# Final Calibration of the Elwha Impact Plate System

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## Abstract

The Elwha impact plate system was installed on the Elwha River in 2008-2009 for the purpose of continually measuring coarse bed load using an acoustic surrogate. The system consists of 72 stainless steel impact plates, 46 of which are instrumented with geophones and 26 of which are instrumented with accelerometers. Both instruments register an impact on the steel plate and respond with a voltage sent to one of three host computers, where these signals are minimally processed and stored for later retrieval and post-processing. Since installation, there have been several operations to measure bed load for the purpose of calibrating the geophone plates, concurrently gathering acoustic data from the plates and measuring bed load using conventional methods. The calibration of the geophone plates for measuring coarse bed load (mass/time) occurred between November 2011 and May 2016. This paper details the final calibration of the geophone instrumented impact plates and draws comparisons with similar systems in Europe. A companion paper by Pittman and Hilldale (this volume) provides additional details on the bed load sampling.

## Introduction

Much discussion has occurred over the past three decades regarding the need for and benefits of continuous bed load measurements (Reid et al. 1980, Reid and Frostick 1986, Habersack et al. 2001), most of which include the use of surrogate methods (Bänziger and Burch 1990, Rickenmann and McArdell 2007, Turowski and Rickenmann 2009, Gray et al. 2010, Barrière et al. 2014, Hilldale et al. 2015, Downs et al. 2015, Mao et al. 2016, Habersack et al. 2017). Among the benefits discussed is a better understanding of bed load transport, including initiation of motion, temporal and spatial variability and the relation of bed load to stage or discharge and hysteretic effects. Indeed, surrogate bed load measurements have the ability to provide the temporal and spatial density needed for a more thorough understanding of these phenomena. In the case of the Elwha River, continuous bed load measurements during and after the removal of two large dams (Magirl et al. 2015, Ritchie et al. 2018) is providing a unique data set that is likely to prove useful as dam decommissioning becomes a viable alternative considering aging infrastructure.

In addition to utilizing continuous bed load data to increase our understanding of bed load transport and evaluate geomorphic change, these data can be used to evaluate and better understand aquatic habitat conditions. A wide variety of vertebrates and invertebrates inhabiting river systems depend on bed material and its condition during some portion of their life cycle (Palmer et al. 2000, Dusterhoff et al. 2017). Understanding the flow conditions under which the bed is disturbed, the temporal extent of its disturbance, and the frequency can provide biologists with critical information as it relates to stream health. A study is currently underway on the Elwha River to better understand the relationship between sediment discharge and the egg-to-fry survival of salmonids (George Pess, written comm. Jan. 2018). This effort by Pess is making use of continuous surrogate measurements of both suspended and bed load on the Elwha River (Ritchie et al. 2018).

This paper describes the methodology and the calibration of the Elwha impact plate system using only the plates instrumented with geophones. Comparisons are made between the Elwha impact plate system and similar systems deployed elsewhere. Calibration measurements for bed load were collected between fall 2012 and spring 2016. There is a desire to continue physical bed load measurements for calibration, however the untimely removal of the anchor for the cableway assembly has made further measurements difficult.

## Elwha Setting

The Elwha River flows north from the Olympic Mountain range in the state of Washington, USA and terminates at the Strait of Juan de Fuca (Figure 1), which connects Puget Sound with the Pacific Ocean. The catchment is largely within the protected lands of Olympic National Park, consisting mostly of forested land, much of it pristine wilderness, and covers an area of 830 $km^2$. The Elwha River is supplied with varying contributions of snowmelt, rainfall, and groundwater discharge and has a maritime climate with relatively wet, mild winters and dry, cool summers (Curran et al. 2009). Annual precipitation in the basin ranges from 560 cm in the upper basin (elevation 1,350 m) to 140 cm near the mouth (elevation 0 m) (Munn et al., 1998). The 2-year, 10-year, and 100-year recurrence-interval floods are 400 $m^3/s$, 752 $m^3/s$, and 1,240 $m^3/s$, respectively (Duda et al., 2011).

