CONTINUOUS BED LOAD MEASUREMENT WITH IMPACT PLATES ON THE ELWHA RIVER, WA

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Abstract

A bed load impact plate system has been installed on the Elwha River for the purpose of continuously measuring coarse bed load during and after the removal of two large dams. The surrogate bed load measurement system consists of 72 instrumented stainless steel plates spanning approximately 38 meters across the channel and is currently capable of quantifying coarse bed load ≥16 mm. Each plate is instrumented with either a geophone (46 plates) or an accelerometer (26 plates). To date, a preliminary calibration of the geophone impact plates has been obtained using 16 data points, achieving an r^2 value of 0.796. Each data point is a temporal average of 8 - 10 physical bed load measurements correlated to the impulses measured with the geophones. The most recent calibration data and calibration procedures are presented herein. Observations of temporal and spatial variability in coarse bed load transport during and after dam removal are discussed.

INTRODUCTION

The use of indirect or surrogate technologies for quantifying fluvial sediment transport is a rapidly expanding field, providing the ability to continuously monitor sediment transport with high resolution. In an effort to provide continuous, high resolution measurement of coarse bed load transport on the Elwha River during and after the removal of Elwha and Glines Canyon Dams, a series of instrumented, stainless steel bed load impact plates was installed in 2008 and 2009 at river kilometer 5 (measured upstream from the mouth, Figure 1). The Elwha impact plate system was patterned after the Swiss geophone impact plate system (Bänziger and Burch 1990; Rickenmann and McArdell 2007) installed in several locations throughout Switzerland, Austria, and Israel (Rickenmann et al. 2014). The Elwha impact plate system differs from the Swiss system by installing accelerometers on 26 of the 72 instrumented steel plates, with 46 plates instrumented with a geophone. Additionally, the dimensions of the Elwha impact plates vary slightly from the Swiss system. A thorough review of surrogate methods for quantifying bed load transport is given in Gray et al. (2010), Rickenmann et al. (2012), and Tsakiris et al. (2014). This manuscript will discuss the installation, preliminary calibration, and observations of bed load transport with respect to spatial and temporal variability. Observations of continuously measured bed load transport on the Elwha are presented and discussed.

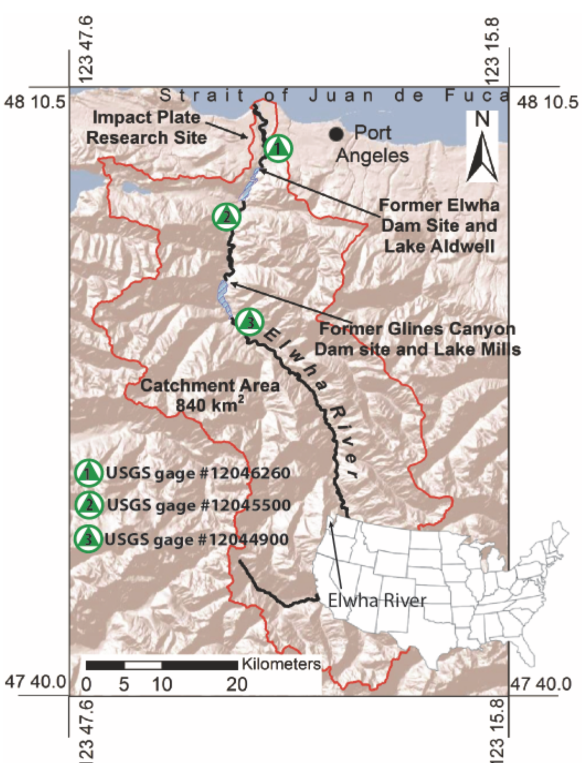

Figure 1: Location map of the Elwha River, Washington.

The decision to construct a series of impact plates was based on the following: (1) maturity of the Swiss impact plate system (Rickenmann et al. 2012, 2014); (2) the ability to continuously collect bed-load data without operating personnel; (3) robust construction and demonstrated longevity (>10 years); (4) limited maintenance requirements for the physical system; (5) ability to measure bed load with a 0.5-m resolution across the stream; and (6) nonintrusive and compatible with an ecologically sensitive river (Hilldale et al. 2014). The primary drawback of the Elwha impact plate system is its inability to register a response to particles < 16 mm on the geophone plates and particles < 8 mm on the accelerometer plates. The impact plate system on the Elwha River was installed in conjunction with a previously planned concrete weir for the purpose of surface water diversion.

The Elwha River

The Elwha River flows north from the Olympic Mountain range of Washington State, 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. 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 U.S. Geological Survey has operated the McDonald Bridge gage (USGS streamflow-gaging station #12045500) since 1918. The mean annual discharge is 42.8 m^3/s (Magirl et al. 2014). 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).

Elwha and Glines Canyon Dams

The removal of Elwha and Glines Canyon Dams on the Elwha River in Washington State is the largest dam removal project in U.S. history to date (Duda et al 2011). A total of 21 million m^3 of sediment was stored behind both dams; including an estimated 2.5 million m^3 of gravel and cobble sized sediment. Elwha Dam (32 m high, located at river kilometer 7.9) constructed in 1913, and Glines Canyon Dam (64 m high, located at river kilometer 21.6) constructed in 1927 (Figure 1) began concurrent removal beginning in September 2011. The removal of Elwha Dam was completed in May 2012, and the final portion of Glines Canyon Dam was removed in September 2014. Detailed information on the Elwha river's response to dam removal during the first two years can be found in East et al. (2014) and Magirl et al. (2014).

Figure 2: (A) Installation of impact plate, sensors on river right, and wiring for the entire system, 2008. (B) Installation of remaining impact plates and sensors in 2009.

