source: Lagasse et al. (2009)

Chapter 3: Options for Bridge Scour Ex Situ Monitoring

Chapter 2 dealt mostly with bridge-specific monitoring options to detect and measure scour at a particular location of concern. Chapter 3 focuses on rainfall and flood monitoring approaches that can be used to help predict scour and trigger warnings to appropriate KDOT personnel as part of a global, statewide monitoring system.

3.1 Background on Ex Situ Monitoring

Ex situ monitoring for rainfall and flood events that can lead to bridge scour implies a regional or statewide system for predicting scour events. Such systems can employ real-time rainfall-runoff modeling for watersheds of scour-critical bridges or more low-tech approaches such as triggering alerts (closures and/or inspections) based on rainfall or streamflow conditions.

3.2 Real-Time Modeling

Real-time modeling for bridge scour involves modeling streamflow at specific bridge locations to trigger alerts when the flow rate exceeds a predetermined threshold of concern. Real-time models of rainfall-runoff are subject to uncertainty due to two groups of factors:

1. Model uncertainty: Continuous hydrologic models must account for multiple inputs and model states. To reliably predict streamflow on a continuous basis, a model must account for changes in soil moisture, hydraulic conductivity, land cover (vegetation condition), storage in lakes, snowpack, and multiple other factors that influence runoff. Error in the model can be caused by:
    a. Model representation of physical processes: A model is, by definition, a mathematical representation of the actual watershed behavior. As such, all models simplify the actual enormously complex physical processes that convert rainfall to streamflow. Models range in complexity. Complex physically-based models attempt to represent most of the relevant fluxes and storages of water in the watershed system. Conceptual models use a simpler

representation of watershed dynamics and rely on parametrization and model interpretation. The advantages of complex physically-based models are limited by the paucity of data for model forcing, parameterization, and calibration.

b. Watershed characterization: Watershed data are used to parameterize the model. Models range in detail from lumped representations of the watershed (treating the watershed as one hydrologic unit with average properties across the entire basin) to distributed hydrologic models which represent the watershed on a discrete grid. The increased availability of detailed geographic data helps with model characterization. However, even the most detailed distributed hydrologic model will not accurately or precisely capture all topographic, soil, and vegetation features of the watershed.

2. Input uncertainty: Continuous hydrologic models rely on weather data. Multiple inputs are necessary to track evapotranspiration for the computation of soil moisture storage. The most important weather input is precipitation. Relative to the land area of Kansas, there is very little coverage by streamflow or rainfall gauges. This would make rainfall-based alerts or real-time hydrologic modeling using radar-rainfall data a good (or only remaining) option.

   Previous K-TRAN-funded research has improved our understanding of the benefits and limitations of radar-rainfall estimates, including KU-96-7 "Utilization of Precipitation Estimates Derived from Composite Radar" (Young, McEnroe, & Quinn, 1998) and KU-02-8, "Evaluation of NEXRAD Operational Precipitation Estimates in Kansas" (Young, Brown, & Brunsell, 2008). Precipitation estimation has improved dramatically over the past several decades with the advent and improvement of radar-based rainfall estimates. However, uncertainty in rainfall estimates continues to be high. The quality of rainfall estimates varies across the state, with the most accurate estimates in the northeastern portion of the state. Estimates in the western portion of the state are more uncertain due to the sparsity of rain gauges and the distance between NEXRAD radar installations. Despite this uncertainty, the NEXRAD product will generally give more reliable indications of heavy rainfall than a rain gauge located 5 or more miles away (Young, 2010).

Real-time simulation of streamflow would help target bridge closures and/or inspections during flood events. If KDOT adopts a real-time modeling approach, the system must be carefully parameterized, calibrated, and tested to ensure reliable alerts without excessive false positives. Ex situ monitoring would require the evaluation of each scour-critical bridge site to determine what would be a critical "scour-producing" event. HEC-18 gives guidance on which events should be considered for scour (e.g., incipient overtopping, the 100-year flood, or other; Arneson et al., 2012). For example, a bridge scour plan of action might indicate the 100-year flood as the flood of concern. Given the importance of avoiding false negatives, it might be necessary to trigger a closure and/or inspection if the simulated streamflow surpasses a much lower threshold (e.g., a 25-year flow). The appropriate threshold streamflow at each bridge could be determined using historical data to drive the model.

Development of an in-house, real-time flood simulation solution would require significant resources, including redundant computer servers, live feed of gauge-corrected radar-rainfall estimates, and a continuous, real-time modeling framework for over 300 watersheds. Continuous simulation is important to simulate soil-moisture conditions. System set-up would include watershed characterization, model parameterization, and calibration for all watersheds. A real-time warning system should have redundancy with a minimum of two servers in geographically distinct areas.

There are a number of third-party vendors with relatively turn-key systems. Some vendor options are discussed in Section 3.4.

3.3 Flash Flood Warning

Real-time modeling is a resource-intense option for statewide flooding and bridge scour monitoring. Simpler and/or less expensive options are available to trigger alerts. Bridge scour alerts can be issued based on flash flood warning systems, using observed rainfall, streamflow, or stream stage to trigger warnings for specific locations.

3.3.1 Precipitation-Based Alerts

Radar and rain gauge data can be used to trigger alerts if rainfall depths or intensities exceed pre-determined thresholds for a bridge's watershed. Rainfall thresholds are easiest to implement if they are expressed as a rule, for example: if the depth of rainfall over the watershed exceeds P inches over D minutes, trigger an alert. Distinct challenges exist, though, for the development of rainfall thresholds. Runoff depth and corresponding flood magnitude are highly dependent on rainfall amount, but the timing and spatial distribution of rainfall are critically important factors. In addition, watershed soil moisture conditions have a significant impact on runoff and streamflow. A precipitation-threshold based system must be carefully planned to ensure reliable warnings without unnecessary false positives.

3.3.2 Streamflow or Stream Stage Alerts

Flash flood warning systems commonly use stream stage gauges to trigger alerts based on water surface elevation. Although this system requires fixed instrumentation at bridge sites of interest, the installation and maintenance of stage gauges would likely be significantly less expensive than the use of fixed scour monitoring equipment and would have the additional benefit of providing flash flood warning for bridge overtopping scenarios. Research would be necessary to identify the flood stage of concern for each scour-critical bridge.

3.4 Vendor Options

This section presents a brief overview of considerations for contracting with a vendor to provide scour and/or flood warning at bridges across the state. This section is not intended to provide an exhaustive list of vendors or a complete comparison of the character or quality of services provided by them. The information is provided here to help KDOT determine the feasibility of developing a solution in house and/or developing specifications to meet the needs of KDOT's bridge scour monitoring program before putting a project out to bid.

A number of vendors offer weather data services and turn-key flash flood warning systems. The National Weather Service maintains a list of commercial weather vendors, many of whom provide flash flood warning systems (http://www.nws.noaa.gov/im/more.htm). The ALERT (Automated Local Evaluation in Real Time) Users Group lists vendors on their website (http://www.alertsystems.org/vendors). The National Hydrologic Warning Council membership list consists of both providers and clients of flood alert systems (http://www.hydrologicwarning.org/). Selection of a vendor for a statewide flash flood warning system for scour alerts would require a thorough assessment of vendor services, reliability, and costs.