Bed load transport has been monitored on the Elwha River at river kilometer 5 (measured upstream from the mouth) since the removal of Elwha Dam (32 m tall, located at RK 7.9), constructed in 1913, and Glines Canyon Dam (64 m tall, located at RK 21.6), constructed in 1927 (Magirl et al. 2015) (Figure 1). These dams had been operated as run-of-the-river for power generation and provided no flood protection. The two reservoirs behind these dams had trapped 21 million $m^3$ of sediment (Randle et al. 2015) over their lifetime. Additional information about the dam removal, sediment transport, and geomorphic change, can be found in a series of papers (East et al. 2015, Gelfenbaum et al. 2015, Magirl et al. 2015, Randle et al. 2015, and Warrick et al. 2015).

## Measurement Weir Setting

The measurement weir (RK 5), is a vertical concrete wall perpendicular to river flow, spanning the 41 m channel width. The impact plates are mounted flush against the downstream face of the weir (Figure 2). The purpose of the weir is to provide surface water diversion for municipal water supply and fisheries uses. The surface water intake is located at river right with a sizeable platform that provides ample room for the data collection computers. The engineered riffle downstream of the weir is 200 meters long with a bed slope of 0.015 m/m, designed for passage of resident and anadromous salmonids. For a short distance, the channel immediately downstream of the weir is grouted with concrete and contains boulders close to the weir. Depth-averaged velocity approximately 2 meters upstream of the weir exceeds 2.5 m/s at discharges that transport coarse bed load. Flow velocity over and downstream of the weir is significantly higher.