The Elwha Impact Plate System

The Elwha impact plate system was installed in two phases. During the first phase plates 1-12 were installed on river right. Plate numbers 1, 3, 5, 7, 9, 11 and 12 are instrumented with geophones and plates 2, 4, 6, 8, and 10 are instrumented with accelerometers. Wiring was installed in 2008 for the entire system and the wiring to be used for plates 13-72 was stored in a temporary wooden channel constructed in place of the impact plate housing to be built the following year (Figure 2). In 2009 the remaining impact plates and instrumentation were installed (Figure 2B). Plate numbers 13 – 72 are instrumented with a repeating pattern of one accelerometer plate and two geophone plates for the remainder of the cross section (e.g. plate # 13 = accelerometer, plate # 14 and #15 = geophones, plate # 16 = accelerometer…). All wiring was routed through two conduits to the computer cabinet on the right bank and was labeled for later installation of the streamside computer monitoring system in 2011. Details on the computer hardware and software can be found in Hilldale et al. (2014).

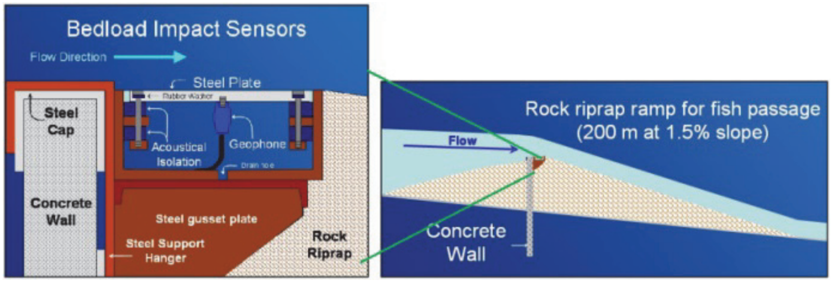

Figure 3: Longitudinal drawing of the Elwha impact plate system.

The stainless steel impact plates are 15.9 mm thick, 349 mm in the longitudinal (flow) direction, and 517 mm in the lateral dimension. The plates are mounted with their short sides adjacent to each other on a steel housing that is mounted to the downstream side of a channel spanning concrete weir. Figure 3 shows the configuration of the weir, which is at the crest of an engineered riffle with a slope of 0.015 m/m. Wiring for each instrument is routed to the stream bank through conduit contained within the housing. A low flow notch has been constructed to force low discharges against the intake structure (Figure 4). Additional details about the impact plate system can be found in Hilldale et al. 2014).

A geophone induces a small voltage when a particle with sufficient mass and velocity causes the plate to deform. The voltage is sent to one of three monitoring computers, where the induced voltage is compared to the predetermined threshold value, 0.1 volts. If the voltage surpasses the threshold value, the computer program registers an impulse. The system samples at 20 kHz, accumulating impulses from individual plates for 1 minute. The software then stops collection for 19 seconds to provide limited post processing and write the data to an ASCII file for each plate.

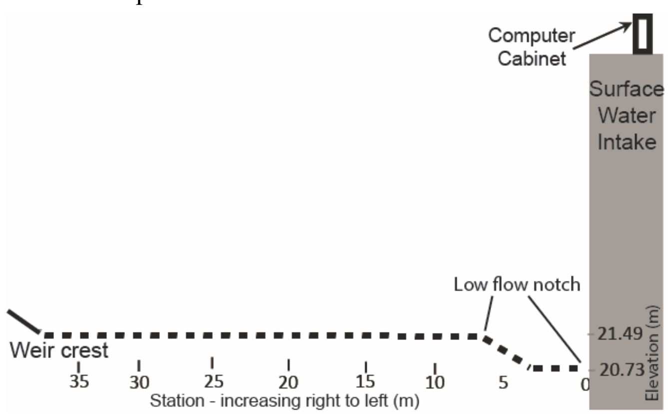

Figure 4: Cross section drawing (looking downstream) of the measurement weir.

System testing and calibration

Testing prior to dam removal indicated that the geophone impact plates are able to detect particles > 16 mm, and the accelerometer plates are capable of detecting particles > 8 mm. Physical bed load measurements for calibration of the geophone plates have been underway since November 2012, shortly after a major release of delta sediment the previous month from Lake Mills during the removal of Glines Canyon Dam. All references to system calibration in this manuscript refer only to those plates instrumented with a geophone. Calibration of the accelerometer plates requires further signal processing prior to field calibration. Flume testing is currently underway to determine an appropriate correlation between the accelerometer signals and measured bed load.

Figure 5: Photographs of the TR-2 (left) and the cataraft (right) used to measure bed load on the Elwha River.

Field measurements of bed load for the purpose of system calibration were made using a TR-2 bed load sampler (Hubble et al 1985) with a 2 mm mesh bag. The TR-2 was deployed using a crane and winch mounted to a 6.4 m long cataraft that was tethered to a tag line across the channel (Figure 5). Five separate bed load sampling trips were made in November 2012, March 2013, May 2013, June 2013, and April 2014.

In November 2012 bed load transport consisted almost entirely of particles finer than 2 mm resulting in no meaningful bed load measurement due to clogging of the 2 mm mesh bag. By March 2013 bed load had coarsened significantly (Figure 6) and obtaining a correlation between measured bed load and registered impulses on the impact plates was possible. However, scatter in the individual surrogate measurements and the physical measurements using very short sample times (1 minute for the impact plate data, < 10 seconds for the physical samples) was significant enough to warrant a different approach to calibration.

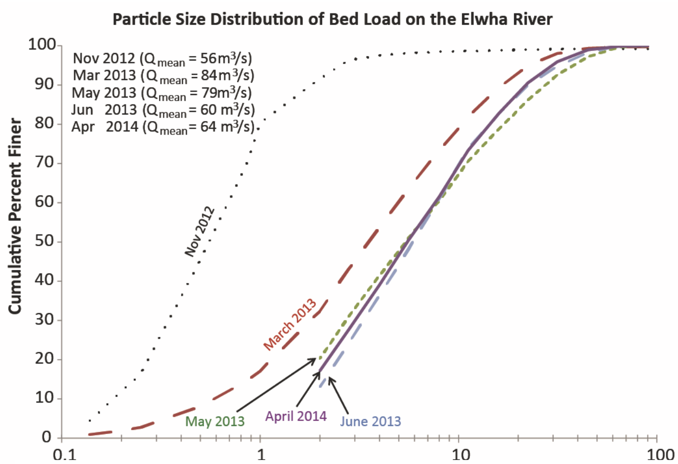

Figure 6: Grain size distribution plots of captured bed load during measurements made for system calibration.