Flood and scour alert systems can range in complexity, predictive sophistication, and cost from a relatively basic to an increasingly complex system as outlined here:

a. An alert system that leverages existing rainfall and streamflow data systems.
b. Combining existing data sources with sensors specific to KDOT's needs.
c. Adding predictive modeling capabilities to the system to improve response time.
d. Including data management tools for tracking and documenting alerts and bridge inspection.

In any regional flood warning system, it is necessary to collect and assimilate data and make appropriate alerts based on information. The hardware and software that provide this data assimilation capability are often collectively referred to as a base station. Several vendors provide base station options, including TriLynx Systems, LLC (product: NovaStar5), OneRain Incorporated (product: Contrail), and DataWise Environmental Monitoring, Inc. (product: DataWise). Each offers a flexible system capable of integrating a variety of data streams.

At a most basic level, a flood alert system can integrate data from radar-based precipitation estimates and USGS stream gauges. To provide more detailed information in specific areas of concern, KDOT could add additional sensors to tie into the base station. These sensors could include rain gauges, stream stage gauges, and fixed scour monitoring devices. A flexible base station platform could be leveraged to include air and bridge surface temperatures, wind speed, and other factors that would enhance KDOT's ability to monitor icing conditions and high wind speeds.

The ALERT2 protocol provides a standard for the transmission of environmental monitoring data between monitoring hardware and base station systems. ALERT2 builds on the ALERT (Automated Local Evaluation in Real Time) system by improving transmission rate, error detection, and messaging capabilities. A number of manufacturers provide ALERT2 compatible equipment. Some examples include Campbell Scientific, Rickly Hydrological Company, and High Sierra Electronics, Inc.

One major consideration is whether KDOT needs to be able to respond to real-time observation data, or whether flood modeling and prediction might be necessary in order to provide timely response in remote areas or in very flashy basins. Flood prediction could involve integration of quantitative precipitation forecasts as well as real-time flash flood modeling. Two vendors providing flash flood modeling systems are Vieux & Associates, Inc., and David Ford Consulting Engineers.

US Engineering Solutions Corporation provides a turn-key solution for statewide flood and scour monitoring called BridgeWatch™. BridgeWatch™ is currently used by seven state DOTs (Iowa, Georgia, Illinois, Pennsylvania, Tennessee, Idaho, and Connecticut). BridgeWatch™ is a web-based solution which integrates data from a wide range of sources, including USGS stream gauges, NEXRAD radar rainfall, and fixed scour monitoring equipment. Alerts can be triggered based on multiple sources of information, providing a flexible system able to provide alerts for a wide range of bridges.

For this project, we conducted interviews with bridge engineers from four DOTs using BridgeWatch™ as well as with Joe Scannell with US Engineering Solutions. Each DOT reported positive experience with the system, including the flexibility and service of US Engineering Solutions. Table 3.1 lists the contacts interviewed at each DOT. Table 3.2 lists the number of bridges in each system along with the approximate annual contract cost for the BridgeWatch™ system. BridgeWatch™ services range in scope and complexity and vary from contract to contract based on project specifications. Three of the DOTs report per-structure costs of less than $200/year.

Table 3.1: Contacts for DOTs using BridgeWatch™

State	Contact	Phone	E-mail
Connecticut	Ted Lapierre and Michael Hogan	(860) 594-3172	Theodore.Lapierre@ct.gov Michael.Hogan@ct.gov
Illinois	Steve Beran	(217) 785-2927	Steve.Beran@illinois.gov
Iowa	David Claman	(515) 239-1487	David.Claman@dot.iowa.gov
Tennessee	Jon Zirkle	(615) 350-4254	jon.zirkle@tn.gov

Table 3.2: Approximate Annual Cost for Implementation of BridgeWatch™

State	Cost	Number of Structures	Cost per Structure
Connecticut	~$65,000	~420	~$155
Illinois	$126,984	650	$195
Iowa	~$85,000	~180	~$472
Tennessee	~$270,000	~1,800	~$150

Vieux & Associates, Inc., developed ScourCast with research funding from the Oklahoma Department of Transportation. ScourCast leverages the rainfall estimation and flash flood modeling capabilities (VFLOW) developed by Vieux & Associates, and is intended to provide a turn-key scour monitoring solution. ScourCast is not currently in use but could represent an option for KDOT.

With careful specification and vendor selection, KDOT might be able to provide scour monitoring with a flash flood warning system. One data point to consider is the Overland Park-run ALERT2 system that provides warning capabilities for Johnson County and the Kansas City metropolitan area. This system incorporates multiple base stations for redundancy and around 700 individual sensors at approximately 100 sites. The total operating budget for the complete flood warning system was $268,850 in 2015, including $133,500 for Overland Park staff time, $60,400 for field hardware and operations, and $71,570 for software and license support (Dan Hurley, personal communication).

Any system will require up-front investment to delineate watershed boundaries for scour-critical bridges, set rainfall and/or streamflow thresholds, and to identify responsibility and chain of command for bridge inspection. The selection of rainfall thresholds can be an iterative process. DOTs contacted for this report point to an iterative learning process for changing the rainfall thresholds for BridgeWatch™ in response to repeated false positives.

3.5 Public Domain Options

Much of the weather and streamflow data used in vendor flash flood or scour warning systems are in the public domain. In some cases, USGS stream gauges may be close enough to a scour-critical bridge to provide reliable warning of dangerous flow conditions. For locations not near USGS gauges, the National Weather Service alert services may provide reasonable options to trigger bridge closure and/or inspections.

3.5.1 Sites Near USGS Gauges

USGS gauges could be used to trigger alerts for scour-critical bridges located upstream or downstream of the gauge. These locations would need to be carefully selected to ensure the USGS gauge accurately reflects conditions at the bridge and to establish meaningful alert thresholds. Criteria to consider may include streambed soil type, route criticality (e.g., hospital or school access), average daily traffic (ADT), bridge structure type, etc. HEC-18 provides guidance for computing scour depths for different scour mechanisms (Arneson et al., 2012).

The United States Geological Survey operates real-time stream gauges at 212 locations in the state of Kansas. Figure 3.1 shows the locations of active USGS stream gauges and the locations of scour-critical bridges in Kansas. From geographic information system (GIS) analysis, it appears that 50 of KDOT's identified scour-critical bridges (about 15% of the total) have active USGS stream gauges either at or very near the bridge location (on the same stream and less than 10% difference in total drainage area between the bridge and the USGS gauge watershed). Table 3.3 lists these 50 sites. For the sites listed in Table 3.3, USGS gauges could be used to trigger alerts using the USGS Water Alert system for end users. Users can set up specific text or e-mail messaging for specified flow rates or stage values. More information regarding the system is available from http://water.usgs.gov/wateralert/.