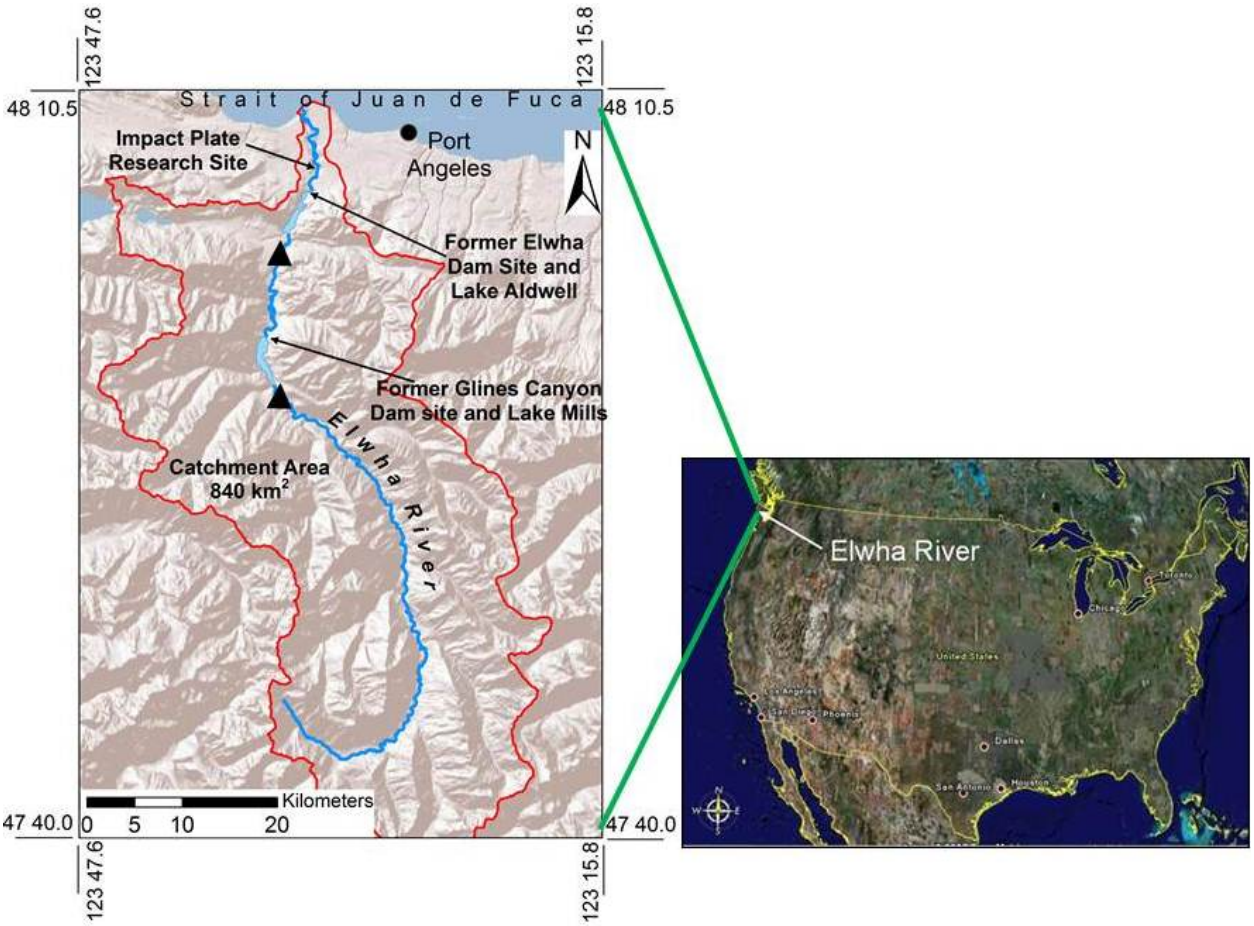

Figure 1. Location map for the Elwha River. Triangles represent the location of gauging stations. Northern gauge is USGS 12045500 Elwha River at McDonald Br., southern gauge is USGS 12044900 Elwha River above Lake Mills.

Figure 2. Photograph of the concrete weir and impact plate system mounted to the downstream side. The intake structure is in the background. Flow (approximately 11.3 m$^3$/s) is from right to left in the photograph (Sep. 2017).

## Impact Plate System

The Elwha impact plate system has been fashioned after the Swiss impact plate system (Bänziger and Burch 1990, Rickenmann and McArdell 2007). The Swiss geophone system has been installed at more than 20 field sites where bed load measurements have been made for calibration (Rickenmann 2017). The decision to pattern the Elwha system after the Swiss system was a pragmatic one. The Swiss plate system had been in operation for over two decades and had proven to be a successful prototype. There are two primary differences between the two systems: 1.) Not all plates in the Elwha system are instrumented with geophones, some are instrumented with accelerometers, and 2.) The instruments in the Elwha system are stud-mounted to the underside of the impact plates, as opposed to being mounted within a box on the underside of the plates.

The Elwha impact plate system includes 72 individual stainless steel plates. The dimensions are L x B x T = 349 mm x 502 mm x 15.9 mm (where L = downstream length, B = transverse width, and T = thickness). Each plate is instrumented with either a geophone (GS-20DX marsh case, Geospace Technologies, Houston, TX) or accelerometer (CMCP-1100, STI Vibration Monitoring, League City, TX). Each impact plate is acoustically isolated with 12.7 mm rubber to minimize cross-plate signal contamination. The acceleration of flow over the weir prevents sediment accumulation on the plates. Figure 3 shows the configuration of the weir, including the location of the surface water intake at river right. The plate numbers and stationing increase from right to left as looking downstream. There are 46 geophone plates and 26 accelerometer plates. For plate numbers 1-12 (within the low flow notch, Figure 3), the geophone and accelerometer plates alternate every other plate. Along the remainder of the weir, the plates are configured such that accelerometers are located every third plate with two geophone plates between. As mobile bed particles move across the plates, their impact causes a deformation (or acceleration) of the steel plate, creating a voltage response from either the geophone or accelerometer. These signals are sent to three host computers for processing.

This paper only describes the calibration of the plates instrumented with a geophone, used for mass/time bed load measurements. Additional details regarding the Elwha impact plate system system can be found in Hilldale et al. (2015).