A new methodology used for calibrating the geophone impact plates was employed beginning with May 2013 bed load measurements and uses both temporal and spatial averaging. The spatial average covers a 2 meter lateral distance (1 meter on either side of the TR-2), which will include two or three plates depending on the sampler location relative to the spatial arrangement of the geophone and accelerometer plates. It is assumed that bed load transport across this distance is uniform, which is consistent with USGS bed load measurement protocol outlined in Edwards and Glysson (1999). The temporal averaging uses a 30 minute sample time to obtain a reliable mean, where the TR-2 is deployed at the same station for 30 minutes, typically resulting in nine physical measurements. The period of 30 minutes was chosen based on a temporal analysis of several arbitrarily chosen geophone plates. The cumulative mean and standard deviation of impulses per minute arrived at a steady value in less than 30 minutes under steady flow conditions. This finding is consistent with those from a field study by Kang (1982) and a flume study by Kuhnle and Southard (1988). All measured bed load values are temporally averaged and correlated with a temporal and spatial average of the surrogate measurement from corresponding geophone impact plates. This correlation provides the necessary information with which to perform a field calibration of the impact plate system. Additional details regarding the sampling protocol can be found in Hilldale et al. 2014).

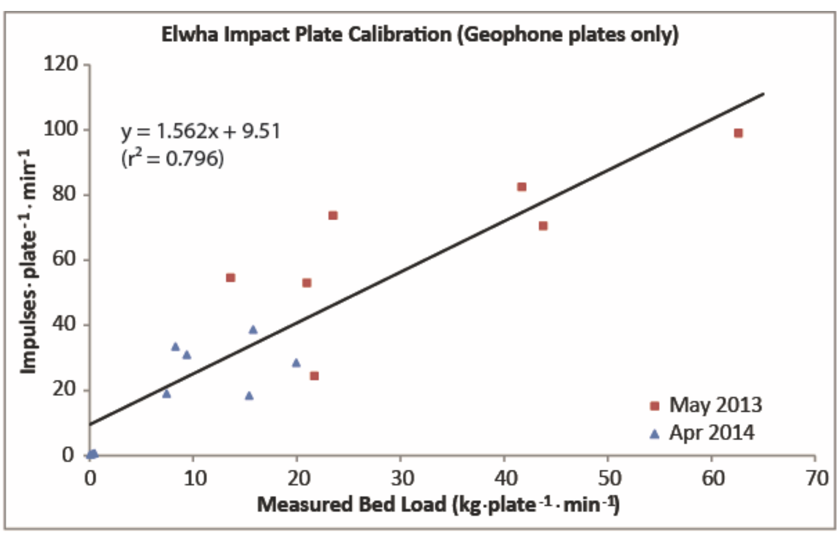

Figure 7: Plot of calibration data for the Elwha impact plate system.

Calibration of the Swiss geophone impact plate system using physical measurements of bed load has been shown to be best represented by a linear regression (Rickenmann et al. 2014). Based on the similarity of the impact plate systems and for comparative purposes, a linear regression has been used for the Elwha impact plate system shown in Equation 1 (Rickenmann et al. 2012):

$$IMP = k_b M \tag{1}$$

Where *IMP* represents the number of registered impulses by the geophone plate(s), *M* is the mass of sediment, and k_b is the calibration coefficient. The most recent calibration of the Elwha geophone impact plates is shown in Figure 7, indicating that k_b = 1.562x + 9.51 with a coefficient of determination (r^2) of 0.796. This calibration factor is considered to be preliminary and may change somewhat with additional data. The k_b value reported here benefits from nine additional calibration points compared to that reported by Hilldale et al. (2014). It should be noted that bed load measurements in June 2013 were not able to be used for calibration due to the malfunction of the computer monitoring system.

BED LOAD MEASUREMENT DURING DAM REMOVAL

Perhaps the most important data obtained from the impact plate system is the measurement of bed load over time. Past research has shown that correlations of bed load transport (Q_s) and discharge (Q) are poor (Habersack 2008) using a power law relationship:

$$BL = aQ^b \tag{2}$$

where BL = bed load in units of mass, Q = discharge in m^3 s^{-1}, a, and b are coefficients. Data from the Elwha bed load impact sensors also indicate that discharge is a poor predictor of bed load transport throughout the year. Figure 8 indicates a wide variability of both the coefficient (a) and exponent (b), varying throughout the year. Exponents nearly span an order of magnitude in this small sample set.

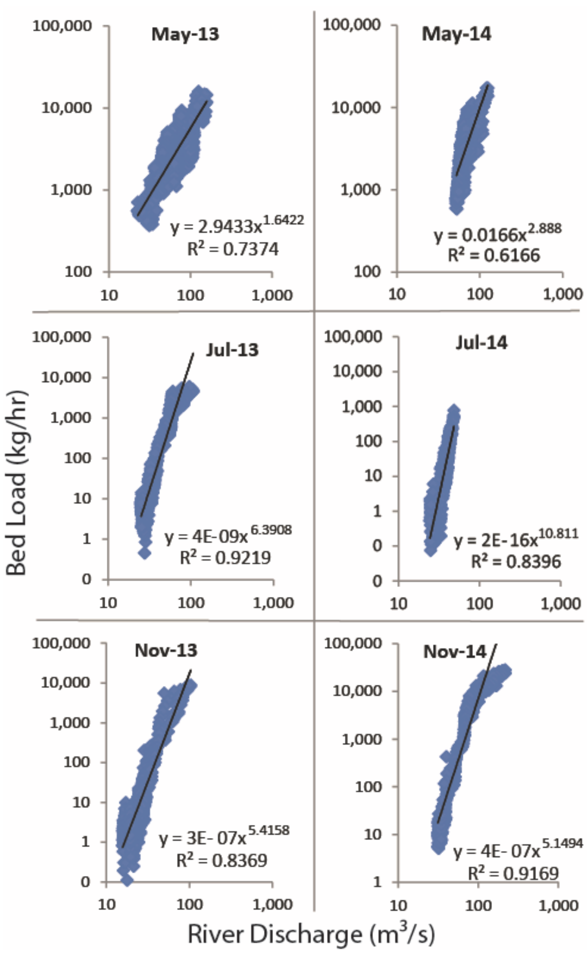

Figure 8: Plots of bed load versus discharge for selected months. November 2014 data reflects only the latter half of the month.