Table 3.3: Scour-Critical Bridges At or Near USGS Gauges (Within 10% of Drainage Area)

BRKEY	District-Area	Route	Stream Name	Location	USGS ID	Area Ratio
004031	5-1	K-2	Medicine River	2.11 MI NE K8	7149000	1.05
005071	5-4	U-281	Arkansas River	0.65 MI S US56	7141300	0.92
006005	4-1	U-54	Marmaton River	0.48 MI N EJCT US69	6917500	1.04
006028	4-1	K-3	Marmaton River	8.11 MI N WJCT K39	6917240	0.92
018001	5-3	U-77	Arkansas River	2.98 MI N OKLA STATE LINE	7146500	1.01
018009	5-3	U-77	Walnut River	1.11 MI S OF JCT US160	7147800	1.07
021030	2-1	I-70	Chapman Creek	0.29 MI E K206, WB	6878000	1.00
021031	2-1	I-70	Chapman Creek	0.28 MI E K206, EB	6878000	1.00
023081	1-4	U-40	Kansas River	1.45 MI EAST OF59 S JCT	6891080	1.00
023082	1-4	U-40	Kansas River	1.45 MI EAST OF 59 S JCT	6891080	1.00
025008	4-3	U-160	Elk River	5.86 MI E EJCT K99	7169800	1.01
026044	3-3	U-183	Smoky Hill River	1.19 MI N RUSH COLN	6862700	1.01
026056	3-3	U-183	Big Creek	0.14 MI NW JCT OLD 40 HWY	6863500	1.04
028004	6-1	U-83	Arkansas River	0.74 MI S SJCT US50	7139000	1.02
028015	6-1	U-83	Arkansas River	1.61 MI NE OF JCT 83 BUS	7139000	1.00
029057	6-3	U-400	Arkansas River	14.24 MI SE 56/ 400 SJCT	7139500	1.01
030028	4-2	I-35	Marais des Cygnes River	2.93 MI NE US59, SB	6913500	1.02
030029	4-2	I-35	Marais des Cygnes River	2.92 MI NE US59, NB	6913500	1.02
030070	4-2	K-68	Marais des Cygnes River	8.65 MI E OSAGE COLN	6913500	0.96
035027	6-3	K-23	Arkansas River	0.60 MI. SOUTH OF US-50	7139500	0.93
046098	1-2	U-69	Blue River	5.13 MI N MIAMI COLN, SB	6893080	0.99
046099	1-2	U-69	Blue River	5.12 MI N MIAMI COLN, NB	6893080	0.99
050008	4-4	U-59	Labette Creek	5.69 MI NW EJCT US-160	7184500	0.99
050065	4-4	U-400	Neosho River	8.26 MI E US59	7183500	1.00
056057	1-4	K-130	Neosho River	7.59 MI S I35	7182390	1.01
056139	1-4	K-99	Neosho River	0.31 MI N I35	7179750	0.97
057042	2-3	U-56	North Cottonwood River	8.58 MI E EJCT K15	7179795	1.00
058044	1-5	K-233	Big Blue River	2.52 MI E US77	6882510	0.93
060015	6-2	K-23	Cimarron River	0.80 MI N OKLA. STATE LN	7156900	NA
067043	4-4	K-47	Neosho River	3.01 MI E US59	7183300	NA
070090	1-4	U-75	Marais des Cygnes River	6.54 MI N COFFEY COLN	6911000	NA
072017	2-4	K-18	Solomon River	2.23 MI NE US81	6876900	0.97
079043	2-2	K-148	Republican River	8.52 MI NE JEWELL COLN	6854500	0.98
081029	1-5	K-18	Wild Cat Creek	0.57 MI E K113, SL, EB	6879815	NA
084043	3-3	U-281	Paradise Creek	3.05MI S WJCT K18	6867500	0.99
085001	2-4	I-135	Smoky Hill River	0.26 MI N MCPHERSON CL	6866000	1.00
085002	2-4	I-135	Smoky Hill River	0.26 MI N MCPHERSON CL	6866000	1.00
085144	2-4	K-4	Smoky Hill River	2.24 MI E K104	6866500	0.98
087007	5-5	I-135	Arkansas River	0.22 MI N MACART RD, NB	7144300	NA
087096	5-5	I-235	Arkansas River	1.09 MI NE BICKELL ST, SB	7143375	NA
087097	5-5	I-235	Arkansas River	1.08 MI NE BICKELL ST, NB	7143375	NA
089154	1-4	U-75	Kansas River	0.50 MI N E-JCT US75-I70	6889000	1.00
096031	5-3	I-35	Ninnescah River	7.65 MI N US-160	7145500	0.00
096032	5-3	I-35	Ninnescah River	7.66 MI N US-160	7145500	0.00
096048	5-3	U-81	Slate Creek	1.50 MI S SJCT US160	7145700	1.04
096072	5-3	U-160	Arkansas River	0.67 MI W COWLEY COLN	7145600	0.76
096094	5-3	K-44	Chikaskia River	0.19 MILES W K-49	7151500	0.99
096107	5-3	K-53	Arkansas River	3.95 MI E US81	7144570	1.03
096116	5-3	K-55	Arkansas River	7.63 MI E US81	7144570	0.93
101018	2-1	K-148	Little Blue River	4.92 MI N K9	6884400	0.97

Table 3.4: Scour-Critical Bridges Near USGS Gauges (Within 25% of Drainage Area)

BRKEY	District-Area	Route	Stream Name	Location	USGS ID	Area Ratio
009050	2-3	K-177	Cottonwood River	.12 MI N MN CTNWOD FLS	7182250	0.80
011075	4-4	U-400	Lightning Creek	6.06 MI E LABETTE COLN	7184000	0.76
013018	6-3	U-183	Cimarron River	4.39 MI N OKLA. STATE LN	7157740	NA
018059	5-3	K-15	Walnut River	1.37 MI W NJCT US77	7147800	0.85
048070	5-1	U-54	S Fork Ninnescah River	9.75 E OF PRATT COLN	7145200	0.76
048071	5-1	U-54	S Fork Ninnescah River	11.47 MI E OF PRATT COLN	7145200	0.80
052039	1-3	I-70	Stranger Creek	9.57 MI E K-32	6892000	1.14
052040	1-3	I-70	Stranger Creek	9.58 MI E K-32	6892000	1.14
071043	3-1	K-181	South Fork Solomon River	5.44 MI S US24	6874000	1.13
071044	3-1	K-181	North Fork Solomon River	1.14 MI S US24	6872500	1.11
073003	5-4	U-56	Pawnee River	15.85 MI NE US183	7141200	1.12
082023	3-1	U-183	South Fork Solomon River	1.37 MI S JCT US24	6873460	0.15
087106	5-5	I-235	Little Arkansas River	1.38 MI E K96, NB	7144200	NA
089056	1-4	I-470	Shunganunga Creek	1.92 MI SE WJCT US75, WB	6889585	NA
089057	1-4	I-470	Shunganunga Creek	1.91 MI SE WJCT US75, EB	6889585	NA
096012	5-3	I-35	Slate Creek	11.01 MI N US-166	7145700	NA
096013	5-3	I-35	Slate Creek	11.02 MI N US-166	7145700	NA
096044	5-3	U-81	Chikaskia River	6.52 MI E K49	7151500	NA