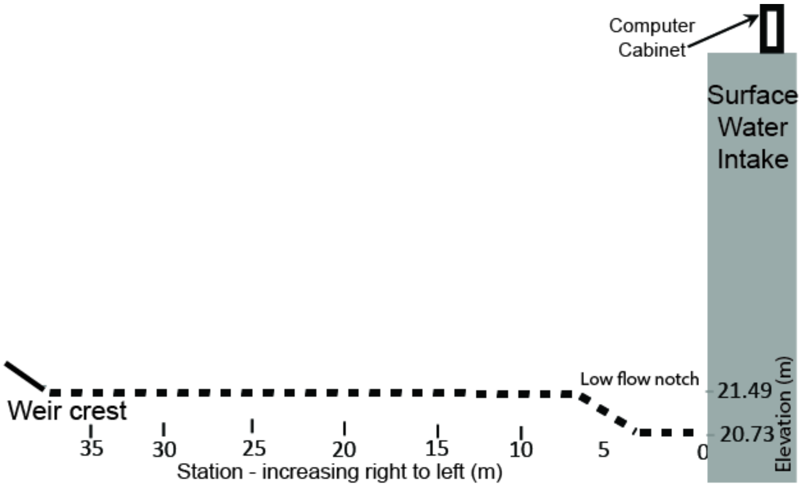

Figure 3: Diagram of the measurement weir showing the surface water intake, location of the computer cabinet, and the low flow notch against the intake

A separate effort is underway to utilize the accelerometer plates to determine the size of particles crossing the plates. One advantage of the accelerometer plates is their ability to detect particles as small as 5.6 mm, determined in the lab using two impact plates identical to those fabricated for the Elwha system. For more information on the effort to utilize accelerometer plates to determine particle size on the Elwha impact plate system, the reader should refer to Kuhnle et al. (2017).

### Minimum Size Detection

A minimum voltage threshold of 0.1 volts is used for calibration, although multiple thresholds were evaluated between 0.01 to 0.2 volts. A similar voltage threshold is being used by other Swiss impact plate systems (Rickenmann et al. 2012). The threshold voltage is used to minimize the noise in the geophone signal generated by ambient flow conditions creating small voltage peaks from the sensors. Correlations to measured bed load had the best fit (highest $r^2$ value) using a threshold voltage of 0.1. When this threshold is used, the smallest reliably detectible particle size is 16 mm. The minimum detectible particle size was determined by releasing particles of known size (sieved to 0.5φ classes) immediately upstream of a given plate and observing the impulses simultaneously recorded on the computer. There was no natural sediment transport occurring in the river at the time of these tests.

## Methodology

Physical bed load measurements were collected for the purpose of calibrating the Elwha impact plate system. These measurements were collected concurrent with the recording of impulses on the impact plates. The physical bed load measurements were collected using a Toutle River-2 (TR-2) pressure difference bedload sampler (Hubble et al. 1985; Childers 1999). TR-2 dimensions are as follows: the nozzle opening is 305 × 152 mm; nozzle expansion ratio is 1.4; overall length is 1.52 m; and the weight is 100 kg. The sample bag has a mesh size of 2 mm. The TR-2 is deployed from a 6.4-m long cataraft using a crane and winch (Figure 4). The cataraft is held stationary in the river by attaching the upstream end of the raft frame to a tag line stretched tightly across the channel.

Figure 4. A – TR-2 used for bed load measurements. B – Cataraft used for bed load measurements. The TR-2 is mounted on the downstream side of the raft, operated with a crane and winch.

The measurement weir imposes limitations to the collection of physical bed load measurements due to its construction and the size of the river. The grouted surface immediately downstream of the plates provides an uneven surface, consisting of cobbles and boulders, preventing proper placement of the bed load sampler. Furthermore, very high flow velocity (> 3 m/s) immediately downstream of the weir adds additional challenges, whereby the sampler drifts well downstream of the weir creating an angle on the cable that is too low for safe and proper retrieval. When the cable angle is too low the sampler will drag forward upon retrieval, causing a potential biasing of the sample due to scooping sediment. Measurements immediately downstream of the weir were attempted one time, and the sampler became caught at the lip of the weir creating a dangerous situation with the tethered raft being pulled downstream against the tag line as the sampler was being retrieved. The only feasible location for physical measurement of bed load is approximately 2 to 3 meters upstream of the weir. This distance allows for variable downstream drift of the sampler, accounting for the length of the sampler (1.52 m) and insuring that the tail was not resting on the plates.