Given the unsatisfying accuracies of quantifying bed load using stage-discharge relationships or transport equations (Bunte 1990, Reid et al. 1985, Habersack et al. 2008, Kuhnle 1992), measurement of bed load presents itself as the better alternative. However, classic means of bed load measurement using pressure difference samplers present other challenges, namely poor temporal resolution, uncertainty related to involuntary particle entrainment (Bunte et al. 2008) and flow disturbance (Habersack et al. 2012). These measurements are difficult and costly to make, and potentially dangerous, on medium to large rivers during peak flows. Additionally, deployment of personnel and equipment to measure bed load during flood events is often logistically prohibitive. The use of surrogate methods for bed load measurement provides a means to eliminate many, if not all, of the challenges regarding physical measurement of bed load (aside from in-situ calibration). Surrogate bed load measurement stands to improve upon the resolution and timeliness of bed load measurement, the accuracy of which being highly dependent upon the in-situ calibration.

Bed load transport > 16 mm on the Elwha River was quantified over the first two years (September 2011 through September 2013) of the incremental removal of Elwha and Glines Canyon dams using the impact plate system and a preliminary calibration of the geophone impact plates (Figure 9, Magirl et al. 2014). Geophone threshold values during most of year-one were set in such a way as to preclude the application of a bed load to surrogate relation. Using the standard deviation of the relative error for the preliminary calibration data (Hilldale 2014), uncertainty of the surrogate measured bed load > 16 mm is ± 52% (Magirl et al. 2014).

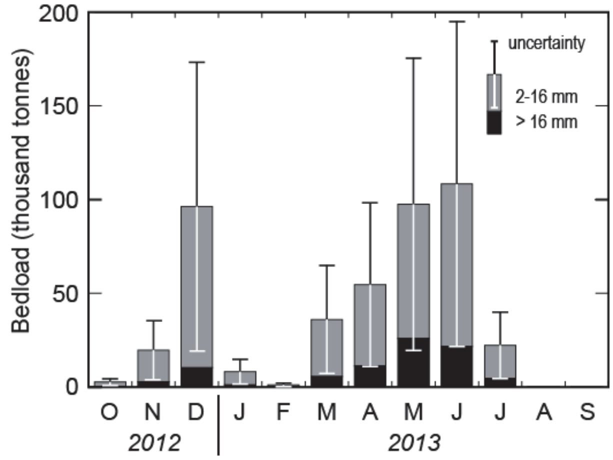

Figure 9: Monthly bed load plot for particles > 16 mm and particles between 2 and 16 mm (from Magirl et al. 2014).

Because there is interest in the total bed load transported during dam removal, bed load from 2–16 mm was estimated using the ratio of coarse-grained (> 16 mm) to finer-grained (2–16 mm) material from the measured bed load samples (Figure 6) and by linearly interpolating between sample periods. The sediment-size distributions from sampled data were used to determine monthly proportions of the two size ranges, providing monthly bed load transport estimates (Figure 9). Uncertainty for bed load between 2 and 16 mm is estimated to be ± 80% (Magirl et al. 2014). For the purpose of this discussion bed load is considered to consist of particles > 2 mm. Readers are referred to Magirl et al. (2014) for additional information regarding sediment loads on the Elwha River during the first two years of dam removal.

BED LOAD TRANSPORT FLUCTUATIONS

Temporal and spatial variation of bed load transport has been documented in both flume (Kuhnle and Southard 1988) and field studies (Kang 1982, Reid et al. 1985, Bunte 1990, Habersack et al. 2001, Habersack et al. 2008, Habersack et al. 2012). Observations of coarse bed load transport on the Elwha present marked temporal and spatial fluctuations over more than three years of observation.

Lateral Variability

Monthly bed load data from November 2012, 2013, and 2014 (Figure 10) indicates significant variability in bed load transport (> 16 mm) across the channel. In November 2012 and November 2014 the greatest proportion of bed load transport is at river right against the surface water intake. During November 2013 bed load transport is primarily focused at stations 9.6 m to 11.7 m (Figure 10). A consistent drop in sediment transport exists at station 6.6 m, where the weir transitions from the low flow notch at river right to the flat portion across the remainder of the channel (see Figure 4). Additionally, coarse bed load transport is consistently very low or non-existent beyond station 32.5 m.

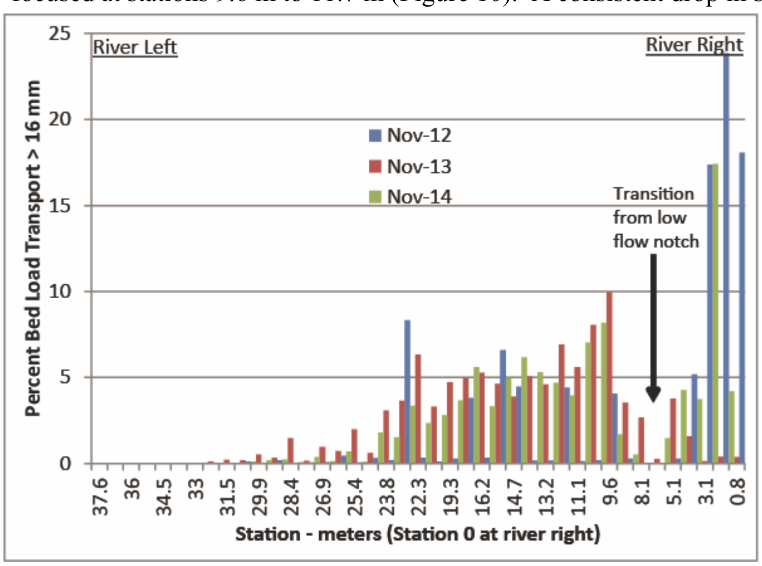

Figure 10: Graph showing the proportion of bed load transported across the channel using impact data from each geophone in the Elwha impact plate system. The transition from the low flow notch to the flat portion of the weir is shown in Figure 4.