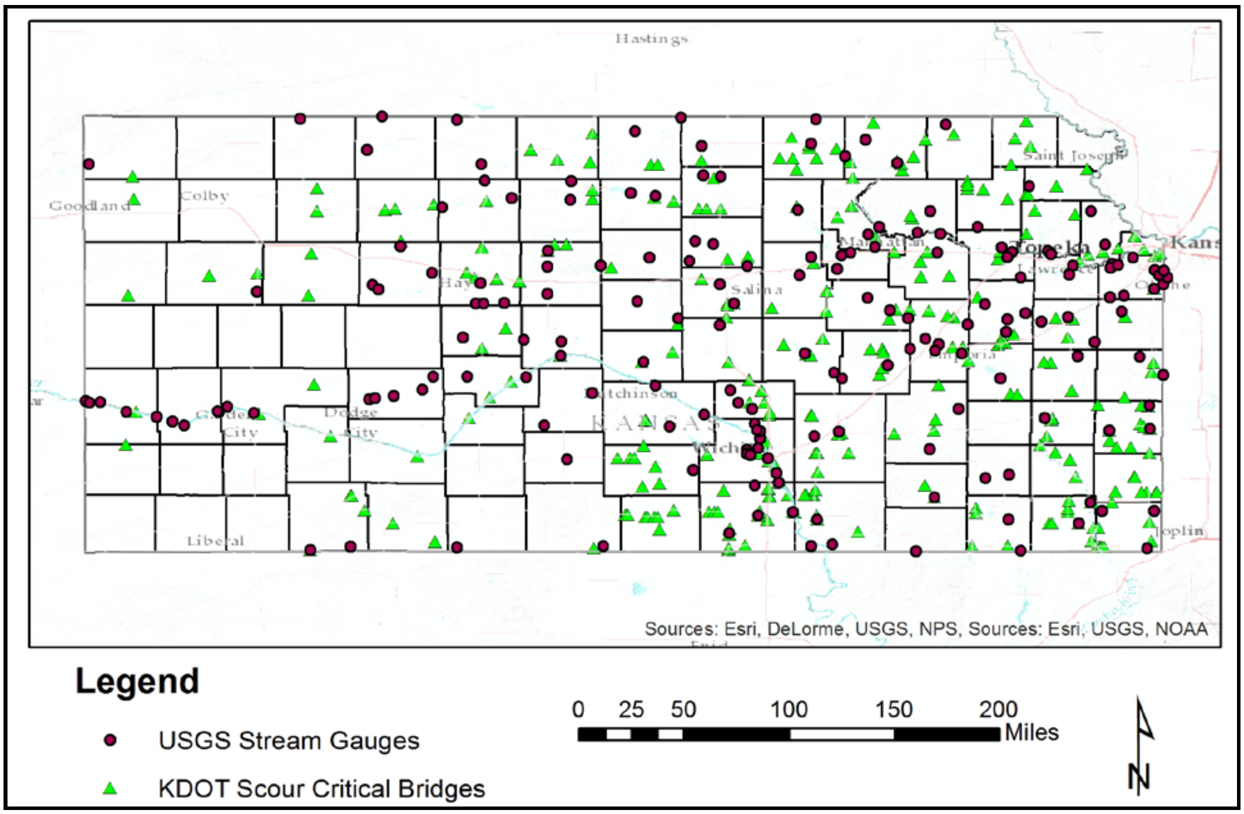

Figure 3.1: Scour-Critical Bridge and USGS Gauge Locations in the State of Kansas

Another 18 scour-critical bridges are located upstream or downstream of USGS gauges within 25% of the drainage area. Table 3.4 lists these 18 gauges. USGS Water Alerts could be used to trigger warnings for these 18 bridges; however, supplemental monitoring from other data sources may be necessary.

KDOT could set up USGS Water Alert messaging for all scour-critical bridges sufficiently close to existing and active USGS gauges. Threshold flow and/or stage values would need to be determined for these bridges.

3.5.2 Sites Not Near USGS Gauges

Most of the 323 scour-critical bridges in Kansas are too distant from existing USGS stream gauges to use the USGS WaterAlert system for flooding and scour monitoring. The Interactive National Weather Service (iNWS) system could be used to trigger alerts at the remaining scour-critical bridges.

The iNWS service can be configured to issue text and/or e-mail messages based on either Hydrology Alert Points or iNWS Alert Areas.

Hydrology Alert Points are available at 197 locations across the state (Figure 3.2) and will trigger messages for any observed or forecast change in flood status. There are four flood statuses in the system: Near Flood Stage, Minor Flooding, Moderate Flooding, and Major Flooding. Hydrology alerts are only available at AHPS (Advanced Hydrologic Prediction Service) points. The majority of these observations are from active USGS stream gauges and are thus redundant to the map in Figure 3.1.

