IDAHO TRANSPORTATION DEPARTMENT

RESEARCH REPORT

Your Safety • Your Mobility
Your Economic Opportunity

RP 243

A Temperature-Based Monitoring System for Scour and Deposition at Bridge Piers

By

Aston M. Carpenter, Dr. Daniele Tonina

University of Idaho

Dr Charles H. Luce

US Forest Service

Prepared for

Idaho Transportation Department

Research Program, Contracting Services

Division of Engineering Services

http://itd.idaho.gov/alt-programs/?target=research-program

May 2017

1. Report No. FHWA-ID-17-243	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Temperature Based Novel Monitoring System for Scour and Deposition at Bridge Piers		5. Report Date May 2017 6. Performing Organization Code FLK138
7. Author(s) Aston M. Carpenter, Dr. Daniele Tonina, Dr. Charles H. Luce		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Idaho Center for Ecohydraulics 322 E. Front St. Boise, ID 83706		10. Work Unit No. (TRAIS) 11. Contract or Grant No. UI-15-03
12. Sponsoring Agency Name and Address Idaho Transportation Department Division of Engineering Services, Contracting Services, Research Program PO Box 7129 Boise, ID 83707-7129		13. Type of Report and Period Covered Final 01/15/2015 – 05/25/2017 14. Sponsoring Agency Code RP 243

15. Supplementary Notes

Project performed in cooperation with the Idaho Transportation Department and Federal Highway Administration.

16. Abstract

Stream flows around a bridge pier can be fast and highly turbulent causing large shear stresses that may mobilize streambed sediment resulting in scour around bridge foundations. Scour is the leading cause of bridge failure in the USA because it compromises bridge structural stability. However, streambed surface elevation may decrease (sediment scour) or increase (deposition of sediment) depending on local upstream sediment transport and water flow conditions. Consequently, yearly or biyearly measurements of streambed elevations may not provide an accurate evaluation of the scour risk at bridges. Current techniques are too expensive, difficult to install or provide only maximum scour. Thus, this project tests a low-cost and simple methodology to monitor streambed elevation changes continuously. The method uses the naturally occurring oscillations of stream water temperature as a tracer. As the water temperature signal propagates through the sediment, it undergoes advection dispersion and diffusion, which change the phase and amplitude of the original signal (stream water temperature). The proposed method detects changes in local streambed elevation from paired analysis of the phase and amplitude of in-stream and in-sediment water temperature signals. Our test at five Idaho bridges in five different watersheds proves that the method is robust. The method detects streambed elevation changes and maximum scour, which are verified with time series of ground-surveyed streambed elevations and scour chains, respectively.

17. Key Words Monitoring, Scour, Bridge Scour, Deposition, Streambed Elevation	18. Distribution Statement Copies available online at http://itd.idaho.gov/alt-programs/?target=research-program

19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 40	22. Price None

FHWA Form F 1700.7

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
^oF	Fahrenheit temperature	5/9 (^oF-32)	Celsius temperature	^oC
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
^oC	Celsius temperature	9/5 ^oC+32	Fahrenheit temperature	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

Acknowledgements

This research was supported by the Idaho Transportation Department. We thank Mr. Timothy DeWeese from the Bureau of Reclamation for assistance with project installation and early guidance on sensor development.

We would also like to show our gratitude to the scour team at Idaho Transportation Department for sharing their wisdom and experience throughout the course of this research. We thank our reviewer, Dr Robert Ettema for his insight, comments and feedback. We are also grateful to Donna Welch, William J. Reeder and Richard Carmichael for their comments on an earlier version of the report. Any opinions, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the supporting agency and reviewers.

Technical Advisory Committee

Each research project is overseen by a technical advisory committee (TAC), which is led by an ITD project sponsor and project manager. The Technical Advisory Committee (TAC) is responsible for monitoring project progress, reviewing deliverables, ensuring that study objective are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

Project Sponsor – Lotwick Reese, P.E.

Project Manager – Jake Legler, P.E.

TAC Members
Tri Buu, P.E.
Dan Gorley, P.E.
Bryan Martin, P.E.
Luis Zarate, P.E.

FHWA-Idaho Advisor – Ed Miltner, P.E.

Table of Contents

Executive Summary ix
Introduction ix
Theory/Method ix
Results x
Recommendations xi
Chapter 1 Introduction 1
Background 1
Sites 3
Chapter 2 Methods 7
Theory 7
Thermal Scour/Deposition Chain Probe 7
Project Installation 9
Data Analysis and Verification 10
Chapter 3 Results 11
Chapter 4 Conclusions and Recommendations 17
Conclusions 17
Suggestions for Further Research 19
References 21
Appendix A Project Equipment Costs 25

List of Tables

Table 1. Accuracy Assessment of Method for Each Bridge Location xi
Table 2. List of Items Needed for TSDC Probe, Data Logger, and Installation 25

List of Figures

Figure 1. Project Site Locations 4
Figure 2. Scour Equations Derived from One-Dimensional Heat Diffusion and Advection Equations 7
Figure 3. TSDC Probe with Scour Chain 8
Figure 4. TSDC with Telemetry System and Its Separate Parts 9
Figure 5. Banks Bridge Calculated Bed Elevation and Measured Maximum Scour 11
Figure 6. Pinehurst Bridge Raw Temperature Data Collected from Both Probes 12
Figure 7. Pine Bridge Calculated Vs. Measured Bed Elevations 13
Figure 8. Lemhi Bridge - Calculated vs. Measured Bed Elevations 14
Figure 9. Camas Bridge - C1 Bed Elevation from Telemetry System 15
Figure 10. Camas Bridge May 2017 15
Figure 11. Streambed Elevation Changes at Pine Bridge Compared with the Daily Rate of Change of the Water Flow 18

Executive Summary

Introduction

A major cause of bridge failure is scour, which is the removal of streambed sediment by stream flow, around bridge foundations. Flow around a bridge pier can be fast and highly turbulent causing large hydrodynamic forces that mobilize streambed sediment and form scour holes. The size, extend and potential formation of scour holes also depend on local upstream supply of sediment, which may cause streambed surface to degrade or aggrade. Consequently, bridges may experience both depositional and erosion processes within the same flow event. Due to this dynamic sequence of events, monitoring the evolution of streambed surface elevation is necessary in evaluating scour risk of bridge piers, because scour holes may compromise bridge structural stability. Available methods are typically limited by cost, installation difficulties, may not provide continuous monitoring of streambed elevation changes and their instrumentations can became target for vandalism.

Thus, this project tests a novel low-cost and simple methodology, which overcomes the most common issues with current methods, to monitor streambed elevation continuously. The method uses the naturally occurring daily oscillations of stream water temperatures which present low temperatures at night and high temperatures during the day. This oscillation causes a temperature signal of the stream water, which propagates through the streambed sediment where its phase and amplitude change due to advection, dispersion and diffusion processes. The analysis of these changes can quantify the thermal properties of the sediment and successively the changes in streambed thickness above the point of measurement within the sediment once the thermal property is known. This report presents the findings of field-testing of the method at five Idaho bridges in five different watersheds and demonstrates that the method is robust. The performance of the method was tested to detect maximum scour with scour chains buried near the sensor and to monitor streambed elevations with time series of surveyed streambed elevations.

Theory/Method

Energy exchange (heat) between streams and their surrounding environment causes stream water temperature to have daily oscillations, which resemble a sinusoidal signal. The amplitude and phase of temperature signal change as the signal propagates through the streambed sediment, due to diffusion-dispersion and advection. The proposed method is based on the one dimensional heat diffusion and advection equation and uses the changes in phase and amplitude between stream and pore water temperature signals to detect the sediment thickness between sensors in the stream and in the streambed sediment. The method uses a set of temperature sensors distributed vertically within the streambed sediment to measure pore water temperature. One sensor is always placed in the stream waters and provides the reference temperature signal. The temperature sensors could be embedded into a stake (probe), which is driven into the sediment deeper than the expected scour, if a bridge is already in place, or attached to the bridge foundation as it is built.

The method was tested at five bridges in Idaho: four treatment bridges and a control bridge. The four treatment bridges are Pine Bridge, Lemhi Bridge, Pinehurst Bridge and Camas Bridge and they are scour prone, whereas the control bridge, Banks Bridge, has not been observed with any scour since large rip-rap was placed to protect its piers. At each bridge, two probes approximately 3 to 6.5 feet in length with sensors spaced every 6 inches were installed at one bridge pier. Each probe is installed with a scour chain, whose measurement is then compared with the temperature calculated maximum scour.

The Discrete Fourier Transform method was coded in the programming software, R, with the RStudio interface, to analyze the temperature data and extract phase and amplitude with a two-day window. The thermal property of sediment can be quantified from the phase and amplitude during a period where the streambed elevation does not change. This value is expected to be time invariant because it depends on the sediment characteristics, which should not change much during erosion and deposition unless there is a strong change in sediment composition. Then the thermal property is fixed and it is used along with the phase and amplitude to monitor streambed elevation changes. In this project, the thermal property is calculated from the first ten days of data collection when flow was low and no sediment transport was expected and then is held constant throughout the rest of data analysis.