Temporal Variability

Short term and long term fluctuations of coarse bed load transport can be examined in detail using 1 minute continuous bed load data. Observations shown in Figure 11 are at a single plate (#18, station 10.1 m) over a selected day of steady flow on May 28, 2013 and May 3, 2014. Plate #18 was chosen because it is within an active portion of the cross section, and the month of May was chosen because it coincides with spring runoff, a period of typically high bed load transport. Upon examination, the periodicity of peak transport typically occurs between 15 and 35 minutes, with a mean fluctuation of approximately 26 and 29 minutes in May 2013 and 2014, respectively.

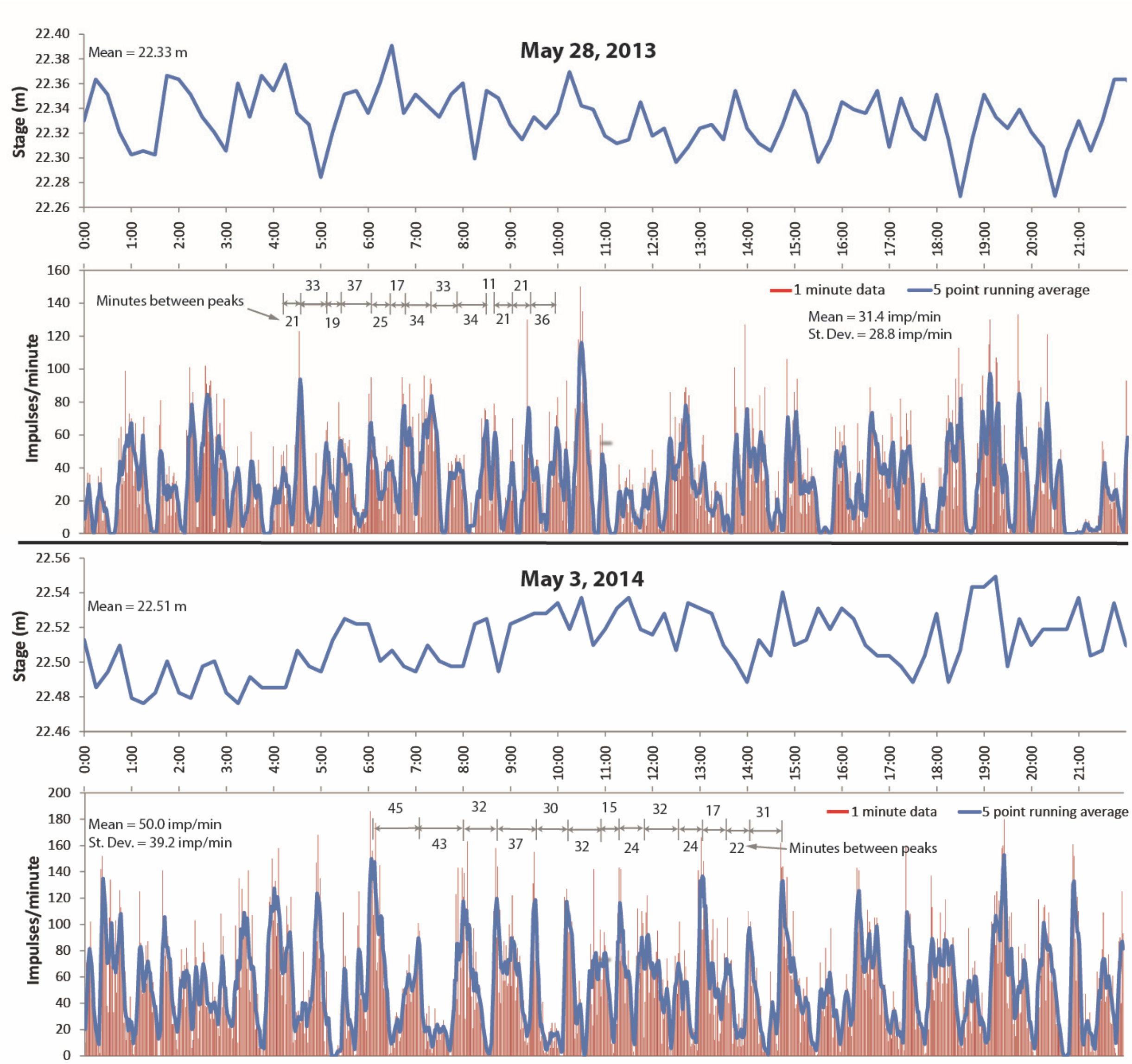

Figure 11: Plot of 1-minute bed load data during steady flow periods, May 28, 2013 and May 3, 2013.

DISCUSSION

The temporal variability in bed load measured with the Elwha impact plate system shows similarities to that measured by Habersack et al. (2008, 2012) on the River Drau, which is a perennial river similarly sized to the Elwha. Bed load measurements by Habersack et al. (2012) were accomplished with; a large Helley-Smith sampler, a bedload trap, and geophone impact plates. Habersack (2012) collected several bed load measurements at a single station using the large Helley-Smith sampler, while high temporal resolution was obtained using the bedload traps and geophone impact plates. All three methods indicate a periodicity of bed load peaks ranging from 15 – 35 minutes, very similar to that found on the Elwha River (Figure 11). Short term temporal variations in bed load have been attributed to the stochastic nature of sediment supply and the passage of dunes or migrating sheets of bed load (Habersack et al. 2008).