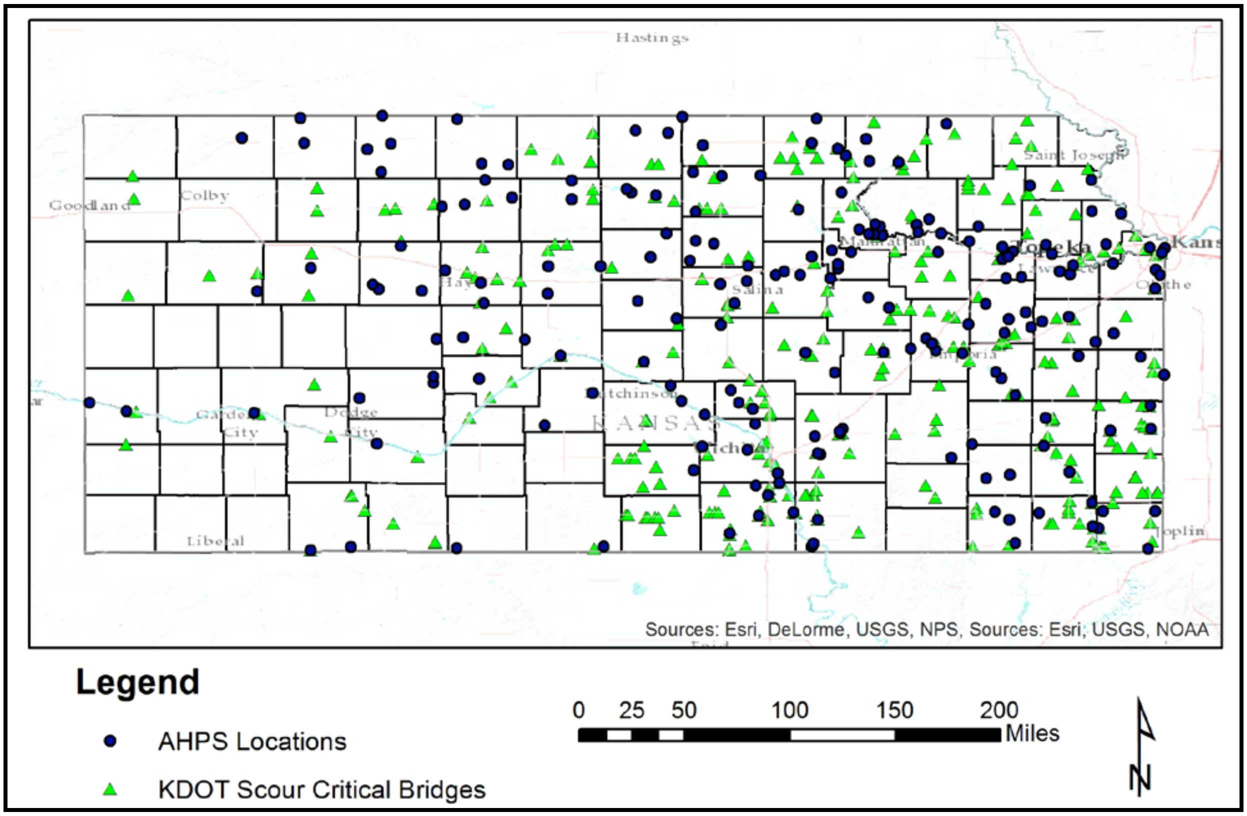

Figure 3.2: Location of AHPS Observation Points in the State of Kansas

iNWS Alert Areas can be specified based on address, county, or by user-drawn features on the iNWS map system. iNWS can issue alerts based on a number of options (see Table 3.5) including Hydrology Alerts, which include flash flood and areal flood watches and warnings. Alert areas must be manually entered (there is no provision at this time for batch loading based on GIS data). Alerts could be set based on bridge locations (points), watershed areas (polygons), or bounding boxes (polygons) for the watershed extents.

The iNWS system is available online: https://inws.ncep.noaa.gov/. KDOT could set up alerts for all scour-critical bridges in the area with e-mail and/or text messaging sent to relevant maintenance personnel.

Table 3.5: iNWS Alert Area Options

Severe

- Severe Thunderstorm Watches, Warnings, and Statements
- Tornado Watches and Warnings

Winter Weather

- Avalanche Watches, Warnings, and Special Bulletins
- Blizzard Watches and Warnings
- Lake Effect Snow Watches, Warnings, and Advisories
- Wind Chill Watches, Warnings, and Advisories
- Winter Storm Watches and Warnings
- Winter Weather Advisories
- Freezing Rain Advisories
- Ice Storm Warnings

Hydrology

- Flood Statements and Warnings
- Flash Flood Watches, Statements, and Warnings

Marine Weather

- Coastal Waters Forecasts (CWF)
- Open Lake Forecasts (GLF)
- Special Marine Warnings and Marine Weather Statements
- Gale Watches and Warnings
- Storm Watches and Warnings
- Hurricane Force Wind Watches and Warnings
- Heavy Freezing Spray Watches and Warnings
- Hazardous Seas Watches and Warnings
- Ashfall Warnings
- Nearshore Marine Forecasts (NSH)
- Offshore Water Forecasts (OFF)

Coastal Hazards

- Coastal Flood Watches, Warnings, and Advisories
- Lakeshore Flood Watches, Warnings, and Advisories
- High Surf Advisories and Warnings
- Rip Current Statements
- Beach Hazard Statements
- Public Tsunami Messages (TSU)
- LSH Products
- TIB Products

Tropical

- Hurricane/Typhoon Local Statements (HLS)
- Tropical Cyclone Forecasts and Advisories (TCM)
- Tropical Cyclone Public Advisories (TCP)
- Hurricane Watches and Warnings
- Tropical Storm Watches and Warnings
- Typhoon Watches and Warnings

Aviation

- Airport Weather Warnings Non-Precipitation
- Excessive Heat Watches and Warnings
- Freeze Watches and Warnings
- High Wind Watches and Warnings
- Extreme Cold Watches and Warnings
- Dust Storm Warnings
- Hard Freeze Warnings
- Air Stagnation Advisories
- Ashfall Advisories
- Blowing Dust Advisories
- Dense Fog Advisories
- Dense Smoke Advisories
- Freezing Fog Advisories
- Frost Advisories
- Heat Advisories
- Lake Wind Advisories

Civil Emergencies

- Child Abduction Emergencies
- Civil Danger Warnings
- Civil Emergency Messages
- Earthquake Warnings
- Evacuation Immediate
- Fire Warnings
- Hazardous Materials Warnings
- Local Area Emergencies
- Law Enforcement Warnings
- Nuclear Power Plant Warnings
- Radiological Hazard Warnings
- Shelter In Place Warnings
- 911 Telephone Outage Emergencies
- Volcano Warnings

Fire Weather

- Rangeland/Grassland Fire Danger Statements
- Fire Weather Watches
- Red Flag Warnings

Other

- Local Storm Reports

Source: National Weather Service (n.d.)

During active weather periods, iNWS warnings can be frequent and could become overwhelming for KDOT staff. The authors have been monitoring a few locations using the iNWS system to gauge the frequency of notifications. For example, iNWS issued 51 hydro alerts (AHPS Mobile Alerts) for Stranger Creek at Easton in May and June of 2015. These alerts notify of any change in flood category status (including the receding end of a flood). Although the iNWS system does not currently allow filtering for specific flood stages, e-mail server rules could be established to filter out all but the flood levels of interest for each bridge site. For example, KDOT personnel could filter iNWS e-mails such that only e-mails with “New Forecast: Moderate Flooding” are forwarded for a given bridge location.

3.5.3 Other Promising Developments

3.5.3.1 NWS Distributed Hydrologic Model

The NWS recently started using the Distributed Hydrologic Model (DHM) to issue gridded estimates of flow recurrence interval. The grid used by DHM is the same 4 × 4-km grid used for NEXRAD precipitation estimates. The process for calibrating the DHM is described in detail by Reed, Schaake, and Zhang (2007). In brief, the model is run for multiple years using the available record of NEXRAD radar rainfall estimates. The annual maximum predicted flow for each grid cell is extracted, and flood frequency analysis is conducted for the results in each cell. The DHM model is run in real time to compute flow values for each model cell. These flow results are not reported to the public; instead, the flow is compared to the flood frequency results for the grid cell and is reported as an approximate return period. This approach presents the end user with a relative frequency of the predicted flow. The grids are published as Google Earth KMZ files, which can be opened in Google Earth or imported to ArcGIS.

The NWS Missouri Basin River Forecast Center (MBRFC) recently calibrated and implemented DHM. MBRFC results are posted in Google Earth compatible KMZ files (which can be imported to ArcGIS) to http://www.riverwatch.noaa.gov/rtimages/mbrfc/dhm-tf/. Figure 3.3 shows a sample image of the MBRFC results.

The Lower Mississippi River Forecast Center (LMRFC) has been generating DHM output grids for some time. Results for the LMRFC are online at http://www.riverwatch.noaa.gov/rtimages/lmrfc/dhm-tf/. An example is shown in Figure 3.4.

