Thermal scour-deposition chain

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Executive summary

A new thermal scour-deposition chain is currently under development. The instrument will be capable of measuring scour and deposition in stream beds at a daily time scale using temperature differences induced by diurnal temperature variation. This device will be an improvement upon the frequently utilized scour chain, which is capable only of measuring maximum scour and subsequent maximum deposition, with timing information limited to the period deployment.

This project has two objectives: (1) demonstrate precision in predicting and quantifying scour-deposition using temperature time series data through laboratory experimentation and (2) develop a prototype field temperature sensing and data logging instrument for future commercialization. To demonstrate precision in the laboratory, a sediment tank was designed to mimic natural streambed processes, including cyclic temperature surface water flow, a sand stream bed with pore water flux in both upwelling or downwelling conditions, and scour-deposition sequences. Design elements included the sediment tank and water flow control, supply water temperature mixing controls, and temperature sensing and data logging equipment. Laboratory design efforts were also used to aid in development of the thermal scour chain for use in the field. A modular temperature sensing probe and data logger system was designed and applied in a live stream. The new thermal scour chain uses digital temperature sensors and an on board microcontroller to collect temperature data from up to 1 meter deep in a river bed.

Results from the laboratory show promise, and the thermal scour chain instrument design is improving. Laboratory results demonstrate excellent streambed elevation predictions during scour and deposition sequences, with root mean squared error (RMSE) less than 15%. Error may be reduced with added turbulence in the sediment tank surface water to decrease temperature stratification within the surface water. Thermal scour chain instrument improvements were necessary during field deployment, including redundant waterproofing and programming. Future development efforts will include these modifications. Next steps for commercialization of the thermal scour chain include (1) upgrades to the instrument for improved waterproofing, installation, and strength (2) added wireless networking capabilities for remote scour-deposition monitoring and (3) development of a computer graphical user interface (GUI) that simplifies scour-deposition calculation and plotting procedures.

Project expenditures totaled $44,675.67, leaving a balance of $1074.33 after budget closing. Patent applications have been submitted: U.S. Patent Application No. 13/890,919, METHOD AND APPARATUS FOR MONITORING WATERBED ENVIRONMENT USING TEMPERATURE MEASUREMENTS; U of I Ref. No. 12-009, KS Ref. No. 7832-91088-01. Project collaboration is ongoing and includes the Idaho Department of Transportation and the Hydro Research Foundation.

Thermal scour chain instrument development is ongoing, and results from this project show promise. Future outcome will be a tool which will not only provide real time monitoring of stream bed scour-deposition, but also simultaneously measure surface/subsurface water exchange and sediment thermal regime, both highly applicable for river ecology, engineering, and management knowledge advancement.

Table of Contents

Table of Figures

1. Introduction

A new thermal scour-deposition chain instrument is currently under development. Using a new mathematical method (Tonina, et al., 2014) and (Luce, et al., 2013), the device will be capable of indirectly measuring erosion (scour) and deposition in a stream bed at a daily time scale using temperature differences in surface and pore waters induced by diurnal temperature variation. A common method of measuring scour-deposition is the scour chain. This device can provide maximum scour and deposition during a time frame of installation but cannot provide time series data of scour-deposition (Mueller, 1998). This new thermal scour-deposition chain aims to provide an improved and inexpensive method to provide real time stream data useful in water resource management practice.

A laboratory model has been designed, assembled, and run to demonstrate reduced error using the temperature scour chain theory, as well as provide design basis for temperature scour chain product development. The model is a scaled system that attempts to replicate pore water flow into and out of a stream bed, periodic temperature cycling, and can measure temperature data throughout the sediment layer in the tank. A sinusoidal wave temperature source mimics naturally occurring daily temperature variation in a stream. Temperature data is logged over time and plotted to provide values necessary for calculating sediment scour or deposition. A prototype for the field application temperature scour-deposition chain is under development, and the second beta testing version has been installed in a live stream for testing. This report outlines project design in the laboratory and thermal scour chain development progress.