Results

Project results are very promising showing a high level of accuracy as shown in Table 1. Both scour-chain measured and temperature calculated methods report zero maximum scour at the control bridge, Banks Bridge. Stream water depths were too deep to allow check the scour chain at the Pine Bridge, where we surveyed streambed elevations with an engineering level approximately every month at both probes. The surveyed elevation time series well matched those predicted with the proposed method. High flows at the end of the monitoring period likely tore the wires connecting the sensors to the data logger at Pine Bridge. High flows during the writing of this report prevented us to check whether both probes were scoured or only the cables were broke. However data analysis shows and sudden high scour occurring before sensor data stopped. Calculated maximum scours were within 2 inches of those measured with the scour chain at the Lemhi Bridge. Camas Bridge was used as the primary location to test the telemetry capability of the data loggers. Cellular signal was unreliable at Camas for most of the project period. This caused long periods of missing data, which limited the use of the method. Data at Pinehurst could not be analyzed because all temperature probes provided similar signal. We suggest that a malfunctioning of the temperature sensor or data logger is to cause of the issue.

Table 1. Accuracy Assessment of Method for Each Bridge Location

Bridge and Probe	Measured Maximum Scour (in)	Calculated Maximum Scour (in)	Maximum Error (in)	Minimum Error (in)
Banks – B1	0	0	0	-
Pine – P1	-	-	7.0	0.086
Pine – P2	-	-	18.1	0.51
Lemhi – L1	4	4.91	0.91	-
Lemhi – L2	7.8	10.9	3.05	-
Camas – C1	N/A	N/A	N/A	N/A

The continuous monitoring of streambed elevations with the proposed method shows a yearly pattern of scour and depositional events at all bridges (Chapter 3). This pattern suggests that semi-annual or annual measurements of scour are not sufficient to quantify scour and scour risk. Thus, continuous monitoring methods, such as that proposed in this study, may provide important information, which may help quantify scour risk. The advantages of the proposed method are that (1) it is economical, (2) easy installation especially for new construction, (3) robust and flexible to accommodate different conditions, (4) small such that vandalism may be negligible and (5) coupled with telemetry can provide daily information even for remote locations.

Results of our test at bridges where data was properly collected prove that the method is robust for measuring maximum scour and monitoring streambed elevations. Comparison between ground measured elevation and temperature calculated elevation show some discrepancy after depositional of material very different than the original substrate. We suggest that some of this error could be due to the sharp change in grain size from sand (original substrate) to gravel (new depositional material). This change was observed in the field where gravel deposition occurred after sand was scoured. A stark change in sediment type may change the thermal property of the sediment, which is used to calculate sediment thickness above a sensor. The thermal property is calculated from the first ten days of data collection and then is held constant throughout the rest of data collection. By recalculating the thermal property will reduce the amount of error seen at the Pine Bridge.

Recommendations

We listed below the recommendations based on the literature review and these project results on improving and extending the application of the method:

1. In this project, the maximum scour was 2 feet. However, bridge stability typically depends on several feet of scour. Our probes can be easily manufactured to be longer and still provide an accurate representation of the streambed elevation. Depending on site location, it is recommended that each probe build as assembling modules, which can fit different depths. Thus, each probe can be prepared before installation and then assembled at the site (temperature probe, data logger, and connecting wires).

2. Installation of the probes should occur during low flows for accessibility. In the case of large rivers where depths are not wadable year round, installation can be done with divers, of driving the probes from a crane or bridge deck. For new bridges, installation could occur during construction but additional research is needed to quantify the life span of temperature sensors to match that of the bridge. Research is also needed to explore different installation methodology from those adopted in the project.
3. Probes can be easily fitted with a screw type drive tip that will allow the probes to be drilled into the sediment much easier than driving them into the streambed.
4. Telemetry technique was successful only where 2G cellular coverage was constant and reliable. In areas such as Camas bridge, where coverage was unreliable, telemetry and data collection were poor. This could be the case in remote bridges. In these cases, satellite data transfer would be a better choice than cellular data plan.
5. Research is needed to quantify the effects of thermal property changes due to sediment type change (for instance deposition of sand from gravel as it occurred during our field test) on the accuracy and precision of monitoring streambed elevations. The current method holds the thermal property constant throughout the duration of data analysis. A deposition event can potentially change the type of material at the probe location and therefore change the thermal property. If the thermal property is updated then this error can be minimized. An example on a way to do this is to evaluate the thermal property during a time where streambed elevations are constant and then hold that thermal property constant for calculation.
6. Research is also needed to test different methods to extract phase and amplitude from the temperature signal. Here the discrete Fourier was used. Research should focus on developing a method to use changes in temperature at time scales shorter than daily fluctuation. This would increase the method temporal resolution, which is now at daily resolution.
7. Our method and system can be useful for other important data collecting items for rivers, beyond the scope of this project. Stream and sediment thermal properties, hyporheic fluxes for aquatic habitat characterization, stream gaining and loosing conditions, water depth, discharge, sediment transport, and streambed morphology are a few of the possible applications of the tested system. This could be useful for river restoration projects and companies such as the United States Geological Survey (USGS) to monitor changes in rivers.

Chapter 1
Introduction

Background

The leading cause of US highway bridge failures, in fluvial environments, is scour around the abutments and piers of bridges. The removal of sediment such as sand and gravels, referred to as scour or local erosion, caused by swiftly flowing waters around bridge piers can hinder the stability of bridges, leading to failure.[1,2,3] Depending on upstream sediment supply, flow can scour or deposit sediment around a bridge pier. The National Cooperative Highway Research Program (NCHRP) reported that 1,502 bridge failures, from 1966 to 2005, were the result of scour, approximately 60 percent of bridge collapses in the United Stated are caused by bridge scour in the last 30 years.[4] This resulted in damage repair costs to highways estimated at $50 million per year. [5] In 1993, a single flood event, in the Mississippi and Missouri river basins, caused 22 of 28 bridges failures due to scour, resulting in more than $8 million in repair costs. [6] With a common occurrence of bridge failure due to scour, it has become increasingly more important to monitor bridge scour.

In Idaho alone approximately 198 highway bridges are rated as scour-critical, meaning they are at risk of failure due to scour. [7] The Idaho Transportation Department (ITD) Scour Committee assesses the risk of a bridge to be scoured based on measurements made during annual or bi-annual inspections. ITD uses a proprietary alert system, Bridge Watch, for scour-critical bridges. Bridge Watch takes rain, snow, and stream gauge information to determine the probability of potential scour due to flow events. Once a high flow has been determined by Bridge Watch to reach a certain probability for potential scour a damage assessment or inspection is required to assess the actual damage to the bridge. [8, 9] The most widespread method to monitor bridges is visual inspections. [10] Visual inspections are commonly used in engineering to detect structural anomalies such as cracking and other damages. [11] Divers and survey teams are used to inspect the condition of foundation elements and to measure the depth of scour using basic instrumentation. [12] These methods are limited because the inspections cannot be carried out during times of high flows, when the risk of scour is at its highest. As water subsides from the flood event, scour holes may fill and the maximum scour may not be surveyed. [13, 14] Missing to quantify the maximum scour is dangerous because it can mislead the actual extent of the scour problem. The Bridge Scour Committee of the Idaho Transportation Department has requested a research project to evaluate a new low-cost and simple method that provides continuous monitor scour.

Many different bridge scour monitoring methods have been proposed, such as sonar, radar, time domain reflectometry, sliding collar, seismic, tilt and motion, float out devices, and magnetic fields. [4, 10, 15-22] Each method has advantages and disadvantages. Sonar and radar techniques contain attenuations and noise that make a signal complex, which can make it difficult to retain important information. The noise in a signal is caused by a range of different phenomena such as, multiple channel reflections, echoes from the shoreline, bridge piers/abutments, sediment plumes, and bubbles. [19, 23, 24] Both two and three dimensional sonar systems were designed to monitor scour across a streambed continuously.[19,24] The accuracy of these sensors relies on the frequency emitted; higher frequencies are better for short distances, while low frequencies are better for capturing depths at long distances. Sonar methods have gaps in data where the sonar signal cannot reach, for instance areas around objects or dead zones in the center of a scour hole. Many of the acoustic methods use large in size equipments and require a housing for protection. [(19)] Having a housing set up on the side of a bridge pier is costly and can impede the water flow, causing an unnatural flow event, which may change the scour that occurs at the pier. Mounted sonar sensors can be used to have near real-time monitoring of scour, but other methods use boats that need to be guided across the river and measurements are only taken periodically.

Ground Penetrating Radar (GPR) is another method similar to the sonar method. It employs a coupled source antenna/receiver that produces a short-period pulsed electromagnetic signal at a regular time or distance interval. [(23)] It has two and three dimensional capabilities that provide an accurate depth-structure model. Similar to sonar methods, GPR also has limits on the effective depth of the signal. [(23, 25)] Intensive labor is required to perform scour measurements by this method, preventing the method from being applicable for real time monitoring of scour measurements. [(26-28)]

Many methods such as, scour collars/chains, magnetic collars, radar, and magnetic field changes, are limited to point data collection rather than continuous data. [(20, 22, 23, 25, 28, 29)] Features such as maximum scour can be obtained, while scour patterns may not be captured or interpreted from the data. A high bridge failure rate caused by pier scouring events illustrates the importance of deploying real-time continuous scour monitoring systems. [(20, 29)] Tao et al. (2013) present a time domain reflectometry (TDR) that demonstrates promise in monitoring scour changes in real-time. [(32)] The TDR technique is based on guided electromagnetic wave technology that uses dielectric property mismatches to determine the water-sediment interface. A vibration-based technique has also proven to be applicable to real-time monitoring of bridge scour. [(20, 29)] Zarafshan et al. (2012) present a field application of the vibration-based method that tracks both scour and depositional events rather than only laboratory experiments. [(29)] However, none of the above real-time monitoring methods had an accuracy assessment, comparing data collected with measured scour events.