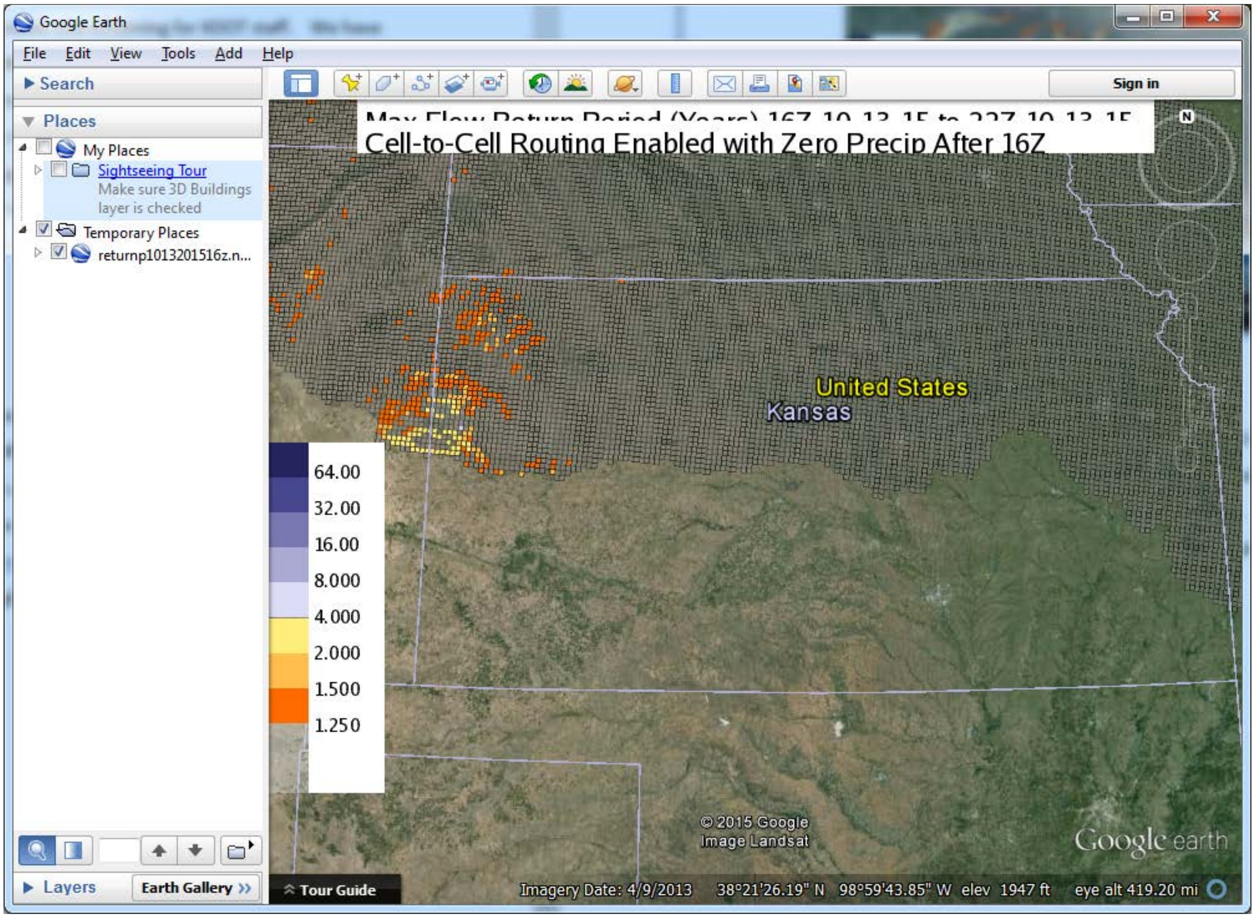

Figure 3.3: Sample Output Grid for the Distributed Hydrologic Model for the Missouri Basin River Forecast Center

The Arkansas-Red Basin River Forecast Center (ABRFC) is not currently using DHM to produce flood frequency grids. The DHM product would therefore not be of use to most of KDOT Districts Four, Five, and Six at the time of this report.

There is no current infrastructure in place to provide automated warnings to end users based on DHM flood predictions. This could be a research avenue for KDOT, perhaps in collaboration with the NWS. In the meantime, KDOT could use iNWS to issue alerts. If the affected area is in northern Kansas (in the Missouri River basin), KDOT personnel could be directed to check DHM predictions to see whether the predicted flood equals or exceeds a pre-determined return period.

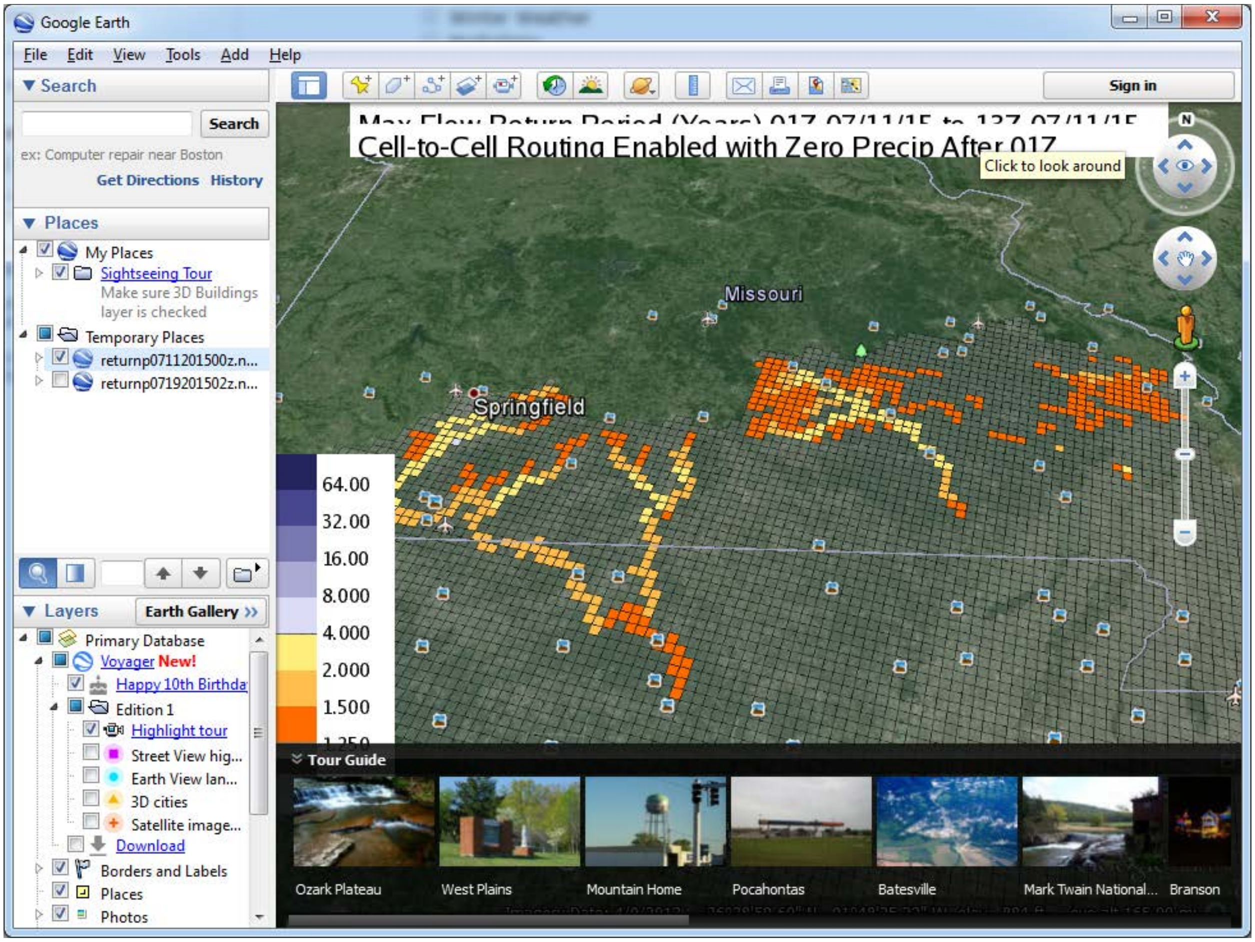

Figure 3.4: Sample Output Grid for the Distributed Hydrologic Model for the Lower Mississippi River Forecast Center