2. Methods

The thermal scour-deposition chain project has two primary objectives: (1) demonstrate precision in predicting and quantifying scour-deposition using temperature time series data through laboratory experimentation and (2) develop a prototype field temperature sensing and data logging instrument for future commercialization. The following laboratory experiment and field temperature probe sections describe designs for these objectives.

2.1 Laboratory Experiment

To demonstrate precision in predicting scour-deposition in the laboratory, a sediment tank was designed to mimic natural streambed processes, including cyclic temperature surface water flow, a sand stream bed with pore water flux in both upwelling or downwelling conditions, and scour-deposition sequences. Design elements included the sediment tank and water flow control, supply water temperature mixing controls, and temperature sensing and data logging equipment. Each design is outlined below.

Sediment tank: The 40 cm square, 80 cm tall sediment tank (Figure 1) is constructed of 3/8 inch clear cast acrylic sheeting. The tank bottom has two layers, the first of which, with respect to water flowing down through the tank, is a grid of 100, 3/16” holes that help maintain vertical flow streamlines through the above sediment matrix. Five centimeters below the grid and 5 cm above the tank wall bottom is the tank bottom, which has a centered barbed hose fitting for

Figure 1. Assembled tank.

connection of the upwelling/downwelling plumbing. This section between the grid and tank bottom is void of sediment and allows draining/upwelling water to be collected without affecting flow lines through the sediment. Clear poly (3/8" OD, 1/4" ID) tubing was selected for the hydraulic system. Flow rate control is accomplished through constant head tanks for supply and upwelling/downwelling flows. The supply tank is fed by the controlled temperature mixing valve, and the upwelling tank is fed by cold water. Constant head is maintained through 1 inch PVC stand pipe drains. Plumbing for the sediment tank is set up such that surface water flows through the top section of the tank and out through a stand pipe drain and down welling or upwelling pore water flow may be induced through a bottom tube to mimic pore water flow in the stream bed. Sand-gravel substrate with grain size ranging from approximately 0.5 mm to 4.0 mm is placed in the tank to an initial total depth of 45 cm.

Temperature control: An Omron CP1L-EL20DR-D programmable logic controller (PLC) automatically operates a Honeywell MN7505 temperature control actuator on a Honeywell VBN3 mechanical mixing valve to provide controlled source water temperature (Figure 2). Temperature control parameters for the PLC are selectable through a programmable graphical user interface (GUI) using Indu-Soft Web Studio (http://www.indusoft.com/Products-Downloads/HMI-Software/InduSoft-Web-Studio). The GUI also provides capability to graph and monitor the controlled temperature. Feedback temperature for PLC control is provided with an HSRTD-3-100-A-180-E, hermetically sealed waterproof resistance temperature detector