Lotwick Reese, a hydraulic engineer and ITD project manager, explains, “Current methods for scour detection, which may include ring rods, acoustic and sonar technology, are too complicated, too costly or just impractical. Measurements of streambed elevation are difficult to obtain using the current methods until after high flows have subsided, and when flows subside silt may be deposited potentially masking a scour problem.” This investigation discusses a new low-cost temperature-based monitoring system, called the thermal scour and deposition chain (TSDC), which was tested in laboratory experiments in addition to preliminary field tests for scour and deposition. [(30, 31)] The TSDC method uses the naturally occurring diurnal temperature signal oscillations of stream waters. The amplitude and phase of temperature signal of stream water change as the signal (and maybe surface water) propagates through the sediment and the analysis of this change provide the thermal properties of the sediment. [(30, 31)] Once the thermal properties is quantified, it can be used along with the analysis of phase and amplitude in equations 1-3 in Chapter 2, derived from the one dimensional heat diffusion-advection equation, to quantify changes in bed elevation. [(30)] Tonina et al. (2014) applies the TSDC method in a small agricultural drainage channel, where large scour does not occur. Scour results obtained a root mean square error (RMSE) on the order of 1 cm or 20% error. [(30)] DeWeese (2015) reports an average

RMSE for bed elevation of 0.35 cm and a range of error from 0.70-8.90 cm for laboratory and field experiments, respectively. [31] Whereas previous results are supportive, the TSDC method has not been applied directly to areas of high turbulence and varied flow, such as around a bridge pier.

This study is designed to address the following issues: (1) the validity of the use of the TSDC for bridge scour monitoring, (2) assess the real-time data collection, and (3) create a robust system that transmits data from the field to a graphical user interface (GUI). To address the three aspects of this study, five bridges were selected throughout Idaho. Each bridge is paired with either a maximum scour measurement or monthly survey measurements of streambed elevation. One bridge was chosen as the control site, where no scour is expected, the other four bridges were selected because they are scour-critical. A telemetry system was installed at one of the scour critical bridges to transmit data to a graphical user interface (GUI).

Sites

The study bridges were selected based on the following criteria: (1) presence of a USGS gauge station nearby, (2) accessibility, (3) observed scour/ high risk scour bridge, (4) low flows during installation and (5) have at least one pier. The presence of a USGS gauge station is important because it allows comparing of time series of discharge and scour and depositional events.

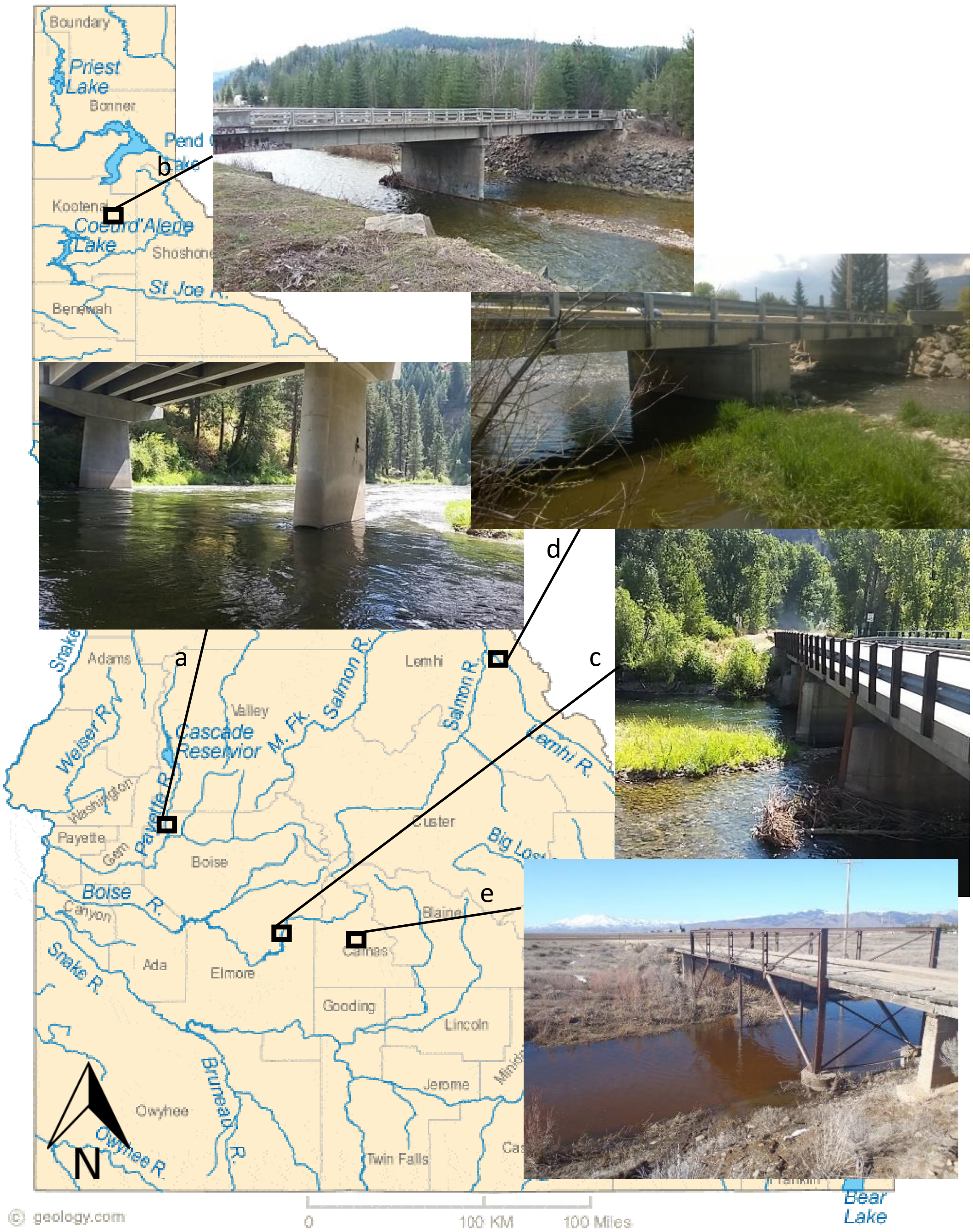

Figure 1. Project Site Locations

Banks Bridge, the control site, is located off of Highway 55 on the North Fork of the Payette River near Banks, Idaho (Figure 1a). The TSDC probe is located on the downstream end of the river right pier. Under the bridge and around the piers, the streambed is highly rip-rapped, therefore no scour is expected to occur.

Pinehurst Bridge is located on Pine Creek in Pinehurst, Idaho just south of Interstate 90 (Figure 1b). The Bridge expands the width of the creek with one pier that is continuously in the water flow. On river left of the pier water can become stagnate during low flows while river right of the pier water flows throughout the year. One probe is located on each side of the pier, where it was possible to drive the probe into the streambed. During installation, gravel was present on both sides of the pier with fine sediment filling in voids. Due to a narrow flow path, higher velocities were expected to occur and thus a substantial amount of scour was expected to occur. A scour chain was pair with each probe.

Pine Bridge is located near Pine, Idaho, on the South Fork Boise River as it enters Anderson Ranch Reservoir. It is a three piers bridge (Figure 1c). The middle pier was selected because of wadable waters during low flows. Two probes were installed at the river right of the middle pier, one on the upstream end and the second just past the center of the pier. At installation, the sediment composition was mainly fine sand and silt material. A gravel bar just upstream of the bridge has been migrating downstream toward the bridge. During site visits, the sediment material visibly changed from fine material to coarser gravel and cobbles. Streambed bathymetric surveys were taken at this site approximately monthly, to compare calculated with measured streambed elevations.

Salmon Bridge, on the Lemhi River, is located in the City of Salmon, Idaho (Figure 1d). The bridge has one pier that is located roughly in the middle of the stream. Two probes are at the downstream end of the pier, placed approximately 10 feet apart. At installation, large gravel and cobbles were located underneath the bridge. We expected to have a minimal amount of scour due to the larger grain size. Calculated scour is verified with maximum scour chain measurements.

Camas Creek Bridge is located on Camas Creek in Fairfield, Idaho (Figure 1e). The bridge has three piers that extend into the streambed, but only one that remains in the main part of the flow throughout the year. One TSDC probe is located just upstream of the middle pier in the main part of the water flow. The Fairfield area has high agricultural use, which introduces a large amount of fine sediment into the creek. At the bridge location, sand and silt cover the creek bed, with bedrock just a few feet below the streambed surface. A large amount of scour and deposition is expected at this site, because of the fine sediment input from anthropogenic sources. Camas Creek Bridge is primarily used as the testing site for the telemetry system and the GUI, ThingSpeak.

Chapter 2
Methods

Theory

Changes in streambed elevations are quantified with analytical solutions based upon the one-dimensional heat advection and diffusion equations from phase and amplitude of the diurnal temperature signals from temperature sensors in the surface water and within the sediment. [30, 33] The streambed elevation is quantified by calculating the sediment thickness between paired sensors in the surface water and the streambed (Eq. 1-3). Differently from previous methods, which estimate the thermal diffusivity from literature, the proposed method quantifies it from the temperature time series obtained during a period, when streambed elevation does not change (Eq. 1 and 2). [34, 35, 37] Then it is kept constant and the sediment thickness is calculated (Eq. 3). The bed elevations are calculated by the addition of the sediment thickness at the temperature sensor elevations. [31]

$$\eta = \frac{-\ln\left(\frac{A_2}{A_1}\right)}{\phi_2 - \phi_1} = \frac{-\ln\,(A_r)}{\Delta\phi} \qquad \text{Eq. (1)}$$

$$K_e = \frac{\omega \Delta z^2}{\Delta\phi^2} * \frac{\eta}{1+\eta^2} \qquad \text{Eq. (2)}$$

$$\Delta z = \Delta\phi \sqrt{\frac{K_e}{\omega}(\eta + \frac{1}{\eta})} \qquad \text{Eq. (3)}$$

Figure 2. Scour Equations Derived from One-Dimensional Heat Diffusion and Advection Equations

Where *A* is the amplitude of the signal, ϕ is the phase of the signal, η is the ratio of the change in amplitude and phase of the paired temperature signals, K_e is the thermal diffusivity of the sediment, ω is the conversion from time into radians and Δz is the calculated sediment thickness above the sensor in the sediment.