3.5.3.2 NWS Flash Flood Guidance

The National Weather Service uses DHM to estimate soil moisture on a continuous basis and to predict the depth of rainfall that would likely trigger flash flooding. The result is the Flash Flood Guidance (FFG) product. FFG is used internally by the NWS to issue flash flood warnings. FFG is produced for cumulative 1-, 3-, and 6-hour rainfall totals. Current FFG grids for the ABRFC can be viewed here: http://www.srh.noaa.gov/abrfc/gffg.php. An example is shown in Figure 3.5. Current FFG grids for the MBRFC can be viewed: http://www.weather.gov/mbrfc/ffg. An example is shown in Figure 3.6.

The FFG product is currently used by NWS forecast centers as part of the flash flood warning system. Forecasters use a number of information sources to trigger alert areas; FFG is a relatively new tool available to them for this purpose.

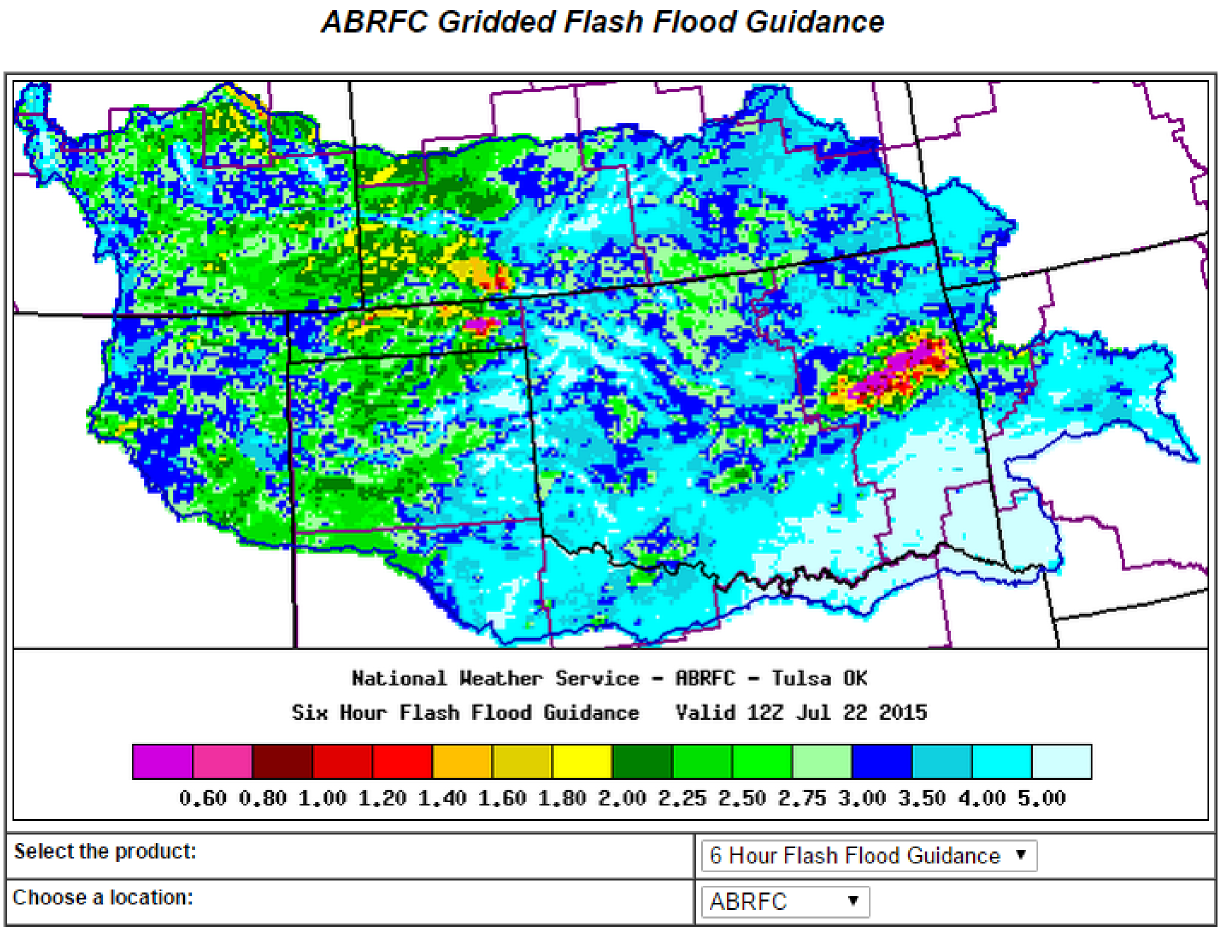

Figure 3.5: Gridded Flash Flood Guidance 6-Hour Map for the Arkansas-Red Basin River Forecast Center