Sediment samples were retained for processing in a lab, where they were dried and sieved at 0.5φ intervals. Sediment smaller than 2 mm was not retained. Only particles sized > 16 mm were used for transport calculations for the purpose of impact plate calibration. The measured fraction of sediment between 2 and 16 mm was used to infer transport rates for the unmeasured portion of gravel (Magirl et al. 2015, Ritchie et al 2018). Further details of the physical collection of bed load samples can be found in Pittman et al. (these proceedings).

## Bed load Measurement Protocol for Geophone Impact Plate Calibration

Attempts to measure bed load for calibrating the geophone impact plates were first made in November 2012 and again in March 2013. In October 2012 the bed material from the reservoir deltas arrived at the measurement weir. This material primarily consisted of sand and finer material in very heavy concentrations near the bed (Figure 5). This bed material was too small to be registered on the impact plates, resulting in no bed load collected for the purpose of calibration. Expecting the bed material to coarsen over the period of a few months another series of bed load measurements was made in March 2013. By this time the bed material of the Elwha was coarsening enough to transport particles large enough to be registered on the geophone impact plates (> 16 mm). After analyzing data and attempting to match the measured bed load to the number of impulses on the corresponding plate, it was realized that the bed load measurements had to include a significant temporal component for time averaging to overcome the variability of coarse bed load transport and the calibration method.

A data collection protocol for impact plate calibration was devised beginning with the third set of measurements for calibration in May 15, 2013. The new protocol collects physical bed load measurements at a single station for 30 min, resulting in approximately nine physical samples, depending on how long the sampler rests on the bed, referred to as sampler down time. The time averaged physical measurements create a single measurement of bed load in kg plate$^{-1}$ min$^{-1}$ at a single station. All individual bed load samples were retained and sieved separately and later combined mathematically to obtain an approximate 30 minute measurement. This bed load measurement is used to correlate impulses from the geophone impact plates in units of impulses plate$^{-1}$ min$^{-1}$. The 30 minute period was chosen based on analyses performed during steady-flow conditions, in which the cumulative mean and standard deviation of bed load flux indicated by the plates arrived at a steady value, indicating a stable average obtained during the sample period. Additional information on temporal bed load variability at this site can be found in Hilldale and Greimann (2018). This bed load measurement and calibration protocol was used for all subsequent calibration efforts.