Thermal Scour/Deposition Chain Probe

The temperature based scour monitoring system for bridge piers uses the same design developed from past research by Tonina et al. (2014) and DeWeese (2015) (Figure 3). The TSDC probe runs from 1 – 1.5 meters in length with water proof temperature sensors spaced 15 cm apart. The probe itself uses a hollow plastic bar. Holes are bored into the plastic bar, spaced 15 cm, and the sensors run through the hollowed section to each hole. An aluminum drive tip is fixed on the tip of the probe to facilitate driving it into the streambed. A scour chain was attached to the drive tip to validate the method with maximum scour. Depending on the length of the probe and the number of sensors included in the probe, the total cost of the probe alone ranges from $100.00 to $150.00.

Figure 3. TSDC Probe with Scour Chain

Two different types of data loggers are deployed in this project, a non-telemetry and a telemetry setup. The non-telemetry system consists of the following: an Arduino Uno, real time clock (RTC) shield, SD card and a battery pack. The non-telemetry data logger uses an Arduino Uno as the micro-controller of the data logger that communicates with a real-time clock (RTC) and the temperature sensors. Every 15 minutes, the RTC wakes up the system to record the temperature data. The system runs on 6 AA batteries, which provide reliable power for over 9 months. Each non-telemetry setup costs approximately $75, a list of prices per item can be found in Appendix A.

The telemetry setup consists of a more complex shield that raises the price of the data logger and system code (Figure 4). The telemetry setup consists of an Arduino mega, GSM cellular shield, RTC shield, SD card, battery pack and a solar panel. Arduino mega acts as the micro-controller that communicates with the RTC, GSM shield and temperature sensors. The GSM shield uses a 2G cellular data line to send temperature information from the site location to ThingSpeak. ThingSpeak is an open source website used as a graphical user interface (GUI), which uses MATLAB to store data and create visual plots. Temperature data is collected every 15 minutes and stored on the SD card. Using the 2G cellular data line, from AT&T, the GSM shield sends data every hour for the previous hour of data collection. The telemetry system is powered by a battery pack charged by a voltaic solar panel, which provides power to the data logger throughout the year. In the case that the solar panel does not recharge its battery pack quickly enough, a separate battery back with 6 AA batteries provides power to the system while the solar system recharges. The total cost of the telemetry data logger is approximately $325 at installation and $10 monthly for AT&T 2G data service. A breakdown of cost per item is found in Appendix A.

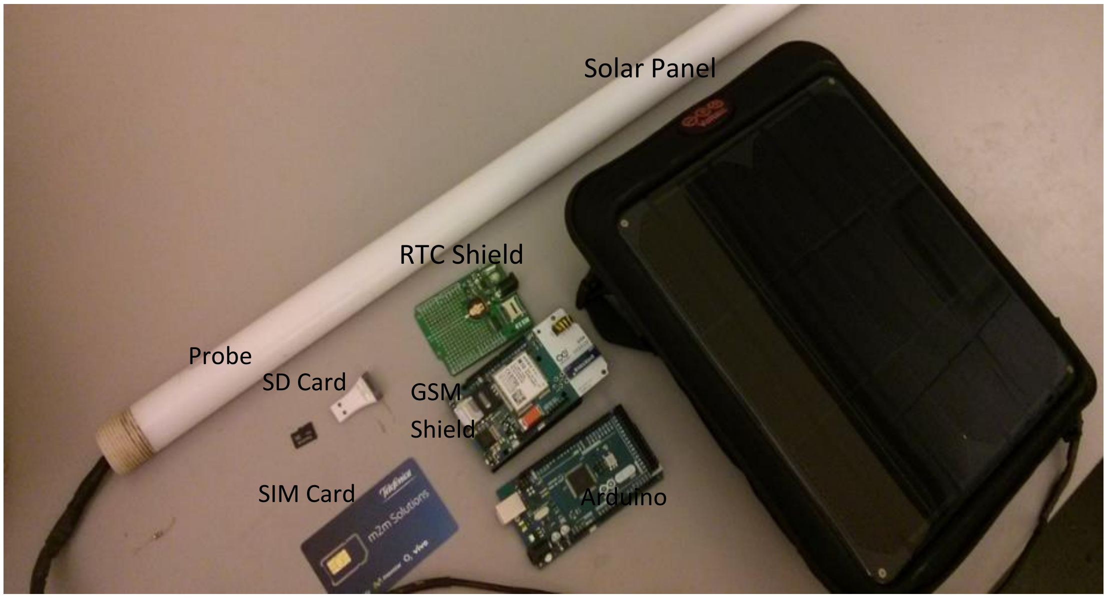

Figure 4. TSDC with Telemetry System and Its Separate Parts

Project Installation

A list of all the required items for project installations is found in Appendix A. The first step is selection of installation location of the probe. For this project, the location of the probe is limited to wadable areas and the probability that a local scour event may occur. At the location, a pilot hole is drilled into the streambed using a 3-foot concrete drill bit. The TSDC probe is then placed into a steel pipe and driven vertically into the pilot hole using a combination of a sledge hammer and a fence post hammer. The probe is driven into the streambed to a depth that leaves at least one sensor in the surface water. After the probe is securely in the streambed, the steel pipe is removed, leaving the instrument in the substrate. A 20ft – 30ft cable is run through half-inch non-metallic flexible conduit, to protect the wires. The conduit is fastened to the side of the bridge pier by using concrete anchors and half-inch steel straps. The data logger is placed inside a Pelican case and strapped underneath the bridge deck or any other place where it is out of reach and sight of the public to prevent vandalism. The cable wires are then run up to the data logger and connected to the Arduino micro-controller using a waterproof cable set. The system then is run either by a 6 AA battery pack or solar panel that is connected to the data logger.

Each site has two probes except, for the control bridge. Once the probes are installed, a survey is taken using an engineering auto level and stadia rod. Three measurements are taken at the streambed, the top of the probe, and a landmark that does not move. An example of a landmark that is used at most bridge sites is one of the conduit anchors on the bridge pier. The streambed and top of probe measurements are compared with the elevation of the landmark to determine the change in bed elevation, as well as, to determine if the probe itself has shifted. At the end of installation, the total cost ranges from $250 to $600 depending on the number of probes installed and the type of data logger used. The estimate does not include labor costs or tools, such as a sledge hammer, drill, drill bit, extra wires, etc (Appendix A). Once installed, the system has a small amount of upkeep, changing the batteries once every 9 months. If a telemetry system is installed, the only other upkeep cost is $10 a month for a 2G cellular service through AT&T.

Data Analysis and Verification

Each temperature sensor buried in the sediment is paired with a sensor in the surface water to quantify the amplitude ratio and the phase shift between surface and subsurface water temperatures. [30] The amplitude and phase of each signal was computed using the Discrete Fourier Transforms with a two-day window, but other techniques are available. [33, 37, 38] All programming is done in R programming language (which is free to use). Once the amplitude and phase of each signal is quantified, equations 1, 2, and 3 are used to determine the thickness of the sediment above each sensor in the sediment. We then compare the thickness above the first sensor in the sediment to calculate the new bed elevation. The addition of the calculated sediment thickness and sensor elevation, obtained from the original survey, gives the new bed elevation. When a scour or deposition event occurs that covers or reveals a sensor to the surface water, we switch the analyzed sensor to compare the first sensor in the sediment with the surface water sensor. Using this method, we can continuously analyze data throughout time.

Results were verified using two different methods: (1) maximum scour chain and (2) monthly streambed elevation surveys using the three original measurements taken. Every probe is fixed with a scour chain so that maximum scour can easily be computed and compared. Banks and Salmon Bridges were verified using a maximum scour chain, but not with monthly surveys, because of travel time to the site location or consistent high flows. The number of chain links out of the bed is counted at installation and the last site visit. When a scour event occurs, the flow from the river pushes the chain that is not lodged in sediment in the downstream direction. At the last site visit, the first chain link to be found vertical in the sediment is the location of maximum scour. Using the difference between the number of links at installation and last data collection event and the length of each chain segment, the maximum scour is computed. Pine Bridge was verified with monthly elevation surveys, but high flows prevented an accurate measure of the scour chain. Each survey consisted of the same three measurements described in the Installation section with an engineering auto level. Comparing the measurements at installation and at each survey provided continuous verification of streambed elevation.

Camas Creek Bridge was not verified with either method because of the hardship with data collection at this site. The bridge served as the test site for the telemetry system. The telemetry system installed at this site uses a Wi-Fi chip to communicate between two different Arduino micro-controllers, because the data signal at the bridge was very weak. One data-logger was installed at the bridge, while the other data logger was elevated on a power line pole to receive a stronger signal. The bridge data logger sent the data to the logger with the GSM cellular shield every four hours. Then the GSM shield system connected to the data network and sends the previous collected data to ThingSpeak.