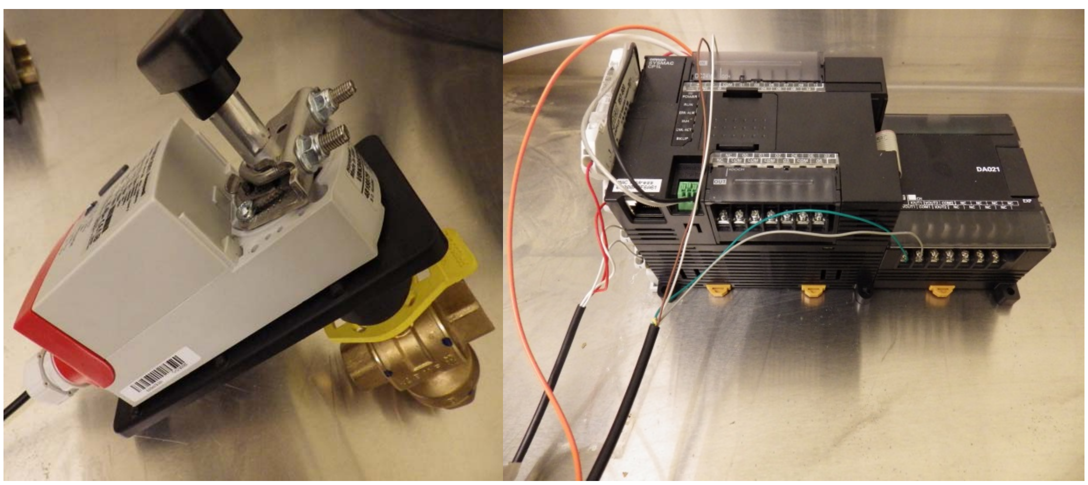

Figure 2. Left: Honeywell MN7505 Temperature control actuator and VBN3 temperature mixing valve. Right: Omron CP1L-EL20DR-D PLC

(RTD) from Omega Engineering (http://www.omega.com/pptst/HSRTD.html). Controlled temperature outlet water is routed to the supply flow head tank.

Data logging: Data logging is a separate system from the temperature control for redundancy and a step toward the field temperature probe development. A microcontroller based system was chosen for its ability to add wireless communication in the future and provide an interface

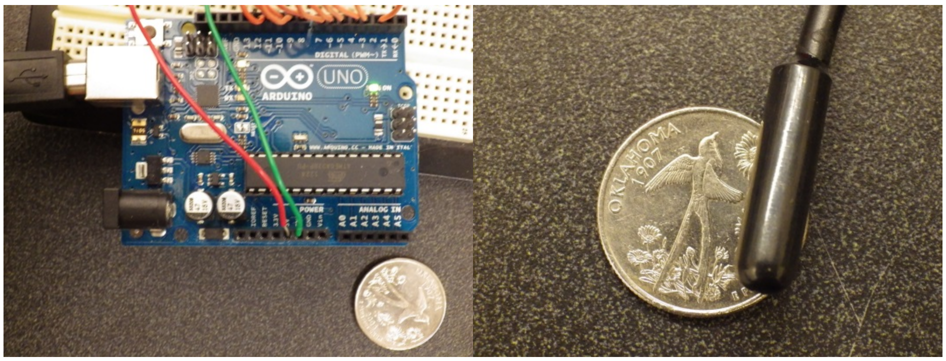

Figure 3. Left: Arduino board. Right: Temperature sensor.

between the lab PC and temperature sensors. An Arduino Uno microcontroller was selected and integrated with Dallas Semiconductor waterproof digital temperature sensors (DS18B20) (Figure 3). These sensors provide 0.625 degree Celsius resolution and 750 millisecond sampling capability, more than capable of providing quality data for analysis.

Eleven sensors placed at five centimeter spacing along a plastic strip (Figure 4) are installed vertically in the center of the tank. An additional sensor is placed at the temperature source to monitor the controlled temperature. Temperature data is collected every 30 seconds and written directly to a text file.

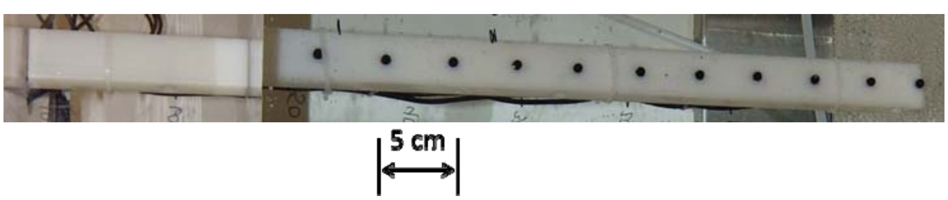

Figure 4. Temperature sensing strip.

Figure 5 displays an image of the complete functioning system.