Flume experiments by Kuhnle and Southard (1988) also indicated measurable bed load periodicity. The researchers attributed the short term (4 – 16 minutes) fluctuations to long, low amplitude bed load sheets, while the cause for longer term fluctuations (~ 25 minutes) was not conclusively determined. However, Kuhnle and Southard (1988) indicated that a possible cause for the longer term periodicity was related to the formation and subsequent destruction of large clasts, or gravel clusters, on the bed.

Although Figure 11 seems to indicate a quasi-periodicity similar to that found by other researchers (Kuhnle and Southard 1988, Habersack et al 2012), a Fourier analysis of the Elwha impact plate data indicates no dominant frequency for peaks of bed load transport. Kuhnle and Southard (1988) report a similar finding for particles > 16 mm. Results from their flume experiments indicate a significant difference in temporal variability for the largest size class in transport, 16-32 mm, when compared to smaller particles. Kuhnle and Southard's (1988) largest size class (16-32 mm) corresponds to what is measured on the Elwha River with the impact plate system, where 16 mm is the minimum detectable size.

Because the bed load measurements made with the Elwha bed load impact plate system were made during and shortly after dam removal, it is presumed that the Elwha River is oversupplied with sediment, resulting in a transport limited system. Measurements of bed load transport on the Elwha River during this time period indicate an ample supply of sand, disproportionately large soon after the release of large volumes of sediment from Lake Mills (Figure 1) in October 2013. Visual observations were made of a point bar repetitively migrating up and downstream 150 m over the course of several hours, also indicative of an oversupply of sediment.

Based on previous studies (e.g. Reid et al. 1985, Kuhnle and Southard 1988, Habersack et al. 2008, Kuhnle 1992 Strom et al 2004) and data provided by the Elwha bed load impact system, temporal fluctuations of coarse bed load transport can be attributed to gravel bed forms and the stochastic nature of bedload transport, especially for the largest particles in motion. Gravel bed forms are generally limited to gravel sheets and clusters. It has been determined (Proffitt and Sutherland 1983, Dietrich et al. 1989, Hassan and Church 2000, Papanicolaou et al. 2003, and Strom et al. 2004) that gravel cluster bed forms develop under low sediment availability, which is certainly not the condition under which the Elwha bed load observations have been made thus far. This indicates the presence of bed load sheets (or a kinematic wave claimed by Reid and Frostick 1986) as the primary explanation of the temporal fluctuations and apparent periodicity observed on the Elwha River. Many researchers indicate a strikingly consistent temporal fluctuation of bed load transport in the range of 15 – 35 minutes, similar to the findings of the Elwha bed load impact system. These fluctuations, or pulses, occur both in natural streams (Kang 1982, Reid and Frostick 1986, Habersack et al. 2012) and flumes (Kuhnle and Southard 1988, Strom et al 2004) under a variety of hydraulic conditions and sediment supply.

The spatial variability at the measurement cross section on the Elwha River (Figure 10) can be attributed to three major factors. 1) The geometry of the measurement weir affects flow patterns in and near the low flow notch influencing bed load transport. 2) Approximately 160 meters upstream of the measurement weir the Elwha River makes a 90 degree turn to the left, forcing flow to river right against bedrock. This forms a point bar at the bend which, at times of very high sediment supply, has extended downstream to the measurement weir on river left. 3) The presence of a wing wall on river right (17-23 m upstream of the measurement weir) focuses high velocity in the center-right portion of the cross section (approximately stations 9 – 12 m). However, these geometrical features do not explain why the highest proportion of bed load transport has changed location throughout the observation period. The temporal fluctuation of the highest concentration of bed load transport is the result of changing bed geometry upstream of the measurement weir during and after dam removal, which can be attributed to the oversupply of sediment. During bed load measurements with a TR-2 in November 2012, shortly after the large release of sediment from Lake Mills, bed elevation was measured at a single station documenting two dune cycles with a period of 12 and 15 minutes and an amplitude of 0.2 m. For three consecutive days in March 2013, depth measurements taken during discharge measurements indicated the position of the thalweg at stations 16.4, 14.4, and 7.4 meters on March

13, 14, and 15, respectively. With such shifting bed conditions it is expected that the location of the highest concentration of bed load transport will be very dynamic.

Power law relationships of coarse bed load to river discharge (Figure 8) indicate a broad range of coefficient *a* and exponent *b* (Eq. 2). Arriving at definitive conclusions regarding the relationship between river discharge and bed load transport on the Elwha River may be premature due to the changing conditions of sediment supply during and after dam removal, but there appears to be a seasonal consistency thus far, with seasonal run-off providing the lowest exponent (*b*) in the power law relationship (Eq. 2). The nature of the hydrograph and antecedent conditions likely plays a role in the intra-annual variability of the coefficient and exponent of the power law relationship. Continuous bed load data from the Elwha impact plate system will provide valuable insight into various bed load transport predictors.

CONCLUSIONS AND OUTLOOK

The Elwha impact plate system is in a state of preliminary calibration of the geophone plates, while the accelerometer plates are currently being tested in the flume. The calibration of the geophone impact plates will improve with additional bed load measurements and calibration data. However, it remains to be seen if the calibration will change significantly with the coarsening grain size distribution and decrease in sediment supply as the Elwha River works toward equilibrium transport conditions. Turowski and Rickenmann (2009) have shown that a cover effect plays a role in the calibration of an impact plate system, where increased sand loads dampen the impact of gravel particles on a plate. This occurrence will be evaluated as the calibration moves forward.