Chapter 3
Results

Both the scour chain and calculated bed elevation show that the maximum scour is zero at Banks (Figure 5). However, the TSDC probe tracked a deposition event of approximately two inches that occurred during low flow events from fall 2015 to February 2016. The deposition event is scoured back to the original bed elevation each year during the high-flow period. This pattern of deposition and scour occurs on a yearly basis. A noise of approximately ±1 inch is present throughout the year, which is smaller than the median grain size of streambed material. This noise could reflect filling and empting the voids among the large particles of the streambed surface with fine sediment. From the middle of November 2015 to late fall 2016 no data was collected due to persistent ice formed around the probe causing the lack of oscillating signal into the sediment.

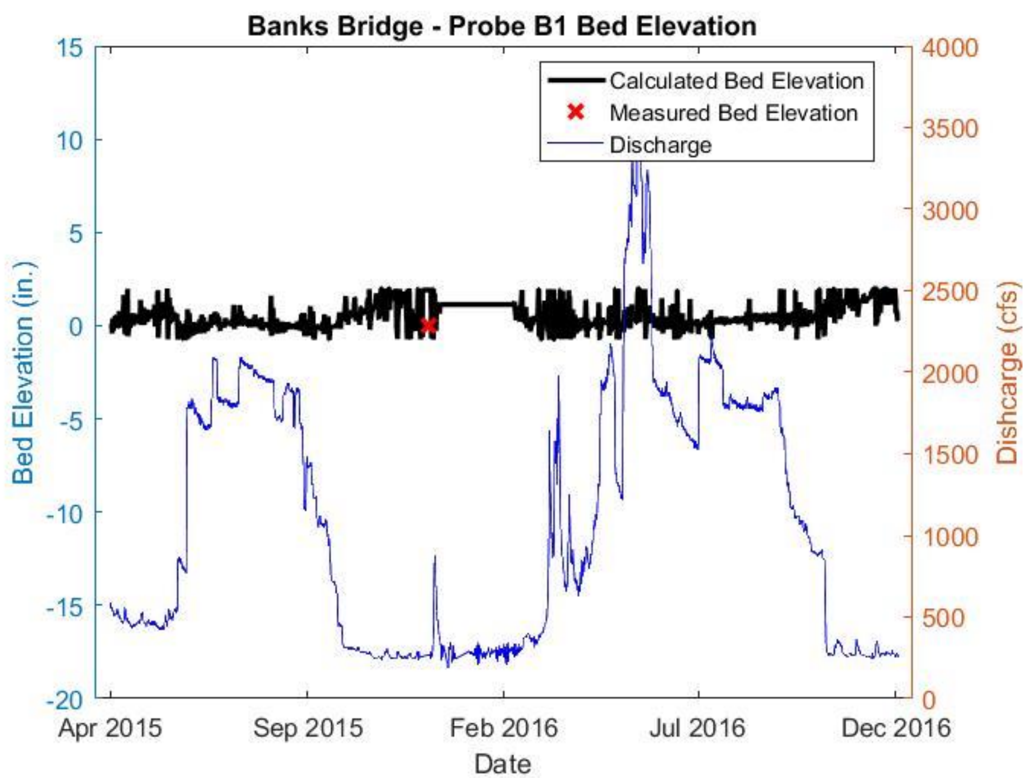

Figure 5. Banks Bridge Calculated Bed Elevation and Measured Maximum Scour

The probes at Pinehurst Bridge had a malfunction in the sensors and no data could be extracted from the signal. Many of the raw temperature data signals extracted from the data laid on top of each other, thus could not differentiate among sensors within the water or sediment (Figure 6). Lack of differences among temperature prevents the use of the method. Pinehurst Bridge was the farthest site from our location and was visited twice besides the installation. During data retrieval, we did not find any issue with the instrumentation and we thought that all was working fine.

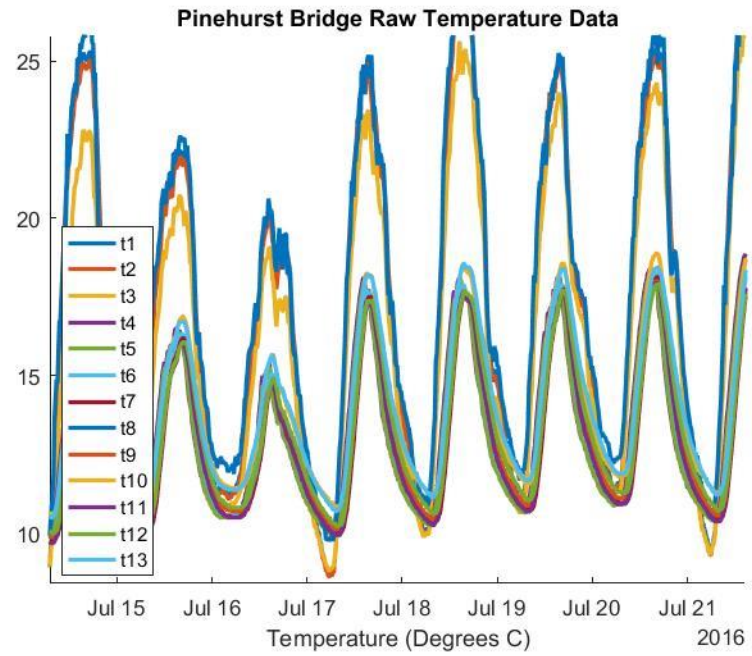

Figure 6. Pinehurst Bridge Raw Temperature Data Collected from Both Probes

The TSDC predicted bed elevations match those surveyed at both probe locations at Pine Bridge (Figure 7). The maximum scour from the scour chain was not available, because the water level at the time of data collection was too high to reach the scour chain on February 2017. The downstream probe has an average error of approximately 4 inches. However, the calculated bed elevation follows same trend of the survey. The continuous monitoring shows scour deposition patter, which occurs yearly. A scour event occurs early, followed by a constant bed elevation up to the winter months where deposition occurs. The maximum scour calculated at the downstream probe was 1.5 feet. The upstream probe has a high level of accuracy in the first half of data collection, with an error of less than an inch, but performance is less accurate from March 2016 to December 2016. Similar to the downstream probe, a scour event happened early on in data collection, however, deposition occurred soon after the scour event. Another rapid scour and then deposition event occurs just from July 2015 to August 2015. During the fall and winter months, the bed elevation remains roughly constant, followed by another scour and deposition event similar to the previous year. During the last visit to collect the data in the first days of May, the wires from the sensor were torn from the data logger and not visible. We expected that the both sensors have been scoured away or the cables detached from their anchors. We could not verify either hypothesis because of the high flows. Probe 1 shows a sudden scour at the beginning of the high flows about 10,000 cfs (Figure 7) but Probe 2 stopped providing data in February during one of our visit.

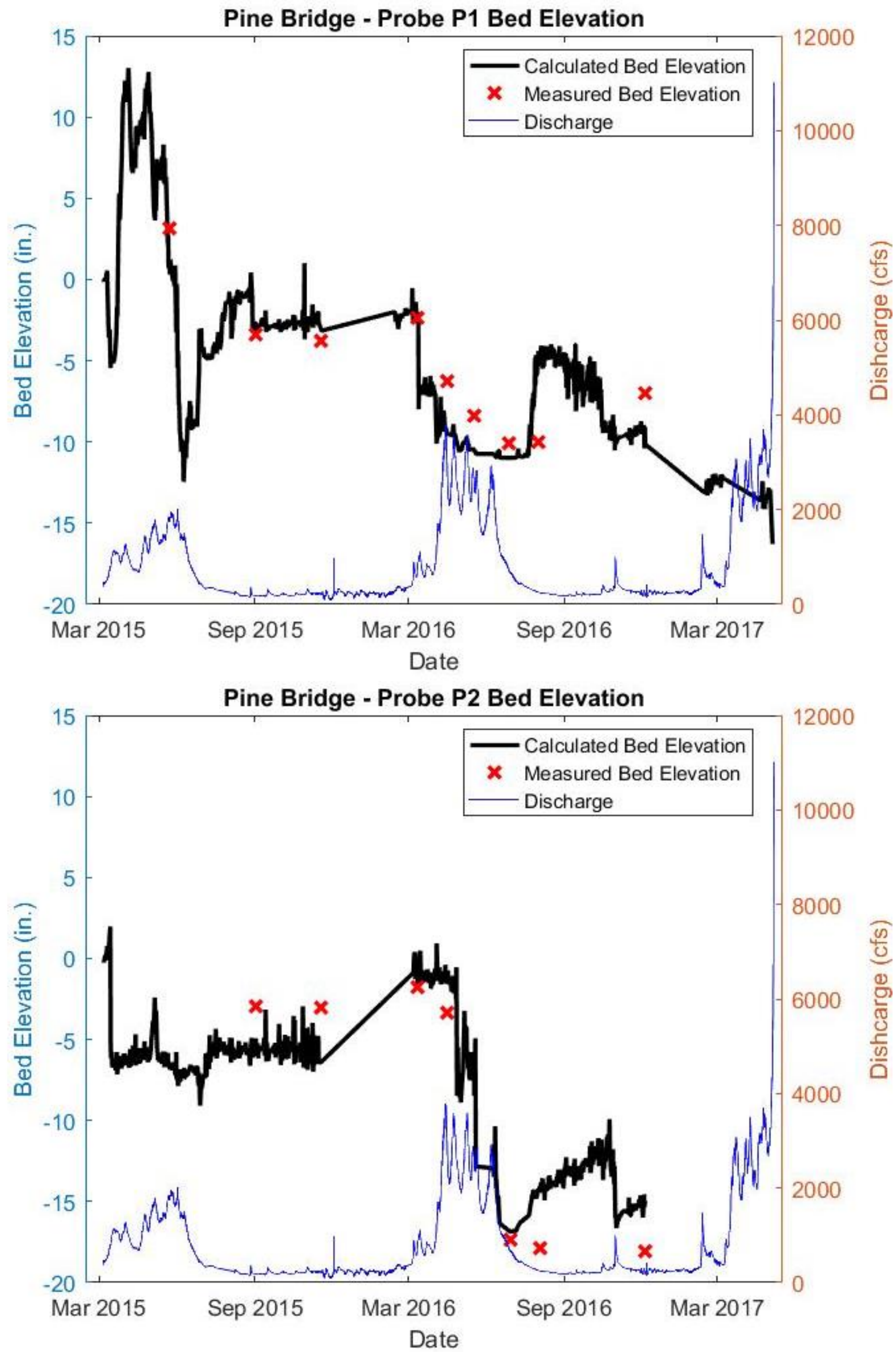

Figure 7. Pine Bridge Calculated Vs. Measured Bed Elevations

TSDC performance has a high accuracy at the Lemhi Bridge (Figure 8). Probe L1 has a maximum scour chain measurement of 4 inches and a maximum scour calculated at just over 4 inches. Probe L2 measured a maximum scour of approximately 8 inches, but a calculated maximum scour of 10 inches. Both probes had a similar pattern of scour early in data collection followed by deposition in the summer. The largest amount of error at Lemhi Bridge was approximately 2 inches, which is comparable to the grain size of the streambed material.