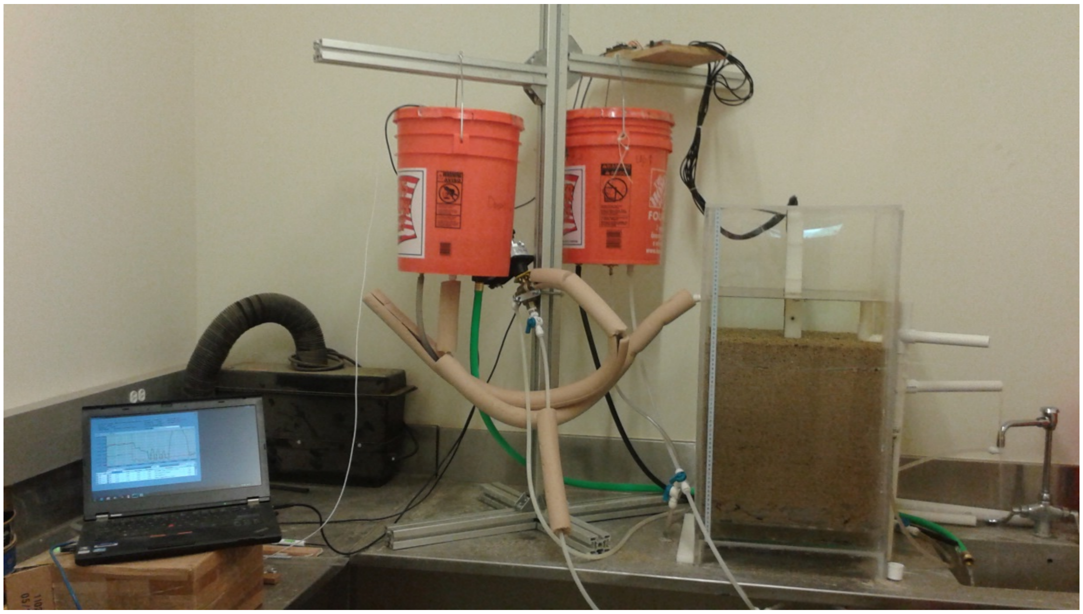

Figure 5. Complete operating laboratory sediment tank.

2.2 Field Temperature Probe

In-stream temperature scour chain (temperature probe) design for temperature data collection was centered on two major elements: the temperature sensor and data storage. A modular system was desired, where one probe design could be utilized whether data is collected via wireless communication or stored in memory at remote locations where there is no wireless connectivity. Thus, a temperature sensing probe and a data logger were designed as separate modular devices. Design elements for each respective device follow.

Temperature probe design: Probe design elements include the following: (1) placement approximately 1 meter deep in a streambed (2) ability to withstand impact from large debris in the channel (3) material with extremely low temperature conductivity to avoid mixed or averaged temperature measurements (4) a rigid stem retaining sensor locations during scour conditions (5) small diameter for ease of insertion into the bed.

UHMW (Ultra High Molecular Weight) plastic tube was selected to house temperature sensors as it meets all of the above design criteria. The same DS18B20 temperature sensors used in the laboratory are installed along the tube, and temperature data from each sensor is collected via serial data. The 1 inch long sensors are placed at a 45 degree angle to allow a smaller diameter tube. For proper analysis, exact sensor locations along the probe are referenced using the unique serial address of each individual sensor. The three wires from each sensor are connected in a star network, allowing one three wire sleeved bundle to exit the top of the probe with a connector for connection to a data logger. This connector provides the advantage to connect the probe to an attached data logger or to run longer wires and connect multiple probes to one central wireless communication device, which transmits data to an office or laboratory location. A 60 degree angled aluminum cone drive tip is inserted and pinned in the bottom of the probe and is larger in diameter at the probe/tip interface, allowing for driving and anchoring the probe. Figure 6 displays the field probe, with sensors along the vertical and a single wire connector extending from the top.

Data logger design: Data logger design elements include the following: (1) waterproof housing connecting directly to the temperature sensing probe to avoid exposing sensitive wiring to

Figure 6. Field temperature probe.

floating debris (2) ability to disconnect from the probe during deployment to upload data or replace batteries (3) as small in size as possible, given time and cost restraints (4) resistant to damage from debris in the channel (5) battery life of six months or greater (6) high capacity for data (7) house a microprocessor and memory capable of collecting data from the DS18B20 sensors.