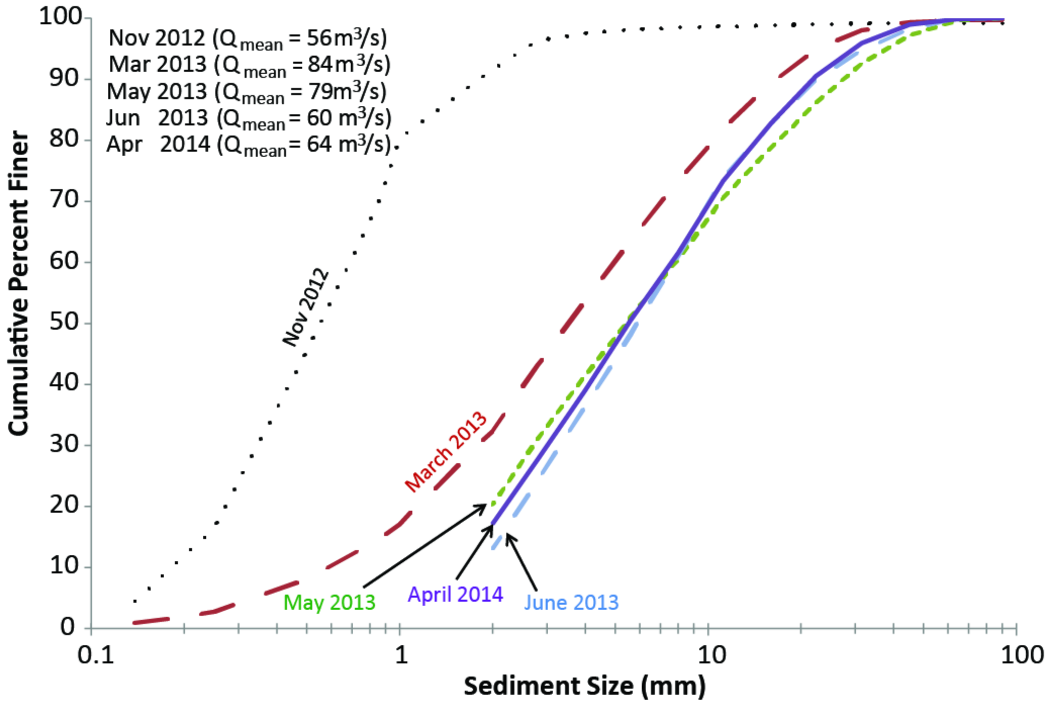

Figure 5. Particle size distribution of captured bed load over 5 separate measurement trips. Discharges were measured at USGS 12045500 Elwha River at McDonald Br.

The measurement protocol described assumes that the interruption of bed load across the plates by the bed load sampler did not create a significant influence on the impact plate measurement. Sampler down times varied from as short as 5 seconds during the May 2013 measurements and 20 – 120 seconds during the April 2014 measurements. Measurements at a single station were used to calibrate plates with a lateral distance of ≤ 1m from the sample station.

## Data Processing

The impulse data collection for the geophones is controlled by three host computers and is remotely accessible via internet connection. Each computer is connected via USB 2.0 to a National Instruments cDAQ-9178 Chassis containing multiple National Instruments NI-9215 Modules. Two computers have 8 modules with 4 channels each, providing 64 channels. The third computer has 2 modules with 4 channels providing an additional 8 channels. Impulse data are collected for all 46 geophones for 1 minute, followed by a 20 second rest period, where data are processed and written to the computer in ASCII format. The sampling rate of the data acquisition system is 20 kHz/channel with a dynamic range of ± 5V for the geophones. The format includes the total number of impulses above a given threshold (0.5, 0.75, 0.1, 0.15, and 0.2 volts) with a time and date stamp. Only the impulses exceeding 0.1 volts are used for bed load calculations. These data are then processed with Matlab to provide temporal interpolation for the 20 second down period. The results of this processing are written to csv files to provide impulses for each plate. A second processing step provides spatial interpolation to account for the absence of geophone data where the accelerometer plates are located or where there is a bad geophone sensor.

# Calibration Data

Of the six separate trips to measure bed load for calibration, only two produced data useful for calibration. November 2012 and March 2013 trips were discussed above. May 2013 is one data set used for calibration. In June 2013 bed load measurements were taken but a malfunction of the computers recording the impulses prevented proper data collection for calibration. April 2014 was a successful calibration measurement trip and is the second data set used for calibration (Table 1). Another attempt was made to collect a third calibration set in May 2016, but there was no coarse bed load in transport during the measurement period.

The calibration of the Elwha impact plate system relies on 16 total calibration points collected in May 2013 and April 2014 (Figure 6). These data points consist of multiple bed load samples over the 30 minute period and were collected at multiple stations (plates) across the channel under various flow conditions.

Table 1. Information about bed load measurements for calibration

| Date | Daily Average Discharge ($m^3/s$)* | Total Number of Bed Load Samples Collected |
|---|---|---|
| May 14, 2013 | 93.4 | 26 |
| May 15, 2013 | 73.9 | 60 |
| April 23, 2014 | 42.5 | 25 |
| April 24, 2014 | 63.1 | 58 |
| *As measured at McDonald Gauge, USGS 12045500 | | |

The data are plotted and regressed following the method outlined in Rickenmann et al. (2014) using a linear model. The chosen regression is the one forced through zero. The measured bed load mass, normalized to $kg \cdot plate^{-1} \cdot minute^{-1}$, is plotted on the independent axis and the number of geophone impulses that exceed the 0.1 V threshold are plotted on the dependent axis with units of $impulses \cdot plate^{-1} \cdot minute^{-1}$. Each data point shown in Figure 6 represents multiple discrete bed load measurements with the TR-2 (typically 7-9) over a period of 30 minutes. Mass measurements only include particles > 16 mm, considered the threshold for detection.