The method of system calibration described in this paper, using spatial and temporal averaging with multiple physical measurements over a 30-miute period, provides a reliable mean bed load transport rate with which to calibrate the impact plate system. It is acknowledged that pressure difference samplers are intrusive (Habersack et al. 2012) and sampling efficiency varies widely depending on the sampler characteristics (Johnson et al. 1977, Beschta 1981, O'Leary and Beschta 1981, Bunte et al. 2008). Every effort was made to insure, to the extent possible, that involuntary entrainment did not take occur upon placement on the bed and that the TR-2 did not scoop sediment upon retrieval during bed load measurements collected for calibration of the Elwha impact plate system. Sampler characteristics and deployment methodology remained constant throughout bed load measurements for system calibration. Given the limitations of physical bed load measurement at the measurement weir, using a pressure difference sampler (e.g. TR-2) deployed from a tethered raft is the only feasible option. Based on the findings of this study and by Kuhnle and Southard (1988), a 30-minute temporal average at a single station appears sufficient to capture the temporal variability in bed load transport, greatly improving the accuracy of the measurement and therefore improving the calibration of the Elwha impact plate system. It is acknowledged that Bunte et al. (2004) concluded that it may take up to 1 hour to sample the largest particles in transport using Dietrich and Whiting's (1989) proposed method for estimating minimum sampling time. Because physical bed load measurements are being collected for several hours for system calibration, it is presumed that the largest particles in transport are being measured and included in the calibration.

Reid and Frostick (1986) claimed that "the predictive modeling of bed load transport in alluvial rivers has made faltering progress over the past 50 years". This statement was made some 30 years ago and the performance of bed load formulas remains poor (Habersack et al. 2008). Certainly, the inability to obtain quality bed load measurements with sufficient temporal and spatial density can be blamed for the lack of progress, as well as the fact that bed load transport is a complex process. Kleinhans and van Rijn (2002) note that the hiding and exposure function in bed load transport equations is the primary uncertainty for predicting fractional bed load transport, which is consistent with temporal variability demonstrated here. Similarly, Kuhnle (1992) concludes that the formation and destruction of bed forms and the presence of bed load sheets are responsible for short term temporal variability in bed load transport. The uncoupled relationship of bed load transport with stage, giving rise to event based and in some cases annual hysteresis is another cause of unsteadiness in bed load flux. The details mentioned here are poorly understood, but given the recent advancements in and implementation of continuous bed load measurement, our understanding of bed load transport stands to improve in the coming decades.

The Elwha impact plate system shows great promise for future evaluation of bed load transport in a moderately sized, perennial, gravel bed river. It will be possible to examine the intricacies of coarse bed load transport with high resolution data from a Eularian perspective. Equally as important will be the knowledge gained from continuous bed load measurement over a period of many years during and after the removal of two large dams. Furthermore, continuous measurement of bed load can be combined with continuous suspended load measurements on the Elwha River through collaboration with the USGS (Magirl et al. 2014), who are continuously measuring suspended sediment concentration using turbidity and acoustic backscatter at the measurement weir containing the bed load impact plates.

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REFERENCES

Bänziger, R., Burch, H. (1990). "Acoustic sensors (hydrophones) as indicators for bed load transport in a Mountain Torrent." *Hydrology in mountain streams. I—Hydrological measurements; The water cycle*, H. Lang and A. Musy, eds., International Association of Hydrological Sciences, Wallingford, U.K., 207–214.

Beschta, R. L. (1981). "Increased bag size improves Helley-Smith bed load sampler for use in streams with high sand and organic matter transport." *Erosion and sediment transport measurement*, International Association of Hydrological Sciences, 17–25.

Bunte, K. (1990). "Experiences and results from using a big-frame bed load sampler for coarse material bed load", *Hydrology in Mountainous Regions I – Hydrological Measurements, the Water Cycle*, Proceedings of two Lausanne Symposia, August, IAHS Publ. no. 193.

Bunte, K., Abt, S. R., Potyondy, J. P., and Swingle, K. W. (2008). "A comparison of coarse bedload transport measured with bedload traps and Helley-Smith samplers." *Geodinamica Acta*, 21(1–2), 53–68.

Curran, C.A., Konrad, C.P., Higgins, J.L., and Bryant, M.K. (2009). "Estimates of sediment load prior to dam removal in the Elwha River, Clallam County, Washington", US Geological Survey Scientific Investigations Report 2009-5221, Reston, VA, 18pp.

Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F. (1989). "Sediment supply and the development of the coarse surface layer in gravel-bedded rivers", *Nature* (London), vol. 340, pp. 215-217.

Dietrich, W. E., and Whiting, P. (1989). ''Boundary shear stress and sediment transport in river meanders of sand and gravels.'' *River Meandering*, S. Ikeda and G. Parker, eds., Water Resource Monograph 12, American Geophysical Union, Washington, D.C., 1–50.

Duda, J.J., Warrick, J.A., Magirl, C.S., 2011. Coastal and lower Elwha River, Washington, prior to dam removal—History, status, and defining characteristics. In Duda, J.J., Warrick, J.A., and Magirl, C.S., eds., Coastal habitats of the Elwha River, Washington—Biological and physical patterns and processes prior to dam removal. U.S. Geological Survey Scientific Investigations Report 2011-5120, 1-26 pp.

East, A.E., Pess, G.R., Bountry, J.A., Magirl, C.S., Ritchie, A.C., Logan, J.B., Randle, T.J., Mastin, M.C., Minear, J.T., Duda, J.J., Liermann, M.C., McHenry, M.L., Beechie, T.J., and Shafroth, P.B., 2015, Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. *Geomorphology*, v. 228, p. 765–786, DOI:10.1016/j.geomorph.2014.08.028.

Edwards, T. K., and Glysson, G. D. (1999). "Field methods for measurement of fluvial sediment." Techniques of water-resources investigations, U.S. Geological Survey, Denver, CO.

Gray, J.R., Laronne, J.B., Marr, J.D.G. (2010). Bedload surrogate monitoring technologies, US Geological Survey Scientific Investigations Report 2010-5091. US Geological Survey, Reston, VA. http://pubs.usgs.gov/sir/2010/5091/ (Accessed Jan 5, 2015).