To achieve an economical and waterproof data logger housing, 1 ½ inch PVC fittings and pipes were selected and fitted to create a sealed tube. The device houses an open source Arduino based microprocessor, micro SD card, and batteries. One 3 wire bundle exits the waterproof case through a waterproof cable gland and has a waterproof connector on the end for connection to the sensor probe. Figure 7 demonstrates the final assembled data logger, with one waterproof wire for connecting to the probe.

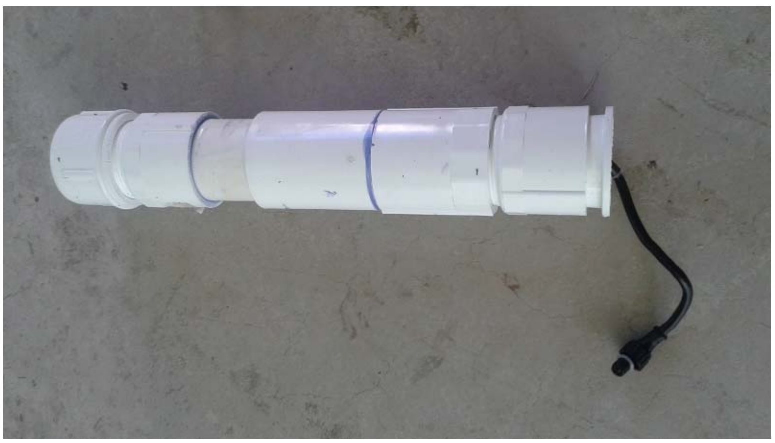

Figure 7. Field temperature probe data logger.

Field installation: Installation in the field can be challenging and involves driving the probe into the bed using a 2 ½ inch diameter cast iron pipe and a large post hammer. The probe drive tip was designed to fit snuggly against the bottom end of the driver and is placed inside the driver with the probe before driving the assembly vertically down into the stream bed. The driver is then carefully pulled up, leaving the installed probe in the bed. The data logger is then connected to the probe with the waterproof connector and placed on top of the probe using the threaded connection. Excess wire is placed within a storage cavity in the data logger housing during deployment.

Field probes were deployed in May, 2014 in the South Fork Boise River (Figure 8) to monitor streambed erosion/deposition associated with dam release flows and high sediment loads from multiple fire related debris flows in the system. Initial bed elevations and probe locations were surveyed using differential global positioning system (DGPS) equipment.

Figure 8. Field installation, South Fork Boise River.

These field probes experienced significant stream bed scour; however no temperature data was collected due to hardware water damage and programming issues. Thus, it was necessary to improve the data logger design for better water resistance under long-term submerged conditions. Improvements included (1) additional sealing over the cable gland wire pass-through into the data logger and (2) covering the electrical hardware inside the housing with a flexible waterproof sleeve. These improvements provided multiple layers of redundancy in waterproofing the electronics. Programming issues were also addressed. In addition, back-up temperature probes were constructed in case of repeat field probe failures. These probes were constructed using Hobo Tidbit (http://www.onsetcomp.com/products/data-loggers/utbi-001) temperature data loggers placed inside PVC pipe and isolated by inserting foam blocks in between the sensor locations.

Updated data loggers and temperature probes were installed in the field on August 6. This installation was planned in time to collect data coincident with a sediment flush flow schedule from the upstream Anderson Ranch Dam in mid-August.

2.3 Data Analysis

Sediment elevation changes are quantified using a mathematical method (equations 1, 2, and 3) from *Tonina, et al., 2014* and *Luce, et al., 2013*, where phase, ϕ, and amplitude, A_r, are extracted from measured cyclic temperature data in the sediment bed. Sediment thickness between temperature sensors, Δz, is the focus of the method. Effective thermal diffusivity (equation 2) is a thermal property of the sediment and pore water matrix and is determined during an intitial steady state elevation of the bed, where Δz is known. With time, κ_e should remain constant through the experiment, thus this value is held constant, and Δz (equation 3) over time is calculated. Bed elevations are then predicted by summing Δz and respective temperature sensor constant elevations.