The resulting calibration for the Elwha impact plate system is as follows:

$$I_g = 1.843 * M_{bl} \tag{1}$$

where $I_g$ is the number of geophone impulses above the 0.1 volt threshold and $M_{bl}$ is bed load mass.

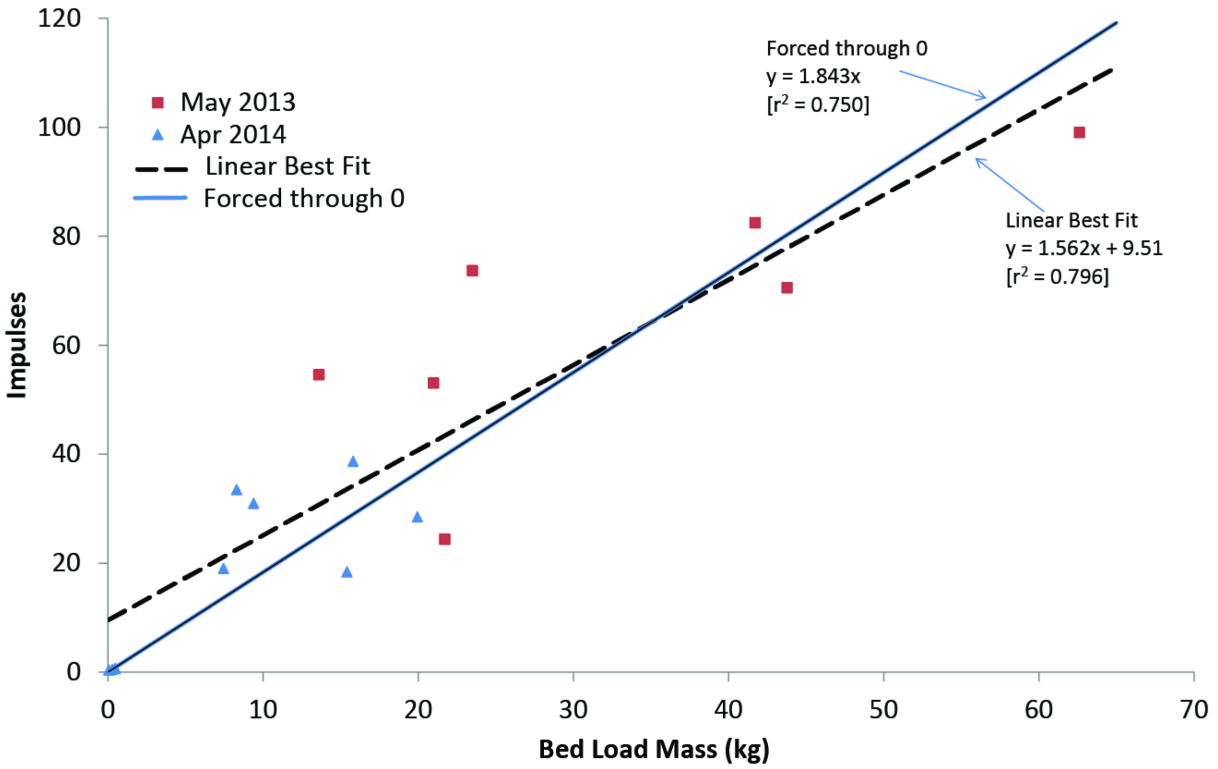

Figure 6. Calibration data for the Elwha impact plate system. The calibration uses the curve that is forced through zero. The units on both axes are normalized to plate-1.minute-1.