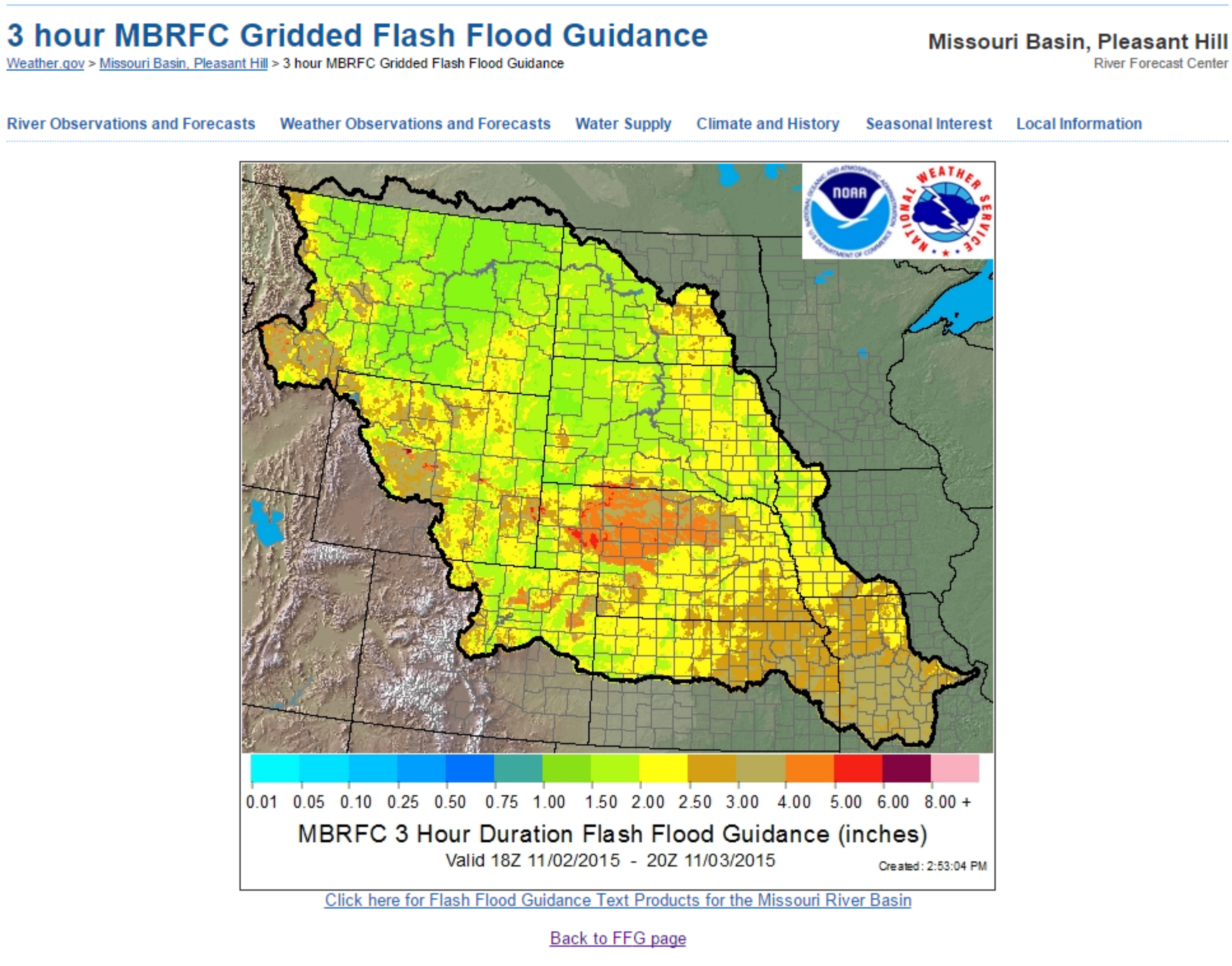

Figure 3.6: Gridded Flash Flood Guidance 3-Hour Map for the Missouri Basin River Forecast Center

Chapter 4: Conclusions and Recommendations

Bridge scour monitoring presents multiple challenges for DOTs. This research project surveyed in situ and ex situ monitoring options with particular attention on warning system options in the public domain. FHWA has three Hydraulic Engineering Circulars that provide guidance on the identification, evaluation, and monitoring of scour-critical bridges (HEC-18, HEC-20, and HEC-23).

Scour monitoring options include both portable and fixed instrumentation options. Fixed instrumentation is expensive to install and maintain, but may be well-suited for high volume bridges with significant scour risk. Fixed instrumentation can be integrated into a statewide flood warning system for critical locations.

A systematic statewide system would be preferable for monitoring scour-capable events at bridges across the state. KDOT could leverage existing USGS and NWS tools to monitor scour-critical bridges. These tools are in the public domain, but use of these resources will require staff overhead to ensure reliable and timely bridge closures and inspections.

There are dozens of vendors who offer flash flood warning and weather data services. KDOT could explore contract options with vendors to implement a statewide warning system. One vendor, US Engineering Systems, has developed a product exclusively focused on scour monitoring for DOT applications. BridgeWatch™ is a turn-key solution currently used by seven state DOTs. BridgeWatch™ integrates weather and streamflow data in the public domain with scour monitoring sensors and includes features for triggering and tracking bridge inspections. BridgeWatch™ costs vary from state to state depending on contract specifications, but the average per-structure cost can be less than $200/year.

Suggestions for future research:

1. Develop a pilot flood/scour warning system for select locations using a combination of the freely available USGS Water Alert and iNWS systems. Pilot project could establish warning parameters and monitor system performance over a 1- or 2-year span.

2. Collect and assimilate data from GIS and Bridge Scour Plans of Action for scour-critical bridges in the state. Work to establish rainfall and streamflow or stream stage thresholds of concern.
3. Assist KDOT with the development of specifications for a flood/scour warning system and provide guidance to KDOT personnel through the bidding process.

References

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F., & Clopper, P.E. (2012). *Evaluating scour at bridges: Fifth edition* (Hydraulic Engineering Circular No. 18, Report No. FHWA-HIF-12-003). Washington, DC: Federal Highway Administration. Retrieved from https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif12003.pdf

Haas, C., Weissmann, J., & Groll, T. (1999). *Remote bridge scour monitoring: A prioritization and implementation guideline* (Report No. TX-00/0-3970-1). Austin, TX: Texas Department of Transportation.

Hunt, B.E. (2009). *Monitoring scour critical bridges* (NCHRP Synthesis 396). Washington, DC: Transportation Research Board.

Lagasse, P.F., Clopper, P.E., Pagán-Ortiz, J.E., Zevenbergen, L.W., Arneson, L.A., Schall, J.D., & Girard, L.G. (2009). *Bridge scour and stream instability countermeasures: Experience, selection, and design guidance: Third edition* (Hydraulic Engineering Circular No. 23, Report No. FHWA-NHI-09-111). Washington, DC: Federal Highway Administration. Retrieved from http://www.fhwa.dot.gov/engineering/hydraulics/pubs/09111/09111.pdf

Lagasse, P.F., Zevenbergen, L.W., Spitz, W.J., & Arneson, L.A. (2012). *Stream stability at highway structures: Fourth edition* (Hydraulic Engineering Circular No. 20, Report No. FHWA-HIF-12-004). Washington, DC: Federal Highway Administration. Retrieved from http://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif12004.pdf

National Weather Service. (n.d.). *iNWS – Interactive NWS*. Retrieved from https://inws.ncep.noaa.gov/

Reed, S., Schaake, J., & Zhang, Z. (2007). A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations. *Journal of Hydrology, 337*(3–4), 402-420.

Young, C.B. (2010). Comparing NEXRAD error to use of a nearby gauge (Paper No. 10-2564). In *TRB 89th Annual Meeting Compendium of Papers*. Washington, DC: Transportation Research Board.

Young, C.B., Brown, T.M., & Brunsell, N.A. (2008). *Evaluation of NEXRAD operational precipitation estimates in Kansas* (Report No. K-TRAN: KU-02-8). Topeka, KS: Kansas Department of Transportation.

Young, C.B., McEnroe, B.M., & Quinn, R.J. (1998). *Utilization of precipitation estimates derived from composite radar* (Report No. K-TRAN: KU-96-7). Topeka, KS: Kansas Department of Transportation.

K-TRAN

KANSAS TRANSPORTATION RESEARCH AND NEW-DEVELOPMENT PROGRAM

Kansas
Department of Transportation

AD ASTRA PER ASPERA