Habersack, H.M., Nachtnebel, H.P., Laronne, J.B. (2001). "The continuous measurement of bedload discharge a large alpine gravel bed river", *Journal of Hydraulic Research*, 39:2, 125-133, DOI:10.1080/00221680109499813.

Habersack, H. M., Seitz, H., and Laronne, J. B. (2008). "Spatio-temporal variability of bedload transport rate: Analysis and 2D modeling approach." *Geodinamica Acta*, 21(1–2), 67–79.

Habersack, H., Kreisler, A., Aigner, J., Leiderman, M., Seitz, H. (2012). "Spatio-temporal variability of bedload transport", in: River Flow 2012, Murillo (Ed)., pp. 423-430, Taylor and Francis Group, London.

Hassan, M. A., Church, M. (2000). "Experiments on surface structure and partial sediment transport on a gravel bed", Water Resources Research, 36(7), pp. 1885-1895.

Hilldale, R.C., Carpenter, W.O., Goodwiller, B., Chambers, J.P., Randle, T.J. (2014). "Installation of Impact Plates to Continuously Measure Bed Load: Elwha River, Washington, USA", *Journal of Hydraulic Engineering*, DOI:10.1061/(ASCE)HY.1943-7900 published on line 11/19/2014 http://ascelibrary.org/doi/abs/10.1061/(ASCE)HY.1943-7900.0000975.

Hubble, D. W., Stevens, H. H., Skinner, J. V., and Beverage, J. P. (1985). "New approach to calibrating bed load samplers." *J. Hydraul. Eng*., 10.1061/(ASCE)0733-9429(1985)111:4(677), 677–694.

Johnson, C. W., Engleman, R. L., Smith, J. P., and Hansen, C. L. (1977). "Helley-Smith bed load samplers." *J. Hydraul. Div*., 103(10), 1217–1221.

Kang, S. (1982). "Sediment transport in a small glacial stream: Hilda Creek, Alberta", M.S. Thesis, 265 pp., Univ. of Illinois at Chicago.

Kleinhans, M.G., van Rijn, L.C. (2002). "Stochastic prediction of sediment transport in sand-gravel bed rivers", *Journal of Hydraulic Engineering*, vol. 128, no. 4, pp. 412-425.

Kuhnle, R.A. and Southard, J.B. (1988). "Bed load transport fluctuations in a gravel bed laboratory channel", *Water Resources Research*, vol. 24, no. 2, February, pp. 247-160.

Kuhnle, R.A. (1992). Bed load transport during rising and falling stages on two small streams", *Earth Surface Processes and Landforms*, vol. 17, pp. 191-197.

Magirl, C.S., Hilldale, R.C., Curran, C.A., Duda, J.J., Straub, T.D., Damanski, M., Foreman, J.R. (2014). "Large-scale dam removal on the Elwha River, Washington, USA: Fluvial sediment load", *Geomorphology*, DOI:10.1016/j.geomorph.2014.12.032. published online 12/26/14, http://www.sciencedirect.com/science/article/pii/S0169555X14006369.

Munn, M.D., Black, R.W., Haggland, A.L., Hummling, M.A., and Huffman, R.L. (1998). "An assessment of stream habitat and nutrients in the Elwha River basin – Implications for restoration", US Geological Survey Water Investigations Report 98-4223, Tacoma, WA, 38p.

O'Leary, S. J., and Beschta, R. L. (1981). "Bed load transport in an Oregon Coast Range stream." *J. Am. Water Resour. Assoc*., 17(5), 886–894.

Papanicolaou, A.N., Strom, K., Schuyler, A., Talebbeydokhti, N. (2003). "The role of sediment specific gravity and availability on cluster evolution", *Earth Surface Processes and Landforms*, vol. 28, pp. 69-86.

Proffitt, G.T., Southerland, A.J. (1983). "Transport of non-uniform sediments", *Journal of Hydraulic Research*, 21(1), pp. 33-43.

Reid, I., Frostick, L.E., Layman, J.T. (1985). "The incidence and nature of bedload transport during floods in coarse-grained alluvial channels", *Earth Surface Process and Landforms*, vol. 10, pp. 33-44.

Reid, I., and Frostick, L.E. (1986). “Dynamics of bedload transport in Turkey Brook, a coarse-grained alluvial channel”, *Earth Surface Processes and Landforms*, vol. 11, pp. 143-155.

Rickenmann, D. and McArdell, B.W. (2007). “Continuous measurement of sediment transport in the Erlenbach stream using piezoelectric bedload impact sensors”, *Earth Surface Processes and Landforms*, **32**, 1362 – 1378.

Rickenmann, D., Turowski, J. M., Fritschi, B., Klaiber, A., and Ludwig, A. (2012). “Bedload transport measurements at the Erlenbach stream with geophones and automated basket samplers.” *Earth Surf. Processes Landforms*, 37(9), 1000–1011.

Rickenmann, D., Turowski, J.M., Fritschi, B., Wyss, C., Laronne, J., Barzilai, R., Reid, I., Kreisler, A., Aigner, J., Seitz, H., Habersack, H. (2014). “Bedload transport measurements with impact plate geophones: Comparison of sensor calibration in different gravel-bed streams.” *Earth Surf. Process. Landforms,* 39(7), 928–942.

Strom, K., Papanicolaou, A.N., Evangelopoulos, N., Odeh, M. (2004). “Microforms in gravel bed rivers: Formation, disintegration, and effects on bedload transport”, *Journal of Hydraulic Engineering*, vol. 130, no. 6, pp. 554-567.

Tsakiris, A.G., Papanicolaou, A.N., Lauth, T.J. (2014). “Signature of bedload particle transport mode on the acoustic signal of a geophone”, *Journal of Hydraulic Research*, vol. 52, no. 2, pp. 185-205, DOI:10.1080/00221686.2013.876454.

Turowski, J. M., and Rickenmann, D. (2009). “Tools and cover effects in bedload transport observations in the Pitzbach, Austria.” *Earth Surf. Processes Landforms*, 34, 26–37.