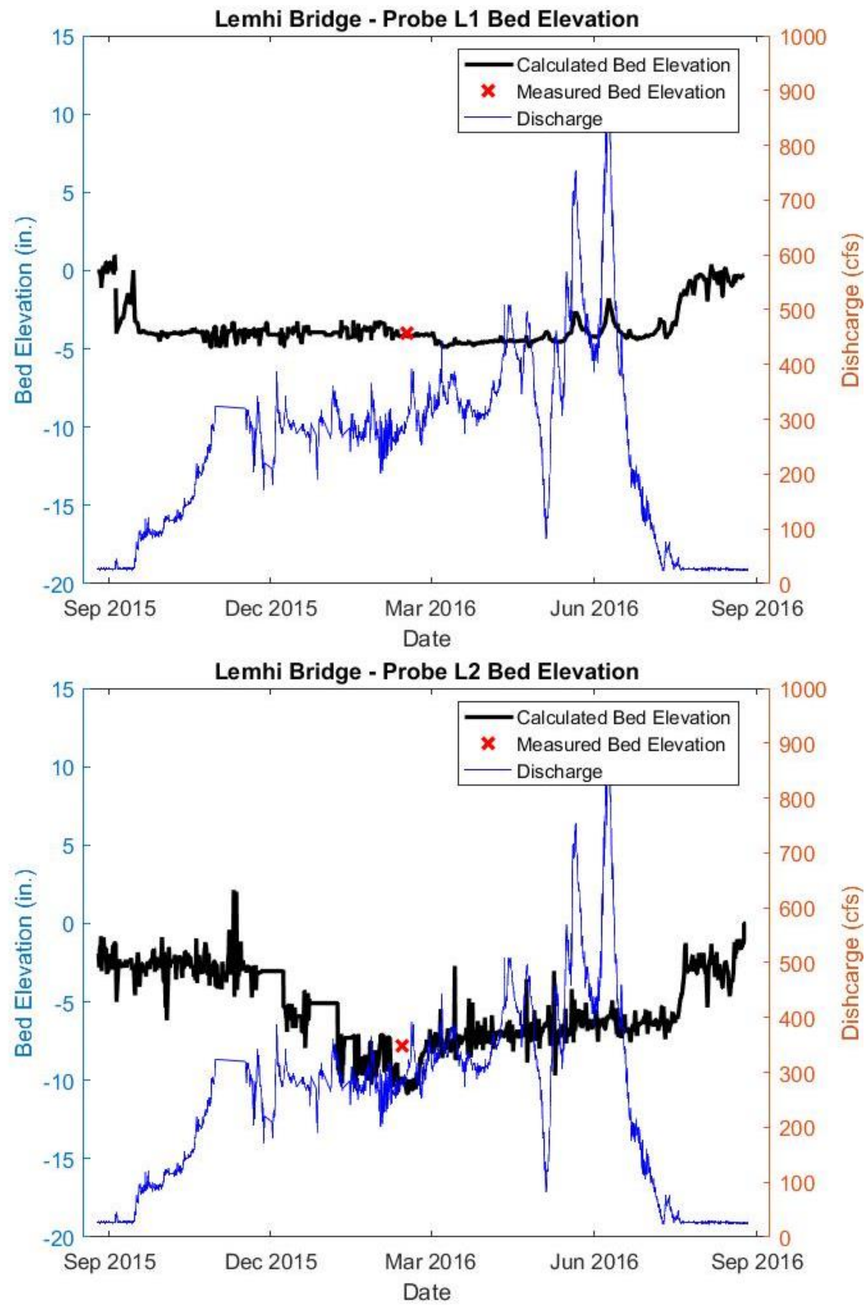

Figure 8. Lemhi Bridge - Calculated vs. Measured Bed Elevations

Camas Creek Bridge was used to test the telemetry system (Figure 9). Data was not sent to ThingSpeak from April 2016 to June 2016. However, data was collected and sent to ThingSpeak from the middle of March 2016 to April 2016 and in June 2016. During times of data collection, bed elevation remained roughly constant, except in the middle of June, 5 inches of deposition occurred.

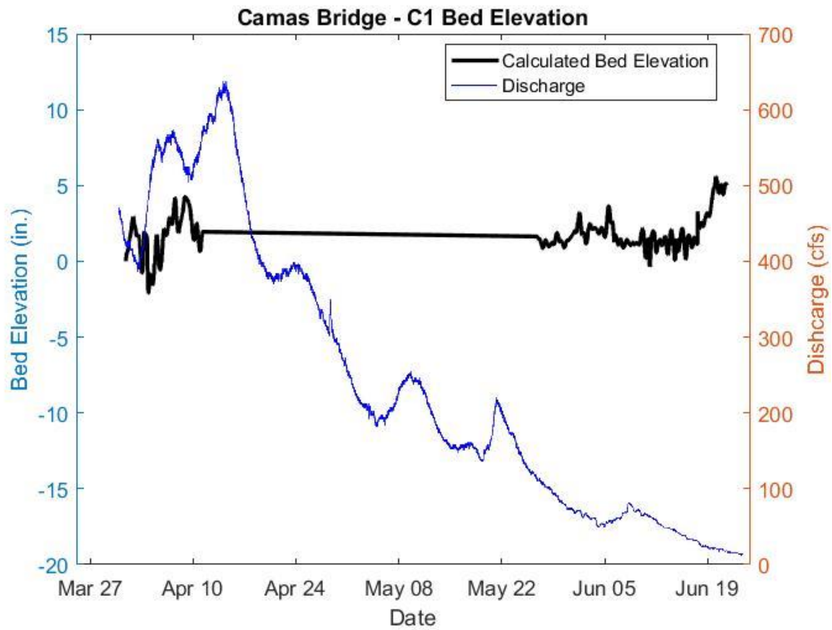

Figure 9. Camas Bridge - C1 Bed Elevation from Telemetry System

A high water year in 2017 made it difficult to successfully collect data and survey certain bridges such as Camas and Pine Bridges. Flooding and high water created obstructions to roadways and did not allow access the data logger and the probes at Camas in Spring 2017 (Figure 10).

Figure 10. Camas Bridge May 2017

Chapter 4
Conclusions and Recommendations

Conclusions

Comparisons of both maximum scour and time series show good match between TSDC and ground surveyed streamed elevation. The maximum error was four inches and occurred at Pine Bridge before we lost connection with the probes due to high flows. We hypothesized that this error is the result of the change in sediment composition, from fine sand to coarse gravel (Figure 7). Pine Bridge has a gravel bar migrating downstream underneath the bridge, depositing a different substrate at the probe location from that observed during installation. During installation, the substrate consisted of fine sand and silt material, while the substrate consisted of gravels and cobbles at the February ground surveys. The change in substrate may cause a potential limitation to our method, because the thermal property may change with substrate size. However, we do not know the sensitivity of the error to changes from sand to coarse gravel. Further research in quantifying the effect of changes in sediment type on thermal properties will help determine the sensitivity of the error. To account for the change in substrate, for the current method, the thermal diffusivity of the sediment has to be recalculated for a period where there is no change in bed elevation, and then held constant for the rest of data collection. As it relates to bridge scour, feet of erosion is of more interest than a few inches. At sites where the substrate did not change (Banks and Salmon Bridges) the maximum scour chain correlated closely with the method results.

The results of this study captured a very dynamic system with multiple scour and deposition events that cannot be detected with surveys taken once or twice a year. Yearly measurements may provide a false picture of stationary streambed elevation, when truly both scour and deposition events are occurring[10]. Banks and Salmon Bridges experience a pattern of scour followed by deposition up to the original bed elevation at low flows. This pattern seems to occur yearly, which may not be captured by a yearly survey of the bridge pier. Perhaps a yearly survey may detect a scour, which may not be the maximum, or may detect a deposition event with the results on false security of low scour risk.

Scour events are often said to be correlated with flood or high flow events. (20, 24, 29, 32) However, our results reveal that high flow is not the only cause of scour events. High discharges and scour have small correlation at all bridge sites in this study. It seems that local conditions, such as sediment supply, have more to do with the amount of scour than high flows. Our results also reveal a correlation between scour and the rate of change in discharge (Figure 11). When a rapid increase in discharge occurs at our bridge location, a scour event happens. We believe that these rapid changes may cause a larger scour because of the change in flow characteristics at the bridge. Quick changes from slow velocities around the pier to fast velocities cause a rapid change in shear stress allowing particles to move. Another factor that may play a role in the rate of discharge is that when discharges are at the highest throughout the year, the maximum scour has already occurred. Therefore, our results report that multiple events contribute to the occurrence of scour rather than just high flow events.