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

$$\kappa_e = \frac{\omega \Delta z^2}{\Delta\phi^2} \frac{\eta}{1+\eta^2} \qquad (2)$$

$$\Delta z = \Delta\phi \sqrt{\frac{\kappa_e}{\omega}\left(\eta + \frac{1}{\eta}\right)} \qquad (3)$$

An open source statistical computing and graphics environment, R, was selected to perform data analysis for the project. A model created by Dr. Charles Luce was provided for the project in R format, which extracts cyclic temperature signal phase and amplitude. This model was expanded to create a flowing sediment elevation prediction model, where collected temperature profile time series data is input and plots are output, which compare predicted elevation versus actual imposed elevations in the sediment tank.

3. Results and Discussion

3.1 Laboratory experiment

Two scour-deposition experiment sequences are presented here, where pore water flux direction is upwelling or downwelling. Data from temperature sensors located 5, 10, and 15 cm (T0, T5, T10) below an arbitrary constant zero location within the surface water are paired with sensor data from the location at 0 cm (T0). In each case, κ_e is calculated during the first 1000, 30 second time steps, with the original Δz between each respective sensor and T0. For every time step after

1000, the calculated *Δz* is added to the constant respective elevation of each temperature sensor, T5, T10, or T15.

In the upwelling case, forcing of cold water temperature up through the sediment bed retards penetration of the cyclic temperature signal from the surface, reducing the depth at which a cyclic signal can be measured. During downwelling, depending on the flux rate, the cyclic temperature signal may not penetrate to lower temperature sensors. Where there is no aparent cyclic signal, the data cannot be used to predict sediment thickness, thus these data have been removed for clarity. T10 and T10 and T15 provided the best temperature cycle penetration data for elevation prediction during the respective upwelling and downwelling experiments.

Figure 9 demonstrates predicted sediment bed elevation against actual imposed values. Elevation predictions during scour and deposition events clearly follow imposed values nicely, with root

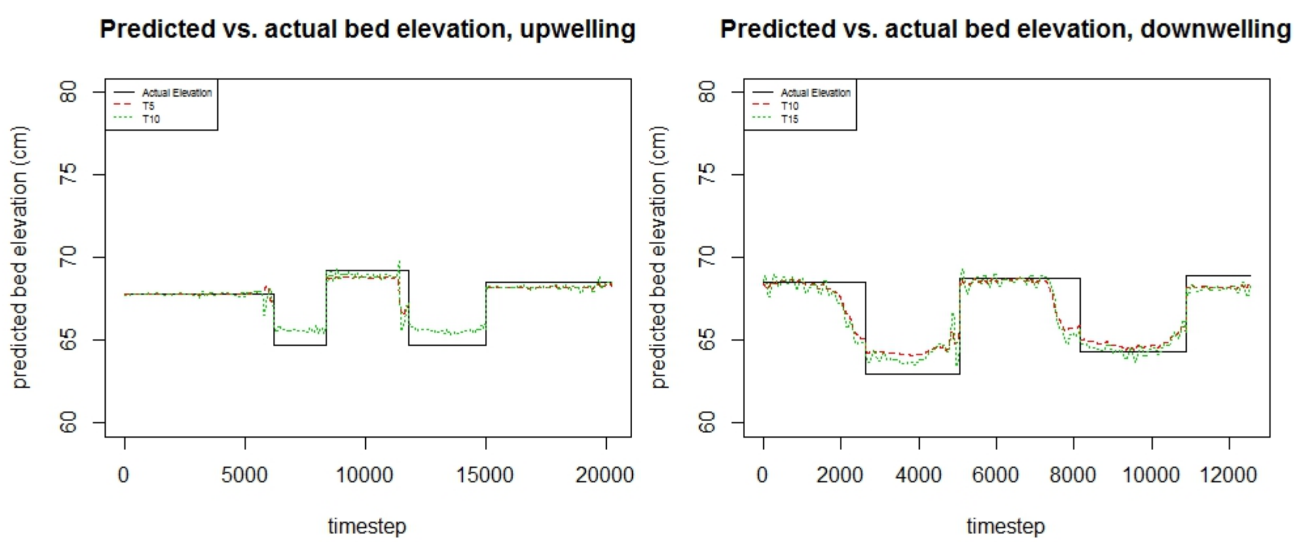

Figure 9. Predicted versus imposed sediment tank bed elevations.

mean squared error (RMSE) of 14.4% and 11.0% for the upwelling and downwelling states, respectively. RMSE is normalized over the maximum scour depth in each case.