# Discussion

## Calibration Comparison to Other Impact Plate Systems:

The Elwha impact plate system calibration (Y=1.843x) falls between the calibration of the Swiss plate systems installed on the Eshtemoa (y=0.419x) and Rofenache (y=3.87x) (Rickenmann et al. 2014). Habersack et al. (2017) indicate a calibration of their impact plate system on the River Drau ofY=3.54x. The calibration of an impact plate system varies for a number of reasons including; bed load sampling method, threshold voltage, plate dimensions, sensor type, instrument mounting style, bed load velocity over the plates, and particle shape. For most of the Swiss impact plate systems the physical parameters are similar. While most of the parameters of the Elwha system are very similar to that of the Swiss system, the mounting style of the geophone is quite different (stud mount on the Elwha vs. box mount for the Swiss system). Additionally, the calibration of the Elwha impact plate system had to be performed immediately upstream of the plates, where the Swiss systems are typically calibrated with physical measurements immediately downstream of the plates.

Turowski and Rickenmann (2009) demonstrate that particle size, shape, velocity, and transport mode (rolling, sliding, or saltating) influence the impulse signal from a geophone plate. The same authors conclude that the influence of particle shape is not trivial. Three-axis measurements were made on 200 randomly picked Elwha bed particles (Figure 8) to determine the distribution of shapes on the Elwha River using the Zingg shape classification (Zingg 1935 in Pettijohn 1975). As shown in (Table 2), the dominant Elwha particle shape is oblate (discoidal). This shape is most likely to result in a sliding transport mode as opposed to rolling or saltation, and particle shape and mode of transport have a greater influence on geophone impulses than particle weight (Turowski and Rickenmann 2009). This information would seem to partly explain why the Elwha plate calibration has a lower slope than comparable systems. It is worth noting that the particle shape analysis indicates that approximately 1/3 of particles (prolate and equiaxial) are more likely to roll than slide across the impact plates. Particle velocity also influences geophone response by influencing saltation length and the energy each particle might impart to the plate. Saltation length may influence the number of particles that may skip over a plate, or register more than one impulse.

Figure 7. Photographs of Elwha River bed material. Dimensions of 200 bed particles were measured with calipers on three axes.

Table 2. Results of a particle shape analysis of the Elwha bed material measuring all three axes (A = greatest length, B = intermediate length, and C = least length.

| Zingg Shape Classes (after Zingg 1935, cited in Pettijohn 1975) | | | | |
|---|---|---|---|---|
| **Class** | **B/A** | **C/B** | **Shape Description** | **Elwha Particles** |
| I | > 2/3 | < 2/3 | Oblate (discoidal, tabular) | 40.0% |
| II | > 2/3 | > 2/3 | Equiaxial (spherical, equant) | 15.5% |
| III | < 2/3 | < 2/3 | Triaxial (bladed) | 26.5% |
| IV | < 2/3 | > 2/3 | Prolate (rods) | 18% |

There are many factors influencing the calibration of an impact plate system, even though the systems may have many things in common. This speaks to the importance of an in-situ calibration under a range of flow conditions. However, Wyss et al. (2016b) have demonstrated that a flume based calibration of an impact plate system is possible although with reduced accuracy.

## Conclusions and Outlook

The Elwha impact plate system is expected to continue operation until a critical failure occurs. To date, several geophone and accelerometer instruments no longer work properly, either due to a failed sensor or splice. Their replacement is very challenging due to the perennial nature of the stream and lack of ability to divert flow away from the weir. The inoperable plates are turned off in the host computer and bed load calculations interpolate across the non-functioning plates.

An effort is planned to publish the time series bed load data from the Elwha impact plate system in a publicly accessible database, hosted by the Bureau of Reclamation. This database is currently being created and is expected to be online by the end of 2019. However, time series bed load data is not expected to be available until the middle of 2020. Readers are referred to the ScienceBase catalog referenced in Ritchie et al. (2018) for available sediment data, WY2012 – WY2016 (https://www.sciencebase.gov/catalog/item/5a033d9ee4b0531197b8d58f).

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