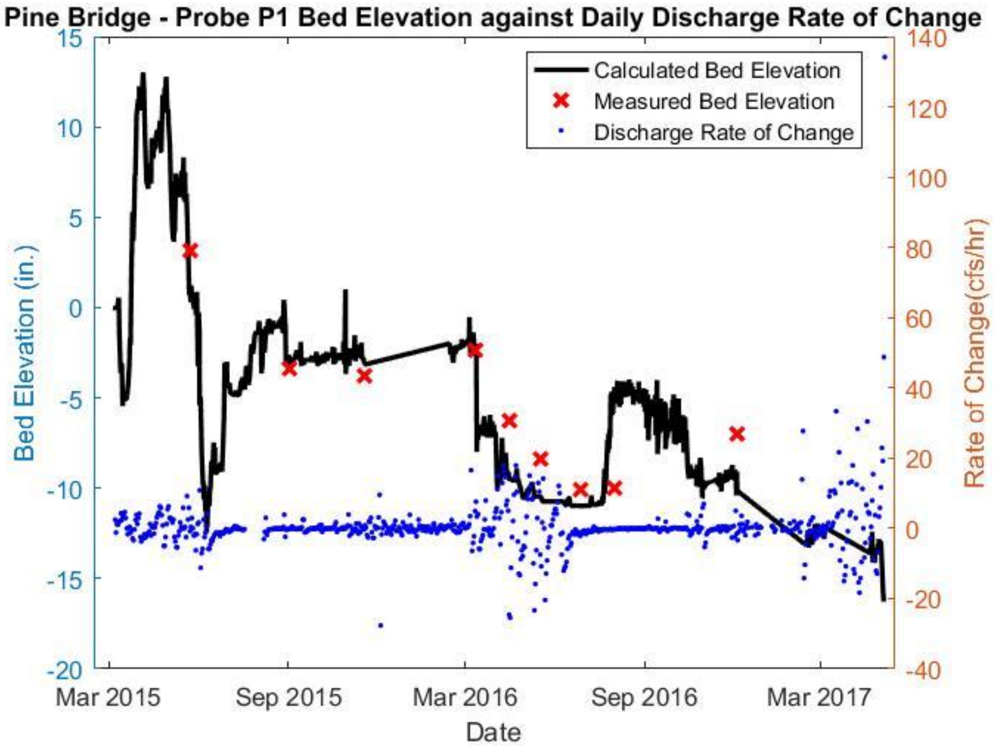

Figure 11. Streambed Elevation Changes at Pine Bridge Compared with the Daily Rate of Change of the Water Flow

Pinehurst Bridge was the only site in which we had difficulty analyzing the temperature data to obtain the correct bed elevation. The phase or lag of the signal propagating through the sediment was not consistent and proposed problems in calculation of bed elevation. Phenomena such as water upwelling, stratified sediment composition, large material, and data location are all factors that could have had an effect on the signal. However, our method is able to account for these phenomena. Thus we hypothesized that probe sensors may have malfunctioned or present some cross-talking which cause several temperature sensors to have nearly identical signals.

Our results for testing the telemetry system at Camas Creek Bridge show that reliable coverage is necessary. There are times when the collected temperature data is reliably sent to ThingSpeak, but some event happens in which the system stops working, comes back online and then completely shuts down later. We suggest that this is due to the instability of the service connection at the bridge location, which is verified with talking to local residents whom acknowledge the lack of consistent cellular service in the area. We were able to set up a system in the city of Boise, in which temperature data is continuously sent to ThingSpeak every hour. In the city, the same 2G cellular service as the location of Camas Creek Bridge is used reliably for several months. We used a 2G cellular service because of the low-cost data plan, however, other data plans including 3G, 4G and satellite are available, but have a higher range of prices per month. The telemetry system is a viable system if a different data plan to send temperature values to ThingSpeak is implemented.

Our method provides an accurate way to measure scour and deposition processes to help in bridge design and assess the stability of bridges. We were able to verify the method in the field by using the combination of a scour chain and periodic field surveys. In our study, we were able to collect data continuously at the majority of the sites for over a year tracking the streambed elevation within a couple of inches of the actual bed elevation. Although, processing the data still takes manual inputs and changes the method can be used to monitor streambed elevations in real-time with a few adjustments to the coding. These adjustments would allow the scour to be detected every fifteen minutes and warning system can be implemented. Our data logger system provided data for over a year at several sites proving how robust the simple data logging system can be. Cellular and data coverage was checked at Camas during installation. However, their reliability varied during the day and season. This affected our study of the telemetry. Changing the method to a more reliable signal, for example satellite, would allow consistent uploads to a GUI, making the telemetry system more reliable. However, with few flaws in the data logging system our method proved to be a reliable method to monitor streambed changes, scour, continuously at low-cost and minimal manual labor. The temperature-based method is not limited to bridge scour monitoring, but can be extended into other monitoring and research applications, such as bank erosion, levee and other hydraulic structures. Using an array of temperature probes, placed perpendicular to the flow, this method can be used to determine water depths and streambed cross sections. With several probes placed throughout the streambed, the evolution of the morphology of the river can also be monitored over time. A research extension of this method includes using the temperature-based systems to determine the amount of fines in the streambed, clogging of gravel. As this report shows, using a temperature-based method is a low-cost easily deployed monitoring system for bridge scour.

Suggestions for Further Research

The following suggestions are provided to improve and extend the scope of the proposed method.

Installation: improvements of the method for bridge scour include creating a more efficient installation process, which is flexible for different water depth conditions and testing the probes at bridges with several feet of scour and deposition, in this project the maximum scour was approximately 2 feet. Current installation method limits the installation during shallow and wadable water conditions. This limits the installation to certain times of the year. This also limits data collection to rivers accessible by wading at time of installation. Therefore, the current installation method cannot be applied to monitor large rivers or areas of deep water. This limitation can be overcome by modifying the installation process. Several alternatives are suggested, which include divers, working with crane from the bridge deck and installing the sensor directly in the bridge structure during construction. Divers could install the sensor in deep locations. From the deck, a drill could place the instruments in the streambed while keeping all the wires intact. During bridge construction, probes can be cast in place to extend the entire length of the pier, while also concealing wires in the pier structure to avoid exposed wires. For locations expecting several feet of scour, a modular probe can be fabricated such that it can be driven easily into the sediment, below the expected maximum scour. The first module could have a drive tip and the installation could occur rotating the entire unit as a screw. The additional modules are then appended as the unit is driven in the sediment.

Another limitation to the TSDC probe is the location where it can be driven into the sediment. Coarse material makes it difficult to drive the probe deep into the sediment. A thinner than presently used diameter design with a drive tip, which acts like a screw would allow easier installation into the streambed, increasing the range of areas where the probe can be installed. Using a data logging system that communicates between two data loggers, one waterproof logger connected to the probe and one on the bridge abutment, eliminates the use of long wires and reduces the possibility of damaging the equipment. However, the communication between two loggers transmitting data through the water can be complicated and unreliable.

Telemetry technique was successful only where coverage was constant and reliable. In areas such as Camas bridge where coverage was unreliable, telemetry and data collection were poor. This could be the case in remote bridges. In these cases, satellite data transfer would be a better choice than cellular data plan because it would be reliable. The amount of data would be very small thus keeping the cost low.

Data analysis: phase and amplitude are currently extracted with Discrete Fourier Transform method. However, other methods are available. Research should test alternative methods to quantify phase and amplitude from the temperature signal. This could potentially improve the accuracy of the system. Additionally, research should also focus on developing algorithms which could use information from the temperature signal at time-scale shorter than daily. This will increase the temporal resolution of the method.

Streambed sediment effect: Research is needed to determine the uncertainty due to change in sediment composition, which may vary the thermal properties of the streambed. The current method holds the thermal property constant throughout data analysis, which may cause some error as scour and deposition events change the composition of the sediment. This effect could be accounted by recalculating the thermal property by holding the bed elevation constant between a sensor in the water and one in the sediment during low flows (when streambed is static) or by pairing the two near-streambed surface adjacent sensors within the sediment because their distance is fixed.

Other applications: the tested method is not limited to the measurement of scour and deposition; it can be implemented to find other information relevant to rivers, such as, stream and streambed thermal properties, hyporheic fluxes, stream gaining and loosing conditions, water depth, sediment transport, and streambed evolution. This method can be used for river restoration monitoring efforts and the United States Geological Survey (USGS) to monitor processes within the river. With only minor adjustments or analysis, this project can be adapted in a variety of ways to help in many areas of river monitoring.

References

1. **Saito E, Sato S, and Shibayama T**., *Local Scour around a Large Circular Cylinder Due to Wave Action,* 22nd International Conference on Coastal Engineering, 1990.

2. **Katsui, H., & Toue, T.**, *Methodology of Estimation of Scouring Around Large-Scale Offshore Structures,* International Society of Offshore and Polar Engineers, 1993.

3. **Sumer, B. Mutlu and Jorgen Fredsoe**, "Scour around Pile in Combined Waves and Current", *Journal of Hydraulic Engineering,* 2001.

4. **Hunt, B.E.,** *Monitoring Scour Critical Bridges: A Synthesis of Highway Practice*, NCHRP Synthesis 396, Transportation Research Board, National Academy of Science, Washington, DC, 2009.