Noteworthy is discovery of surface water temperature stratification during analysis. Very minor stratification was anticipated but not expected to lead to significant error in elevation predictions. Thus, it was necessary to pair sediment temperature readings during scour events to the sensor nearest the bed to avoid error associated with the temperature differences in the surface water.

Thermal scour-deposition chain, final report. September 2014. University of Idaho.

Future experiments will include a system for increased turbulence in the surface water to better mix temperatures and avoid stratification issues.

3.2 Field Temperature Probe

Because the field probes are still deployed and surveying is not complete, analysis of this portion of the project is in the context of product development for commercialization. As mentioned previously, data logger improvements were necessary during field deployment, and other development needs have been noted: reduced diameter for easier installation, smaller data logger housing with more advanced waterproofing, and increased rigidity of the probe to reduce deformation during scour events.

An ideal scour-deposition monitoring system would provide a wireless, gridded network of temperature probes allowing scour data collection both laterally and longitudinally. Location of installation can simplify or hinder networking efforts. A bridge with in-stream piers has a built-in infrastructure where wires can connect devices and be retained against piers and girders to avoid damage from floating debris. When placement is directly in the river with no such infrastructure, there is no place to run wires other than in the bed itself. Current wireless communication technology does not economically allow live data transmission through water, thus at least one wire must be run to a dry location for the microcontroller to collect and send data wirelessly. Additional design effort should address this issue and lead to a robust wireless data collection system.

A complete thermal scour chain package would also include a computer based graphical user interface (GUI). The GUI would be set up such that scour calculations can be performed and plotted without programming and results can be exported for use in other programs or data archiving.

4. Budget

The original project budget was $45,750, and expenditures totaled $44,675.67, leaving a balance of $1074.33 after budget closing.

Thermal scour-deposition chain, final report. September 2014. University of Idaho.

5. Patent/Collaboration information

Patent applications have been submitted: U.S. Patent Application No. 13/890,919, METHOD AND APPARATUS FOR MONITORING WATERBED ENVIRONMENT USING TEMPERATURE MEASUREMENTS; U of I Ref. No. 12-009, KS Ref. No. 7832-91088-01.

Future collaboration for product development is planned with the Idaho Department of Transportation, with focus on bridge pier scour monitoring. A graduate student research award has also been provided from the Hydro Research Foundation (http://www.hydrofoundation.org/), where additional focus is placed on environmental monitoring associated with dam operation.

6. Conclusions

Laboratory results verify the method of *Tonina, et al., 2014* and *Luce, et al., 2013,* using time series temperature data from surface and sediment pore water sensor pairing to predict streambed elevation changes, where prediction error was demonstrated under 15%. To reach higher precision, some minor adjustments are needed and will be implemented in the laboratory experiment. In stream and river environments are highly turbulent and generally do not exhibit stratification of temperature excepting slow moving, deep pools, and adjustments will reflect natural environments.

After development upgrades are implemented, the thermal scour chain will not only provide a useful tool for real time monitoring of stream bed scour-deposition. It will also simultaneously be capable of measuring surface/subsurface water exchange and sediment thermal regime, both highly applicable for river ecology, engineering, and management knowledge advancement.

7. Acknowlegements

We would like to thank electrical engineer John Berndt, from Bolen's Control House, in Boise, Idaho for volunteering his time to program the PLC for the temperature mixing control and providing the GUI for setting temperature control parameters. John also aided in selecting the actuator and mixing valve for the temperature control system.

Thermal scour-deposition chain, final report. September 2014. University of Idaho.

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