5. **Lagasse PF, Schall JK, Johnson F, Richardson EV, and Chang F.**, *Stream Stability at Highway Structures,* Washington DC, 1995.

6. **Kamojjala S, Gattu NP, Parola AC, Hagerty DJ.**, *Analysis of 1993 Upper Mississippi flood highway infrastructure damage,* In:Proceedings of the 1st international conference of water resource engineering. New York: American Society of Civil Engineers, pp. 1061-5, 1994.

7. **The Transportation Department**, *Field Manual. Scour Critical Bridges: High-Flow Monitoring and Emergency Procedures*. Boise, ID. Ayres Associates. Fort Collins, Colorado. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/idfieldpoa.pdf, 2004.

8. "Researchers Test Low-cost Thermal Method to Monitor Bridge Scour." Blog post. *The Transporter*. Idaho Transportation Department, 13 Mar. 2015, Web. 25 Apr. 2017, <http://apps.itd.idaho.gov/apps/MediaManagerMVC/transporter/2015/032015_Trans/032015_BridgeScourStory.html>.

9. **The Transportation Department**, *Idaho Manual for Bridge Evaluation,* http://apps.itd.idaho.gov/apps/bridge/manual/IMBE2016.pdf, 2016.

10. **Prendergast, L.J. and Gavin, K.**, "A review of bridge scour monitoring techniques", *Journal of Rock Mechanics and Geotechnical Engineering,* 6, pp. 138-149, 2014.

11. **Sohn H, Farrar CR, Hermez F, and Czarnecki J.,** *A review of structural health monitoring literature: 1996-2001*. Los Alamos National Laboratory, pp. 1-311, 2004.

12. **Avent RR and Alawady**, "Bridge scour and substructure deterioration: case study", *Journal of Bridge Engineering*, 10(3), pp. 247-54, 2005.

13. **Lin YB, Lai JS, Chang WY, Lee FZ, and Tan YC**., "Using mems sensors in the bridge scour monitoring system", *Journal of the Chinese Institute of Engineers*, 33(1), pp. 25-35, 2010.

14. **Foti S and Sabia D.**, "Influence of foundation scour on the dynamic response of existing bridge", *Journal of Bridge Engineering,* 16(2), pp. 295-304, 2011.

15. **De Falco F, & Mele R**., "The monitoring of bridges for scour by sonar and sedimetri" *NDT&E International,* 35(2), pp. 117-23, 2002.

16. **Kenney, T. A., & McKinney, T. S**., *Hydraulic and Geomorphic Monitoring of Experimental Bridge Scour Mitigation at Selected Bridges in Utah*, 2003-05. Salt Lake City, UT: United States Geological Survey, 2006.

17. **Lee, S., & Sturm, T**., "Effect of Sediment Size Scaling on Physical Modeling of Bridge Pier Scour", *Journal Of Hydraulic Engineering-Asce*, 135(10), pp. 793-802, 2009.

18. **Yao, C., Darby, C., Hurlebaus, S., Price, G., Sharma, H., Hunt, B.E., Yu, O.-Y., Briaud, J.-L**., *Scour Monitoring Development for two Bridges in Texas,* International Conference on Scour and Erosion 2010, pp. 958-967, 2010.

19. **Hayden, J. T., & Puleo, J. A.,** "Near Real-Time Scour Monitoring System: Application to Indian River Inlet, Delaware" *Journal Of Hydraulic Engineering – ASCE,* 137(9), pp. 1037-1046, 2011.

20. **Fisher, A. M., & Khan, A.,** "A novel vibration-based monitoring technique for bridge pier and abutment scour", *Structural Health Monitoring,* 12(2), pp. 114-125, 2013.

21. **Junliang, T., Yu, X., & Yu, X.,** *Real-time TDR Field Bridge Scour Monitoring System,* Structures Congress 2013: Bridging Your Passion with Your Profession, pp. 2996-3009, 2013.

22. **Chen, G., Schafer, P. B., Zhibin, L., Huang, Y., Suaznabar, O., Shen, J., & Kerenyi, K.**, "Maximum scour depth based on magnetic field change in smart rocks for foundation stability evaluation of bridges", *Structural Health Monitoring*, pp. 86-99, 2015.

23. **Anderson, N., Ismael, A., & Thitimakorn, T.**, "Ground-penetrating radar; a tool for monitoring bridge scour" *Environmental & Engineering Geoscience*,13(1), pp. 1-10, 2007.

24. **Topczewski, Lukasz, Ciesla, Juliusz, Mikolajewski, Pawel, Admaski, Pawel, and Markowski, Zenon,** "Monitoring of scour around bridge piers and abutments", *Transportation Research Procedia*, 14, pp. 3963-3971, 2016.

25. **Nichol D. & Reynolds J.M.**, "Ground penetrating radar survey to detect scour holes beneath the A525 highway at Nant-y-Garth, Wales: a case history", *Quarterly Journal of Engineering Geology,* 32, pp. 157-162, 1999.

26. **Horne, W.A.,** *Scour Inspection using Ground Penetrating Radar,* Proceedings of National Conference on Hydraulic Engineering, San Francisco 1993, pp. 1888-1893, 1993.

27. **Forde, M.C., McCann, D.M., Clark, M.R., Broughton, K.J., Fenning, P.J. and Brown, A**., "Radar Measurement of Bridge Scour", *NDT&E International* 32, pp. 481-492, 1999.

28. **Webb, D.J., Anderson, N.L., Newton, T. and Cardimona, S**. *Bridge Scour: Application of Ground Penetrating Radar*, Federal Highway Administration and Missouri Department of Transportation Special Publication, 2000.

29. **Zarafshan, A., Iranmanesh, A., and Ansari, F.,** "Vibration-Based Method and Sensor for Monitoring of Bridge Scour", *J. Bridge Eng.*, 17(6), pp. 829-838, 2012.

30. **Tonina, Daniele, Charles Luce, and Frank Gariglio**. "Quantifying Streambed Deposition and Scour from Stream and Hyporheic Water Temperature Time Series", *Water Resources Research* 50 (1), pp. 287-92, doi:10.1002/2013WR014567, 2014.

31. **DeWeese, T.,** *Monitoring streambed scour/deposition using non-sinusoidal water temperature signals and during flood events*. MS Thesis, Department of Civil Engineering, University of Idaho, 2015.

32. **Tao, Juliang, Yu, Xinbao, and Yu, Xiong.**, *Real-time Field Bridge Scour Monitoring System,* 2013 ASCE Structures Congress, 2013.

33. **Luce, Charles H., Daniele Tonina, Frank Gariglio, and Ralph Applebee**,"Solutions for the Diurnally Forced Advection-Diffusion Equation to Estimate Bulk Fluid Velocity and Diffusivity in Streambeds from Temperature Time Series", *Water Resources Research,* 49 (1), pp. 488-506, doi:10.1029/2012WR012380, 2013.

34. **Constantz, Jim**, "Interaction between Stream Temperature, Streamflow, and Groundwater Exchanges in Alpine Streams"' *Water Resources Research,* 34 (7), pp. 1609-15, doi:10.1029/98WR00998, 1998.

35. **Lautz, Laura K.**, "Observing Temporal Patterns of Vertical Fluz through Streambed Sediments Using Time-Series Analysis of Temperature Records", *Journal of Hydrology* ,464-465, pp. 199-215, doi:10.1016/j.jhydrol.2012.07.006, 2012.

36. **Hatch, Christine E., Andrewe T. Fisher, Justin S. Revenaugh, Jim Constantz, and Chris Ruehl**, "Quantifying Surface Water-groundwater Interactions Using Time Series Analysis of Streambed Thermal Records: Method Development", *Water Resources Research,* 42 (10), W10410, doi:10.1029/2005WR004787, 2006.

37. **Keery, John, Andrew Binley, Nigel Crook, and JOnathan W.N. Smith**, "Temporal and Spatial Variability of Groundwater-surface Water Fluxes: Development and Application of an Analytical Method Using Temperature Time Series", *Journal of Hydrology,* 336 (1-2), pp. 1-16, doi:10.1016/j.jhydrol.2006.12.003, 2007

38. **Swanson, Travis E., and M. Bayani Cardenas**, "Diel Heat Transport within the Hyporheic Zone of a Pool-Riffle-Pool Sequence of a Losing Stream and Evaluation of Models for Fluid Flux Estimation Using Heat", *Limnology and Oceanography,* 55 (4), pp. 1741-54, doi:10.4319/lo.2010.55.4.174, 2010.

Appendix A
Project Equipment Costs

Table 2. List of Items Needed for TSDC Probe, Data Logger, and Installation

	Item	Cost
TSDC Probe	Water proof temperature sensor (DS18B20)	$10.00/sensor
	Water proof wire cable connector set	$2.00/set
	Aluminum drive tip (1.5” diameter)	$1.00/in.
	Engineering plastic bar (1.25” diameter)	$4.22/ft.
	Scour Chain	$2.00/ft.
Data Logger: Non – Telemetry System	Arduino Uno	$30.00
	Data Logging Shield with Real Time Clock	$14.00
	4GB micro SD card	$7.00
	Pelican case	$20.00
Data Logger: Telemetry System	Arduino Mega	$45.00
	GSM shield	$40.00
	MicroSD card	$7.00
	Data Logging Shield with Real Time Clock	$14.00
	AT&T 2G data service	$10.00/month
	Voltaic Solar Panel	$200.00
	Pelican case	$20.00
Installation tools	Steel pipe	
	Sledge hammer	
	Fence post hammer	
	3/4” flexible conduit	
	Concrete anchors and straps	
	Engineering Auto Level	
	Stadia Rod	
	20’-30’ cables	